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Field Implementation and Evaluation of Low-Cost Countermeasures for Wrong-Way Driving Crashes in Alabama

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Wrong-way driving (WWD) has been identified as a critical traffic safety problem. Research efforts have been made to mitigate WWD issues in Alabama, including investigating factors contributing to WWD crashes, modeling WWD risks at interchange terminals, and developing training materials for WWD countermeasures. The Alabama Department of Transportation (ALDOT) crash database, along with the hardcopy of WWD crashes, was used to identify the crashes caused by wrong-way (WW) drivers. Based on the analysis results, factors, including time of day, driver age, driver condition, driver residency distance, vehicle age, and roadway conditions, were found to contribute to WWD crashes. A follow-up study funded by ALDOT developed the predictive models to quantify the risk of WWD at freeway off-ramp terminals (Zhou and Atiquzzaman 2019). Mathematical models and network screening tools were developed for full diamond and partial cloverleaf (parclo) interchanges for state transportation agencies to identify high-risk locations for improvement to deter WWD incidents. Training materials on WWD countributing factors and solutions were developed for ALDOT to train state and local agencies on guidelines for reducing WWD on freeways. Two pilot trainings were conducted in Montgomery, AL in 2017 and 2018, respectively. Additional three local transportation assistance program (LTAP) classes were hold in Mobile, Montgomery, and Birminham, AL, respectively, in 2019.

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1. INTRODUCTION

Wrong-way driving (WWD) has been identified as a critical traffic safety problem. Research efforts have been made to mitigate WWD issues in Alabama, including investigating factors contributing to WWD crashes, modeling WWD risks at interchange terminals, and developing training materials for WWD countermeasures. A statewide study identified the contributing factors to WWD crashes on freeways and divided highways in Alabama (Zhou et al. 2015b; Zhou et al. 2016). The Alabama Department of Transportation (ALDOT) crash database, along with the hardcopy of WWD crashes, was used to identify the crashes caused by wrong-way (WW) drivers. Based on the analysis results, factors, including time of day, driver age, driver condition, driver residency distance, vehicle age, and roadway conditions, were found to contribute to WWD crashes. A follow-up study funded by ALDOT developed the predictive models to quantify the risk of WWD at freeway off-ramp terminals (Zhou and Atiquzzaman 2019). Mathematical models and network screening tools were developed for full diamond and partial cloverleaf (parclo) interchanges for state transportation agencies to identify high-risk locations for improvement to deter WWD incidents. Training materials on WWD countributing factors and solutions were developed for ALDOT to train state and local agencies on guidelines for reducing WWD on freeways. Two pilot training sessions were conducted in Montgomery, AL in 2017 and 2018, respectively. Three additional local transportation assistance program (LTAP) classes were hold in Mobile, Montgomery, and Birmingham, AL, respectively, in 2019.

Various Intelligent Transportation System (ITS) technologies have recently been implemented by transportation agencies to deter WWD. However, few were implemented in Alabama due to higher cost and lack of quick emergency responses in rural areas. The cost of sensor/camera-based ITS countermeasures range from $50,000 to $150,000 per site, including initial installation and maintenance (NCRRS 2018), which makes it unlikely to deploy them at every WWD-prone location. Low-cost countermeasures, such as rumble strips, signs, and pavement markings, are relatively inexpensive. However, their effectiveness remains unclear. The main objective of this study is to evaluate the effectiveness of a set of low-cost countermeasures on deterring WWD through field implementation at freeway off-ramp terminals in Alabama. In addition, four case studies were conducted on multilane divided highways to evaluate strategies for reducing WWD through access management strategies. The field WWD incident data collected indicated that a high percentage of WWD incidents were caused by truck drivers. Therefore, an extra effort was made to conduct an in-person survey of truck drivers to assess their needs and preferences on WWD countermeasures.

Southbound (SB) off-ramps at Exits 208 and 284 on I-65 in Alabama were ranked as high-risk locations for WWD based on the prediction model results (Zhou and Atiquzzaman 2019). Both are partial cloverleaf (parclo) interchanges with the similar design features that may induce WWD incidents. Based on the model, the probability of having one WWD crash over five years is 60% at Exit 208 and 71% at Exit 284. Video cameras initially recorded an average of 10 WWD incidents at each location during a typical weekend (48 hours). ALDOT regional engineers implemented a set of low-cost countermeasures to mitigate WWD activities at these two locations.

The Auburn research team worked closely with ALDOT regional engineers to evaluate impacts of the low-cost countermeasures on deterring WWD incidents at these two locations. Two before-and-after studies were conducted at I-65 Exits 208 and 284. One was conducted to evaluate the effectiveness of traditional low-cost countermeasures, including signs, pavement markings, and geometric features implemented by ALDOT. More than 800 hours of video data were collected for both before-and-after periods. The primary measure of effectiveness (MOE) for the evaluation is the frequency of WWD incidents before and after the improvements. Another before-and-after study was conducted to evaluate the directional rumble strips (DRS) implemented at these two locations by Auburn University. A previous project (Zhou et al. 2018) recommended to implement three DRS design patterns in the field. The objective of the second before-and-after study was to evaluate the impacts of these three DRS patterns on WWD incidents and distance, as well as right-way drivers' speed and behavior. Based on the findings, guidelines for implementing the DRS on off-ramps were developed to reduce WWD incidents and right-way traffic speed .

The before-and-after study results showed that a large percentage of WWD vehicles are trucks, especially at I-65 Exit 208. An in-person survey was conducted to collect truck drivers' feedback on WWD countermeasures at a truck station near I-65 Exit 208 and another truck driver rest area near I-85 Exit 147 in Georgia. . One hundred and fifteen completed questionnaires were collected. Results can be used to improve traffic control devices (TCDs) and geometric design features for reducing WWD risk by truck drivers at off-ramp terminals.

In addition to freeway off-ramps, four case studies were conducted to collect WWD incident data on divided highways (US 280) in Alabama. According to the previous results (Zhou et al. 2015b), researchers identified ten locations with WWD crash history on multilane divided highways to collect WWD incident data through traffic cameras. Four of these locations were selected in this study to represent four different access management deficiencies that can result in intentional WWD incidents, including driveways with a close upstream median opening and a long weaving distance for J-turns, poor front access control, lack of backage road connection, and median openings with limited sight distance due to significant grade difference. The confirmed WWD activities for a 48-hour period on a typical weekend were recorded and analyzed to better understand why people intentionally drive the WW and what access management techniques can be applied to prevent such undesirable movements.

This report summarizes the research activities and findings for the project funded by ALDOT on field implementation and evaluation of low-cost countermeasures on deterring WWD in Alabama. Chapter 2 reviews the literature of existing countermeasures/strategies for deterring WWD. Chapter 3 discusses the effects of signs, pavement markings, and geometric design features on reducing WWD incidents at freeway off-ramp terminals. Chapter 4 provides the field implementation results of DRS for deterring WWD on freeway off-ramps. To assess the needs and preferences for WWD countermeasures, Chapter 5 summarizes the survey results of truck drivers regarding WWD at freeway off-ramps. Chapter 6 elaborates on the case studies of WWD on multilane divided highways. Conclusions and recommendations are contained in Chapter 7.

2. LITERATURE REVIEW

2.1 WWD Countermeasures for Freeways

In 2013, the first National WWD Summit provided a platform for practitioners and researchers to exchange ideas on the current practices to reduce WWD incidents and crashes. Attendees included members from the National Transportation Safety Board (NTSB), Federal Highway Administration (FHWA), American Traffic Safety Services Association (ATSSA), state departments of transportation (DOTs), state police, state highway patrols, tollway authorities, universities, and consulting firms. Based on the survey, discussions, and presentations at the summit, the countermeasures outlined in Table 1 are candidates that were either implemented or worthy of implementation for mitigating WWD incidents and crashes (Pour-Rouholamin et al. 2015a; Zhou and Pour-Rouholamin 2014a; Zhou and Pour-Rouholamin 2014b).

Advanced ITS technologies have been adopted by transportation agencies for deterring WW entries at freeway off-ramp terminals. In 2004, California DOT (Caltrans) deployed in-pavement warning lights on off-ramps, which were susceptible to deter WWD incidents (Cooner et al. 2004). The lights were activated when a vehicle was detected to enter the WW direction; however, no evaluation regarding their success was conducted. In 2007, the Harris County Toll Road Authority in Texas installed a WW detection system on 13.2 miles of toll roads (TransCore 2008). The system consisted of radar sensors for detecting WW vehicles and audible alarm software for dispatching the closest law enforcement. Accordingly, 23 WW drivers had been stopped or turned around since the implementation. In 2010, the Florida DOT (FDOT) tested video-detection techniques on expressway off-ramps (Rose 2011). A number of false alarms were reported due to movements of vehicles on the shoulder, dark shadows, and the reflection of headlights from the wet pavement. According to a recent study on testing and evaluating video systems in Florida, the systems performed with detection accuracies of above 94%. They were able to send an email notification to the traffic management center (TMC) if a WWD was detected (Lin et al. 2018a). In January 2018, the Arizona DOT (ADOT) implemented the first-in-nation WW driver pilot system along I-17 in Phoenix (Cain et al. 2018). The 15-mile system with a total cost of 3.7 million dollars included thermal cameras, internally illuminated signs with flashing borders, message boards, and the decision-support software. Though the system provided accurate detection, around 10 false detections per month per camera were caused by camera shaking due to the wind. Therefore, the high cost and insufficient reliability of ITS make them less possible to be implemented at every potentially WWD-prone location.

Table 1. Candidate Countermeasures for Mitigating WWD Incidents and Crashes (Pour-Rouholamin et al. 2015a)

ITS Technologies	▪ LED Illuminated Signs ▪ Dynamic Signs: Warn Other Drivers ▪ Use Existing GPS Navigation Technologies to Provide WW Movement Alerts ▪ Provide Consistent Messages or Alerts that are Intuitive to the Driver
Signage	▪ Implementing Standard WW Sign Package ▪ Improved Static Signs ▪ Lowering Sign Height ▪ Using Oversized Signs ▪ Mounting Multiple Signs on the Same Post ▪ Applying Red Retroreflective Strip to the Vertical Posts ▪ "Freeway Entrance" Sign for All On-Ramps
Pavement Marking	▪ Stop Line ▪ WW Arrow ▪ Turn/Through Lane Only Arrow ▪ Red Raised Pavement Markers ▪ Short Dashed Lane Delineation Through Turns
Geometric Improvement	▪ On/Off-Ramp Separation ▪ Raised Curb Median ▪ Longitudinal Channelizers ▪ Change in Ramp ▪ Geometrics: Obtuse Angle; Sharp Corner Radii

In order to evaluate the effectiveness of low-cost countermeasures in deterring WWD, the ENTERPRISE Pooled Fund Program recently conducted a project to help increase members' understanding of current practices for WWD countermeasures on freeways (Athey Creek

Consultants 2016). The report provided an overview of countermeasures for mitigating WWD. Selected emerging approaches and technologies were described in Table 2. Preliminary results showed that these low-cost improvements have the potential to reduce WWD incidents but further studies are needed to quantify their effectiveness.

Table 2. Summary of Low-Cost Countermeasures from State DOT's Practice

State DOT	Countermeasures	Deployment Dates	Evaluation Efforts/Results	Data Used
Arizona	▪ Low-mounted WW Signs ▪ WW and DO NOT ENTER (DNE) signs mounted on same post ▪ Red reflective strips on sign posts ▪ Larger WW and DNE signs ▪ WW signs on overhead structures ▪ WW arrows with raised reflective pavement markers ▪ Left-turn pavement marking guides	2014-2015	Formal evaluation not planned	N/A
Connecticut	▪ Low-mounted WW and DNE signs ▪ Larger WW and DNE signs ▪ Additional WW and DNE signs beyond standard minimums ▪ Red reflective tape on posts ▪ Wider stop bars ▪ Skip line extensions to on-ramp ▪ Double yellow line between ramps	2015	Evaluation planned for 2-3 years after deployment (before/after evaluation)	2-3 years of crash data before the ramp improvements and 2-3 years of data after improvements
Florida	▪ Additional DNE, WW, and One-Way signs on both sides of ramp ▪ No Right/Left Turn signs ▪ Low-mounted WW signs ▪ Oversized WW signs ▪ Retroreflective strip on WW sign posts ▪ Dotted guide line for left turns ▪ Reflective yellow paint on ramp median nose ▪ Straight arrow, route shield, and ONLY approaching ramp entrance	2015 (ongoing)	Difficult to evaluate the effectiveness of the countermeasures due to the random nature of WWD crashes	N/A
Michigan	▪ Low-mounted WW and DNE signs ▪ Red reflective tape on sign posts	2012-2017	Formal Evaluation will be conducted after several years	Number of WWD Crashes

Ohio	▪ Two WW signs on same post, lower sign ▪ Dual directional route marker signs at end of ramp ▪ Red reflective tape on sign posts ▪ Additional signs beyond standard minimums ▪ Extension lines to entrance ramp ▪ Painted island between entrance/exit ramps ▪ WW arrows on exit ramps	2008 and 2013	Formal evaluation not planned	N/A
Rhode Island	▪ Type 11 signs (most reflective) ▪ Low-mounted signs ▪ Oversized signs ▪ "No Left Turn" mast arm signing ▪ Signs on both sides of ramp ▪ Red reflective sign post reflectors ▪ Arrows with recessed delineators ▪ Extension lines to entrance ramp ▪ Straight arrow signal indication	2015	Formal evaluation not planned	Video captured by traffic camera were used to verify the effectiveness of system
Washington	▪ Low-mounted signs ▪ Additional DNE and One-Way signs ▪ WW pavement marking arrows ▪ Skip line extensions to entrance ramp	2012-2013	Evaluation in progress (Tracking of the number and the location of WWD events)	WWD events notified by State Patrol
Wisconsin	▪ WW and DNE signs on same post, with lower WW sign ▪ Additional signs - both sides of ramp ▪ Added "No Left /Right Turn" signs ▪ Added Freeway Entrance Signs at side by side ramps ▪ Skip lines to entrance ramps ▪ Additional turn arrows or WW arrows ▪ WW signs with LED around border on each side of ramp	2013-2015	Began tracking data to assess the effectiveness of the countermeasures	WW report, WWD incidents, WWD crashes

A number of studies have also been conducted to evaluate the effectiveness of low-cost countermeasures for deterring WWD. A recent study conducted by Lin and Ozkul evaluated seven WWD countermeasures in Florida by field WWD testing, surveying, and driving simulator experiments (Lin et al. 2018b). The study evaluated the newly developed minimum Signing & Pavement Marking (S&PM) standards for interstate off-ramp intersections, published by FDOT, as a positive countermeasure on arterials to mitigate WW entries on freeways (Lin et al. 2017). The study also proved the effectiveness of red Rectangular Rapid Flash Beacons (RRFBs), Wigwag Flashing Beacons, detection-triggered blank-out signs that flash “WRONG WAY”, and detection-triggered LED lights around WRONG WAY signs in mitigating WWD on freeway off-ramps. The study also pointed out that the red flush-mount Internally Illuminated Raised Pavement Markers (IIRPMs) can be used as a supplemental countermeasure. The delineators along off-ramps was deemed as the least effective countermeasure (Lin et al. 2018b). In 2017, Ozkul, and Lin evaluated the effectiveness of Rapid Flash Beacons (RFBs) and red RRFBs on preventing WWD on freeway off-ramps. The results showed that RRFBs were deemed to be a more effective countermeasure to deter WWD than RFBs (Ozkul and Lin 2017). The Texas DOT (TxDOT) had experienced a 30% reduction in WWD incident frequency after adding Flashing LEDs to WRONG WAY sign borders (Finely et al. 2014). The North Texas Tollway Authority (NTTA) reported that the application and improvement of pavement markings at problematic locations resulted in the reduction of WWD incidents by 40% (Ouyang 2014). In 2008, Miles and Carlson conducted a study to evaluate driver’s understanding of red retroreflective raised pavement markings (RRPMs) through a survey. The research found that replacing supplemental RRPMs with supplemental arrows can always improve the rate of correct responses for all roadway configurations (Miles et al. 2008). In 2005, a before-and-after study was performed in College Station, Texas, to evaluate the effectiveness of directional arrows painted on two-way frontage roads to prevent WW entries. The study found that the WW entries in the study area were reduced from 7.4 percent to 0.7 percent, a 90-percent reduction of the rate due to the implementation of the directional arrows in the after period (Chrysler and Schrock 2005). The evaluation conducted by Leduc showed the sites treated by Caltrans with lower mounting signs experienced a 90% reduction in WWD incident frequency (Leduc 2008). Campbell and Middlebrooks studied the effect of several countermeasures preventing WWD at an off-ramp in Atlanta, Georgia, by using actual counts. These countermeasures include trailblazers, low mounted “WRONG WAY” signs, stop bar at the end of the off-ramp, and yellow ceramic buttons that can be used to improve the visibility of the pavement markings. The study found that the WW entries can be reduced by more than 97% due to the implementation of these countermeasures (Campbell and Middlebrooks 1988).

Conventional countermeasures such as signage or pavement markings may not be effective for certain types of WW drivers, such as DUI or impaired driver. For example, WW signs can only visually alert WW drivers in the assumption of being seen by them. Regardless of the false alarms, most new ITS techniques can provide enhanced visual alert to WW drivers. Few conventional and advanced countermeasures can provide audible and tactile signals to alert WW drivers. To fill this gap, directional rumble strips (DRS) were developed based on transverse rumble strips (TRS), which can provide motorists with audible, visual, and tactile signals when approaching a decision point. The DRS study by Xue et al. (2019) summarized TRS design guides and their effectiveness in terms of sound and vibrations. Five DRS patterns (A to E) were initially developed, but later were filtered to three (C, D, and E) based on the results of a national survey. The initial and verification experiments tested these three patterns with different configurations (e.g., D1, D2, and D3) in a closed course. Both test results pointed out that DRS can alert WW drivers with elevated in-vehicle sound and vibrations. Recommendations were made as follows: Pattern D3 was suggested for installation close to the stop bar/yield line at an off-ramp terminal; Pattern C can be implemented on the straight long segment of an off-ramp; and Pattern E.1 was recommended for installation before the ramp curve of an off-ramp.

Besides WW-related TCDs, studies also showed that geometric design features may have impacts on WWD. A study showed that 93.5% of WWD crashes occurred from drivers entering the freeway through an off-ramp in Illinois (Zhou et al. 2012). The NTTA in Texas proposed to close the median opening at the crossroad to eliminate the possibility of WW left turns onto the off-ramps, which resulted in no more WWD incidents after the project completion (Ouyang 2013). The Michigan DOT applied longitudinal channelizing devices on 161 parclo interchanges (Morena and Ault 2013). The investigation showed that zero WWD crashes have occurred in a year since completion of this project in 2012. Some previous studies investigated the effect of geometric design elements on the probability of WWD incidents, such as the control radius from the crossroad, the type of median on the crossroad, the width of the median between the exit and on-ramps (Pour-Rouholamin and Zhou 2016; Cooner et al. 2004). A recent study conducted by Wang and Zhou (2018) found that an intersection balance of less than 60% can provide better sight distance, which can reduce the risk for WWD. Some interchange design elements have been found to contribute to WWD crashes, such as an interchange with short sight distances, left-side off-ramps, and one-way streets connected with freeways (Cooner et al. 2004; Copelan 1989). Previous studies also concluded that some geometric features could be effective for deterring WW entries at the parclo interchange terminals. The Illinois DOT (IDOT) recommended that the median width between the on- and off-ramp should be more than 50 ft to reduce the risk for WWD (IDOT 2010). The channelizing island is also one of the important geometric design features to reduce the probability of WW entries by narrowing the off-ramp throat, which has been suggested via numerous researches (Zhou and Pour-Rouholamin 2014a; Cooner et al. 2008). Chassande-Mottin and Ganneau reported that having more than one channelizing island at an off-ramp throat could increase the complexity and confuse drivers; as an alternative, the use of roundabouts replacing multiple islands can help to reduce driver confusion (Chassande-Mottin and Ganneau 2008). The American Association of State Highway and Transportation Officials (AASHTO) Green Book suggested that the channelization of three-leg intersections is often desirable for a number of reasons: (a) to separate right-turning vehicles from through movements to provide more space for deceleration and storage and (b) make right-turning vehicles more efficiently merge into a crossroad. At the same time, the right-turning roadways generated by channelizing islands should be designed to discourage WWD (AASHTO 2011).

2.2 WWD Countermeasures for Divided Highways

The majority of previous WWD studies centered on freeways (Zhou and Pour-Rouholamin 2015; Cooner and Ranft 2008; Zhou et al. 2015a; Zhou et al. 2012; Pour-Rouholamin et al. 2016). Few states in the U.S. have conducted WWD studies on divided highways. Two of these studies were conducted in the 1970s. Scifres (1974) showed that on non-interstate four-lane divided highways, about 40% of drivers making WWD entries emerged from intersections with crossroads, about 25% originated from business establishments such as gas stations and motels, and about 20% originated from residential areas, crossovers, beginnings of divided sections, and construction sites, or were associated with U-turns and median openings. Vaswani (1976) studied measures for preventing WW entries on highways based on a 25-month survey of incidents of WWD on 2,000 miles of Virginia's divided highways (including the freeways). The study mentioned the three types of places most in need of immediate attention: (1) intersection with off-ramps or with crossroads; (2) business area (the author found that non-drunken drivers account for more than three times the number of incidents of WWD in business areas than do drunken drivers. It is claimed that many of the non-drunken drivers intentionally drive the WW. The author also gave an example of two WW exits from a gas station through a crossover); (3) crossovers and residential areas. The author pointed out that many WWD cases on divided highways from crossovers and in residential areas were considered to be intentional. Even though Vaswani pointed out the three types of places are in need of immediate attention, decades later there are still limited studies about them, especially for the later two.

Two recent studies (FHWA 2000; ALDOT 2014) identified that the most common WWD scenarios on divided highways occur when drivers: (1) turn left on the nearby directional roadway instead of the far or second directional roadway when joining from a crossroad, (2) enter a roadway going the wrong direction at the median opening, (3) make a U-turn and misunderstand that the next lane will be in the opposite direction, and (4) attempt to get back on the main road after stopping at a service or parking area. Past studies have not investigated access management strategies that can deter intentional WW movements originated on divided highways due to the limited WW incident data records.

2.3 Summary of Literature Review

Although ITS such as cameras and sensors can help detect WWD and warn WW drivers, the high costs and false alarms limit their implementation to only certain urban areas. Low-cost countermeasures, including signs, pavement markings, and minor geometric changes, can be implemented at every off-ramp terminal and access point on multilane divided highways. However, little has been investigated regarding their effectiveness in deterring WWD. Strategies of access management also have the potential to mitigate WWD, but few studies have been conducted to quantify their effectiveness. Moreover, few survey studies have been conducted to assess truck drivers' needs and preferences for WWD countermeasures. This study aims at providing insights of low-cost countermeasures and practical strategies for deterring WWD in Alabama.

3. EFFECTS OF SIGNS, PAVEMENT MARKINGS, AND GEOMETRIC DESIGNS ON DETERRING WWD

Before installing the DRS, the ALDOT regional engineers implemented some low-cost countermeasures to mitigate WWD activities at I-65 Exits 284 and 208. WWD incident data was collected from more than 800 hours of video collected at these two sites during the before and after periods. Frequency of WWD incidents was used to evaluate the effectiveness of the low-cost countermeasures implemented at each location. The study reveals that the improvements of pavement marking can reduce approximately 60% of the total and 75% of nighttime WWD incidents.

3.1 Data Collection

In this study, two freeway off-ramps were selected to conduct before-and-after studies, including two paclo interchanges: I-65 Exit 284 (State Route 160) near Hayden, Alabama and I-65 Exit 208 near Clanton, Alabama. The frequency of WWD incidents and information about driver behaviors were collected by observing traffic videos for different before and after time periods. A total of 48-hours of traffic video were recorded at each location before any improvements. A total of 432 hours of video were collected at I-65 Exit 284 after the improvement of pavement markings at the ramp terminal. A total of 384 hours video was collected at I-65 Exit 208 during the four after periods: (1) a new channelizing island was implemented; (2) a combination of DNE, Stop, and One-Way signs were implemented on the channelizing island and the pavement markings were improved; (3) DNE signs on the channelizing island were removed due to a WWD crash; and (4) a new DNE sign was added on the channelizing island. Table 3 listed the general information on data collection, including total hours, day of week, weather condition, observed deficiencies, and the implemented countermeasures for both before-and-after periods. The research team carefully watched the videos to record the number of WWD incidents, peak-hour traffic volumes, and other data on driver behaviors. Additionally, the researchers conducted several field test drives for both daytime and nighttime. A GoPro camera was put on the driver's head to record the driver's view of roadway conditions and WW-related TCDs.

Table 3. Summary of Traffic Video Data Collection

I-65 Exit 284 SB Ramp								
Before Period				**After Period**				
No.	Video Hours	Monitoring Date (Day of Week)	Observed Deficiencies	No.	Video Hours	Monitoring Date (Day of Week)	Weather	Engineering Improvement
1	48	5/5-5/7, 2017 (Fri-Sun)	1) Faded double yellow line markings 2) No left-turn skip strips 3) No yield line on right turn lane 4) Faded stop bar at the end of the off-ramp 5) Damaged RRPMs	1	48	6/22-6/24, 2018 (Fri-Sun)	Sunny	1) New double yellow line markings 2) New left-turn skip strips 3) New yield line on right turn lane 4) New stop bar at the end of the off-ramp
				2	48	7/6-7/8, 2018 (Fri-Sun)	Sunny	No additional changes
				3	120	9/30-10/5, 2018 (Sun-Fri)	Sunny	No additional changes
				4	72	11/2-11/5, 2018 (Fri-Mon)	2 hrs. Rain	No additional changes
				5	72	12/14-12/16, 2018 (Fri-Mon)	24 hrs. Rain	No additional changes
				6	72	12/21-12/23, 2018 (Fri-Mon)	Sunny	No additional changes
I-65 Exit 208 SB Ramp								
Before Period				**After Period**				
No.	Video Hours	Monitoring Date (Day of Week)	Observed Deficiencies	No.	Video Hours	Monitoring Date (Day of Week)	Weather	Engineering Improvement
1	48	3/23-3/25, 2018 (Fri-Sun)	1) Poor pavement marking, double yellow line on the crossroad discontinued 2) Stop bar on off-ramp throat is not extended to the edges 3) No channelizing island on the wide-open off-ramp throat	1	48	7/13-7/15, 2018 (Fri-Sun)	Sunny	Channelized island
				2	120	9/30-10/5, 2018 (Sun-Thu)	Sunny	Add double yellow line and "DNE" sign
				3	72	11/2-11/5, 2018 (Fri-Mon)	Sunny	"DNE" sign removed
				4	72	12/14-12/16, 2018 (Fri-Mon)	Sunny	New "DNE" sign
				5	72	12/21-12/23, 2018 (Fri-Mon)	Sunny	No additional changes

3.2 Before and After Comparison

3.2.1 Study Location 1: I-65 Exit 284 SB Off-ramp

Before Condition

According to 2017 Alabama traffic data, the Annual Average Daily Traffic (AADT) volume on the southbound (SB) off-ramp was 1,260 vehicles per day (26% heavy vehicles). Existing peak-hour traffic volumes for the AM and PM peak periods are shown in Table 4. The crossroad, State Route 160, is a commuter-heavy corridor. The heaviest movement in the morning peak is SR-160 WB to I-65 SB. The volumes on the off-ramp are very low. The unbalanced volume distribution and other roadway design features make this intersection one of the high-risk WWD locations in Alabama.

Table 4. Existing Peak-Hour Traffic Volumes for the AM and PM Peak Periods

Road Name	Direction		AM Peak Periods Volume	PM Peak Periods Volume
I-65 Exit 284 SB Off-ramp	NB	Left	9	2
		Right	126	19
SR-160	EB	Right	72	27
		Through	195	121
SR-160	WB	Left	735*	272
		Through	65	199
*** the morning peak-hour left turn volume (SR-160 WB to I-65 SB)**				

Figure 1.a illustrates the roadway condition and WW-related TCDs information at I-65 Exit 284 SB off-ramp before the improvements. The lane width of the off-ramp is about 12 ft. The SB on- and off-ramps are separated by a concrete barrier. At the ramp terminal, right-turn traffic is yield-controlled, while left-turn traffic requires a complete stop. A DNE sign was placed on both sides of the off-ramp right-turn lane. A combination of DNE and One-Way signs was placed at the center of the channelization pavement marking. Thirty feet away from the ramp terminal, a Keep Right sign with an object marker (OM1-1 in MUTCD) was installed on the concrete barrier. Dual WW arrows enhanced by RRPMs were placed 100 ft away from the ramp terminal. It should be noted that the dual WW arrows were faded and RRPMs were damaged. Two WW signs were installed sequentially on the right side of the off-ramp, which are 100 and 200 ft away from the ramp terminal. An advisory speed sign of 30 mph is located 690 ft away from the ramp terminal near the freeway gore area. Several deficiencies observed for the before condition include:

1. Faded double yellow line pavement markings on SR-160
2. No left-turn skip strips
3. No yield line on the channelized right turn lane
4. Faded stop bar at the end of the off-ramp
5. Damaged/missing RRPMs

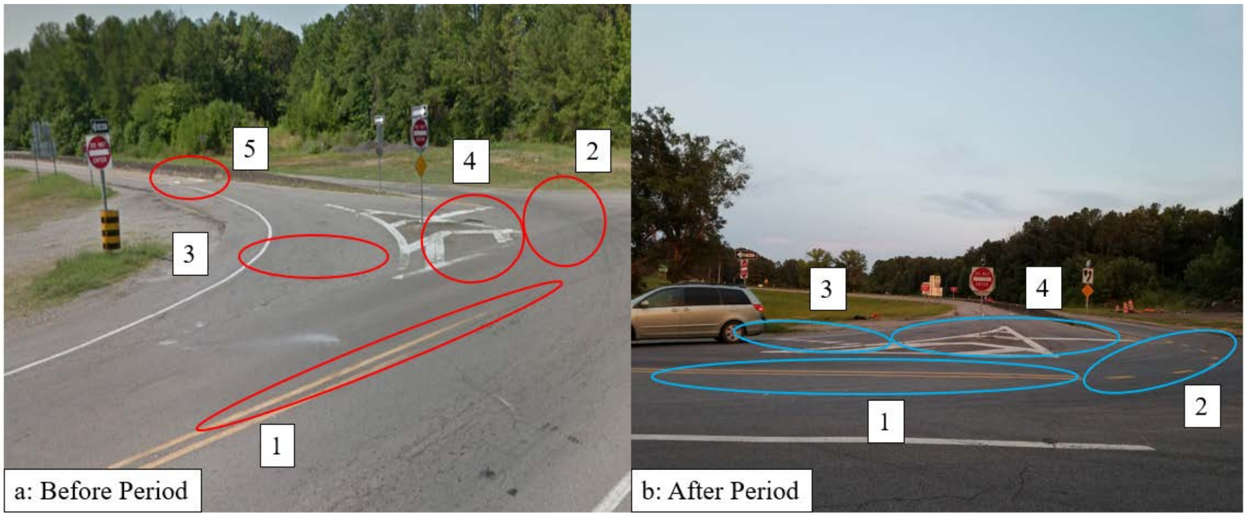


Figure 1. View of I-65 Exit 284 SB Ramp: (a) Before Period and (b) After Period

After Condition

The first four observed deficiencies were improved immediately by ALDOT regional engineers after confirming the WWD incidents at this location. The countermeasures applied are shown in Figure 1.b, including (1) newly painted double yellow lines; (2) added left turn skip strips; (3) new yield line on the right turn lane of off-ramp; and (4) repainted stop bar.

Before-and-After Comparison of WWD incidents

Based on the collected video data, there were 17 WWD incidents recorded in the 48-hour before period and 64 WWD incidents observed in the 432-hour after period. During these periods, there was no significant change in traffic volume. Table 5 listed the total number of WWD incidents and their distribution during daytime and nighttime (daytime: 6:00 am-8:30 pm) before and after the countermeasures were implemented.

According to Table 5, the before period contains 8 WWD incidents at daytime and 9 WWD incidents during nighttime, which resulted in an average of 8.5 WWD incidents per day. After the improvement of the pavement markings, the average WWD incidents for the first three after periods were decreased to 3 or 4 per day. The average WWD incident per day has an approximately 53%-65% reduction compared with the before period. The average WWD incident for all six after periods, after excluding any WWD incidents occurred during the periods with heavy rains, was 3.2 per day. This indicated that the total WWD incidents at this location were reduced by 62% after the improvement. The overall reduction of WWD incidents during the nighttime (73%) was shown larger than the reduction during the daytime (51%), which indicated that the pavement markings could be more effective during nighttime. However, the average WWD incidents increased a little to 4.7 per day for the fourth and fifth after periods compared with other after periods due to the 2 hours and 24 hours of heavy rain, respectively. Particularly, the WWD incidents during the nighttime at these two periods showed a great increase compared with other after periods, which indicated that the pavement markings could be less effective during nighttime with wet road surface condition.

Table 5. WWD Incidents Observed Before and After the Countermeasures Implementation

	Period No.	Total # of WWD	Average (WWD/Day)	Daytime (WWD/Day)	Nighttime (WWD/Day)
Before	1	17.0	8.5	4.0	4.5
After	1	8.0	4.0	3.5	0.5
	2	6.0	3.0	2.0	1.0
	3	15.0	3.0	2.0	1.0
	4*	14.0	4.7	1.3	3.3
	5**	14.0	4.7	0.7	4.0
	6	7.0	2.3	1.0	1.3
	Summary***	51.0	3.0	1.7	1.2
	% decreased		65%	58%	73%

Note:
*4 WWD incidents (0 daytime + 4 nighttime) in 2 hours raining period.
**9 WWD incidents (1 daytime + 8 nighttime) in 24 hours raining period.
***Summary did not include any data in raining period.

Table 6. Drivers' Compliance with Double Yellow Line and Left-Turn Skip Striping on the Crossroad

	Time	Compliant or Not?	Number	Percentage	Chi-Square Test (Daytime vs. Nighttime)	
					X^2	***p*-value**
After Period 1	Daytime Compliance (5:30 PM to 6:30 PM)	Following the line	70	30%	65.19	< 0.0001
		Not Following the line	163	70%		
	Nighttime Compliance (9:00 PM to 10:00 PM)	Following the line	70	81%		
		Not Following the line	16	19%		
After Period 2	Daytime Compliance (5:30 PM to 6:30 PM)	Following the line	50	26%	101.21	< 0.0001
		Not Following the line	146	74%		
	Nighttime Compliance (9:00 PM to 10:00 PM)	Following the line	96	86%		
		Not Following the line	16	14%		

Based on the observations while watching the videos, it was found that more left-turn drivers followed the left turn skip strips to the on-ramp during nighttime than daytime. To support this observation, the team collected additional data to estimate the percentage of drivers that followed the newly painted double yellow line and left-turn skip strips. Table 6 summarized the number of vehicles that complied with the new pavement markings in one hour for both daytime and nighttime. During the first after period, only 30% of the left turn drivers complied with the new double yellow line during daytime compared to 81% during the nighttime. During the second after period, the compliance to the double yellow line remained similar (i.e., 26% during daytime vs. 86% during nighttime). As shown in Table 6, Chi-square tests show that a larger percentage of drivers follow the double yellow line and left-turn skip strips during nighttime than the daytime for both after periods.

Figure 2 illustrates the typical WWD path, and the common left-turning trajectories for daytime and nighttime at this location. During the nighttime, most left-turning vehicles followed closely to the double yellow line and left-turn skip strips (Line A in Figure 2). Line B showed that, most of the left-turn drivers during the daytime chose to cross the solid double yellow line approximately 6 ft (one vehicle width) before the end of the line to make a more comfortable left-turn through a larger turning radius. Due to a large amount of left-turning traffic, this driving behavior would make the newly painted double yellow line fade faster than normal. Line C in Figure 2 showed the most common WWD trajectory, which indicated that most WW drivers tend to enter the WW from the off-ramp right turn lane.

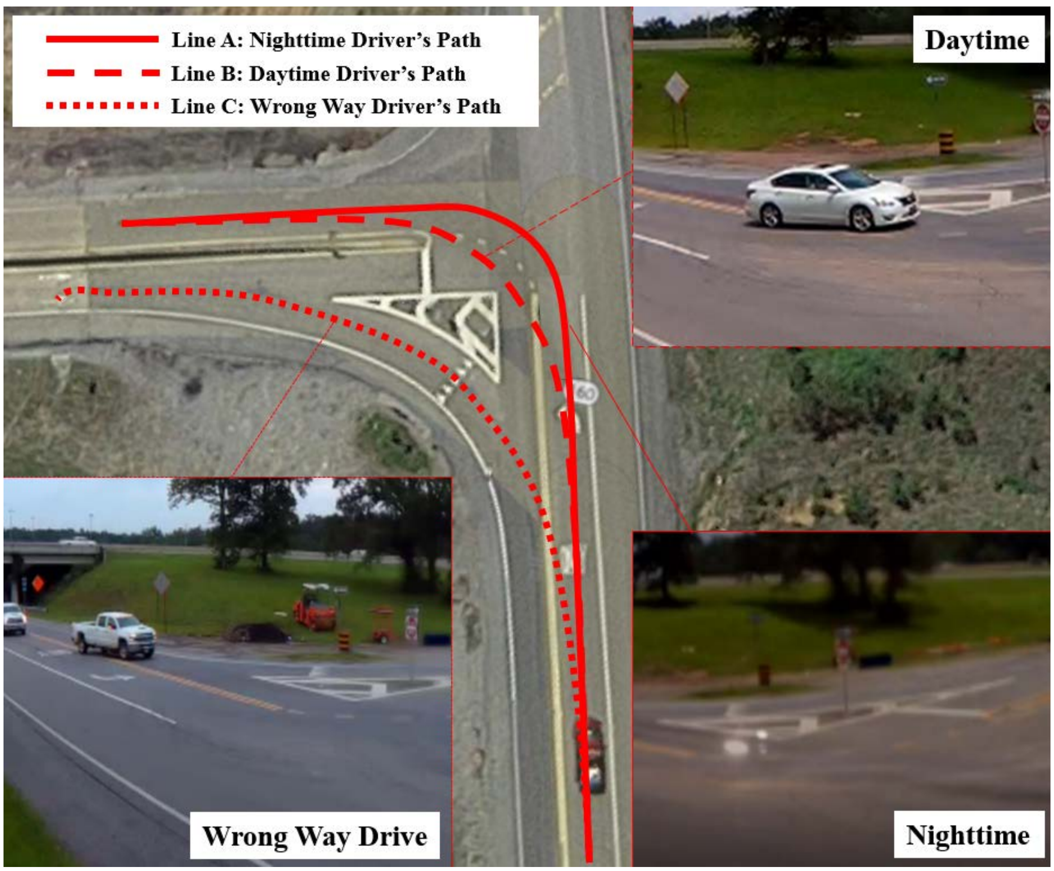


Figure 2. Two WWD Paths and Different Left Turn Paths between Daytime and Nighttime

Another important observation is that more drivers relied on the pavement markings to identify the on-ramps during the nighttime. Figures 3.a and 3.b showed the view of left-turning drivers from the crossroad during nighttime and daytime, respectively. As shown in Figure 3, the pavement markings illuminated by the headlights comprise the major portion of a driver's view during the night and help them to make a decision. This finding also supports the results in Table 6 that the implementation of newly painted pavement markings can be more effective in preventing WWD incidents during nighttime. Therefore, it is very important to maintain highly visible pavement markings to reduce the possibility of nighttime WWD incidents, especially at locations with no street lighting.

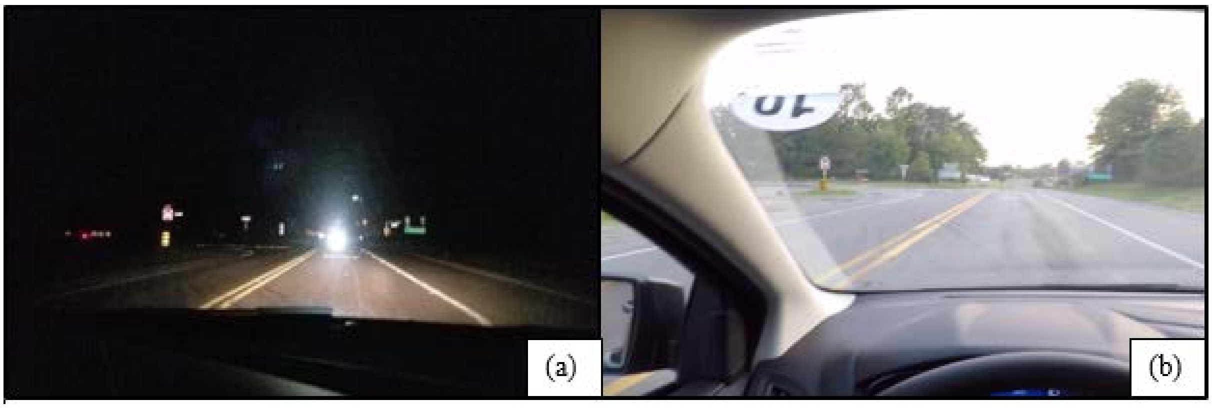


Figure 3. Driver's View of I-65 Exit 284 SB Ramp during (a) Nighttime and (b) Daytime

During the daytime, the right-turn lane on the off-ramp may look like on-ramp if the drivers do not pay attention to the DNE sign and double yellow line on the crossroad. Based on the researcher's observations while watching the videos, the solid double yellow line would not prevent the drivers from entering the WW when they thought the right-turn lane on the off-ramp was the on-ramp. However, during nighttime, the right-turn lane on the off-ramp was not entirely visible to the drivers and the double yellow line became more effective in guiding the left-turning drivers to the proper turning point.

3.2.2 Study Location 2: I-65 Exit 208 SB Off-Ramp

Before Condition

The second case study is another parclo interchange at SB off-ramp terminal along I-65 Exit 208 (Co Rd 28). Existing peak-hour traffic volumes for the AM and PM peak periods are shown in Table 7, which indicated the largest volume in the morning peak hour is Co Rd 28 WB to I-65 SB. According to the 2017 Alabama traffic data, the AADT on the SB off-ramp was 1,550 vehicles per day, including 20% heavy vehicles.

Table 7. Existing Peak Hour Traffic Volumes for the AM and PM Peak Periods

Road Name	Direction		AM Peak Periods Volume	PM Peak Periods Volume
I-65 Exit 208 SB Off-Ramp	NB	Left	67	73
		Right	134	90
Rd 80	EB	Right	85	82
		Through	112	138
Rd 80	WB	Left	171*	165
		Through	68	120
* The largest volume in the morning peak hour (Co Rd 28 WB to I-65 SB)				

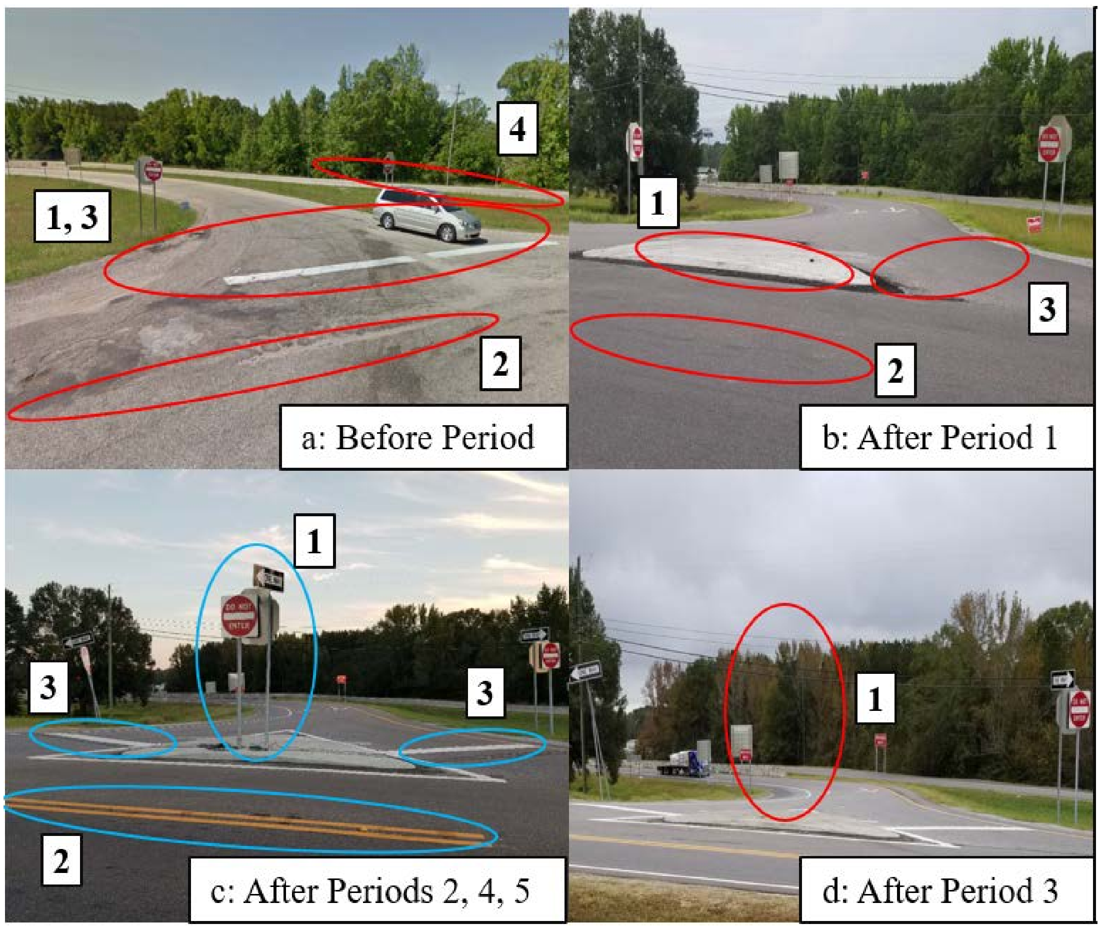


Figure 4. View of I-65 Exit 208 SB Ramp: (a) Before and (b, c, d) After Period

The before conditions at this location is illustrated in Figure 4.a. The lane width of the SB off-ramp is about 16 ft. The SB on- and off-ramps are separated by a wide median. The off-ramp terminal is a stop-controlled unsignalized intersection. Along the SB off-ramp, several TCDs were installed to prevent drivers from entering the WW. Two DNE signs were installed on both sides of the off-ramp at the ramp terminal. Stop signs were mounted on the back of the DNE signs on the right side of the off-ramp. About 50 ft away from the ramp terminal, a pair of large WW arrows were installed. Two WW signs were placed on both sides of the off-ramp about 200 ft farther. Two WW arrows and two lane-use arrows were installed on the off-ramp curve segment. They were 350, 470, 760, and 880 ft away from the stop bar at the ramp terminal, respectively. An advisory speed sign of 25 mph was located 890 ft away from the ramp terminal near the freeway gore area. A new channelization island was installed at the ramp terminal by ALDOT regional engineers in summer 2018. A combination of DNE, Stop, and One-Way signs were placed at the center of the channelization island. A number of deficiencies observed for the before condition include:

- No channelizing island on the wide-open off-ramp throat.
- Poor pavement marking, double yellow line on the crossroad discontinued before reaching the off-ramp.
- The stop bar on the off-ramp throat is not extended to the edges.
- The poor visibility of the on-ramp due to the lower elevation.

After Condition

The initial improvement of the intersection at I-65 Exit 208 SB ramp was completed in early June 2018. As shown in Figure 4.b, after period 1 includes only a raised channelizing island, which was intended to control and guide right turning movements and to reduce the throat width of the off-ramp to discourage WWD. No other improvements such as double yellow line on the crossroad and the stop bars at the end of the off-ramp were implemented in this period. After three months, a combination of DNE, Stop, and One-Way signs were placed at the center of the channelizing island. In addition, the double yellow line was painted to cover the whole off-ramp opening which intended to block the WW entries, and the stop bars at the end of the off-ramp were painted at the same time. Figure 4.c illustrates the field condition in the after periods 2, 4, and 5. Figure 4.d represents the after period 3 when the signages on the channelized island were destroyed by a WW truck making self-correction from the off-ramp to return to the crossroad.

I-65 Exit 208 SB: Before-and-After Comparison

A total of 11 WWD incidents was observed in one 48-hour before period. Additionally, 49 WWD incidents were recorded in the five after periods for a total of 384 hours, including three Property Damage Only (PDO) crashes. Table 8 listed the total number of WWD incidents in each study period, average number of WWD incident per day, and the distributions during daytime and nighttime. Figure 5 shows the average number of WWD incidents for each of the six periods.

According to Table 8 and Figure 5, the before period contains 1 WWD incident at daytime and 10 WWD incidents during nighttime, which resulted in an average of 5.5 WWD incidents per day. After the channelizing island was implemented, the average number of WWD incidents were increased to 9.0 per day in the first after period. Most of them happened during the daytime. Nighttime WWD incidents were reduced from 5 to 2.5 per night. During the second after period, the average number of WWD incidents per day was reduced by 53% compared with the before period after installing a new DNE sign and One-Way sign on the new channelizing island, and repainting the stop bar at the end of the off-ramp and double yellow line on the crossroad. The DNE and One-Way signs on the channelizing island were removed by a WWD incident in the third after period. The average number of WWD incidents during that period increased to 3.7 per day from 2.6 per day in the second after period.

Table 8. WWD Incidents Observed Before and After the Countermeasures Implementation

	Period No.	Total # of WWD	Average (WWD/Day)	Daytime (WWD/Day)	Nighttime (WWD/Day)
Before	1	11.0	5.5	0.5	5.0
After	1*	18.0	9.0	6.5	2.5
	2	13.0	2.6	1.0	1.6
	3**	11.0	3.7	1.7	2.0
	4	2.0	0.7	0.7	0.0
	5	5.0	1.7	0.7	1.0
	Summary***	20	1.8	0.8	1
	%decreased		67%	-60%	80%

Note:
*Single channelizing island implemented (without signage and pavement marking).
**DNE and One-Way signs on the channelizing island removed.
***Summary included after periods 2, 4, 5, with all the improvements are in place.

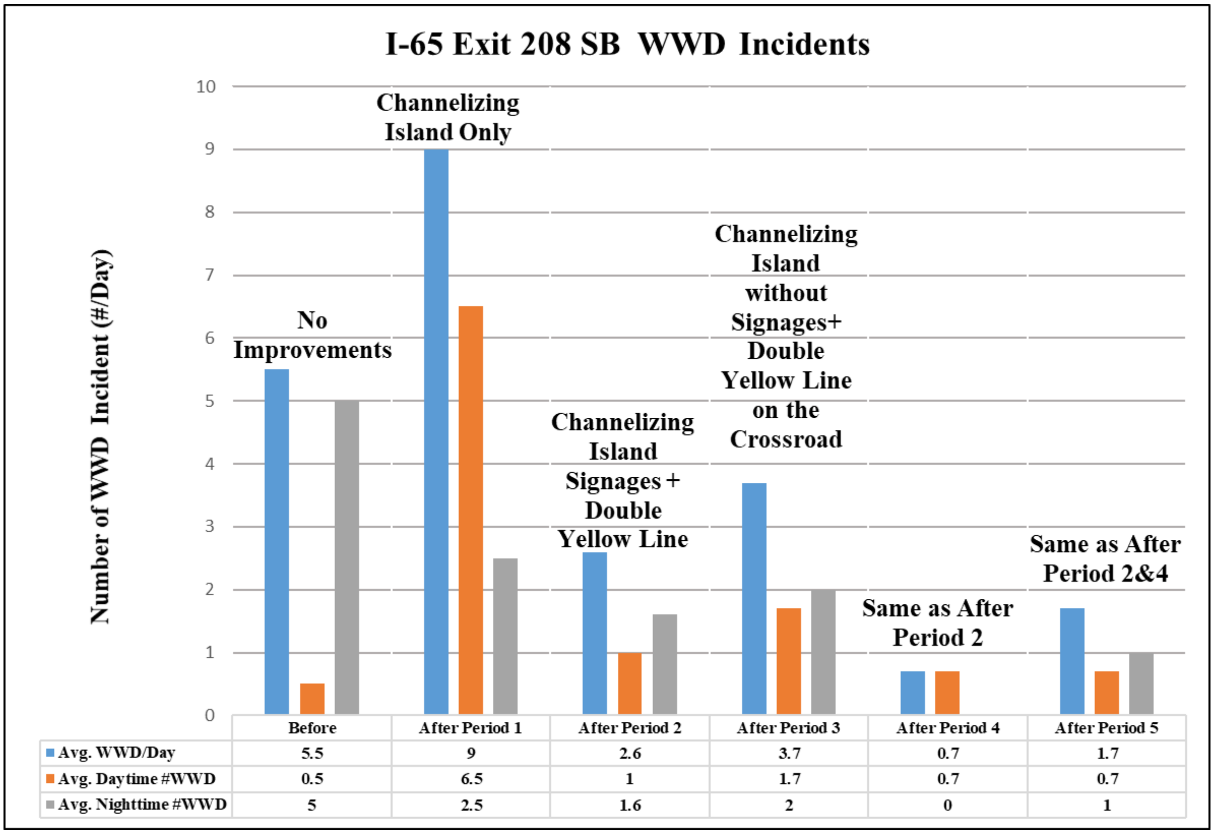


Figure 5. Impact of Different Countermeasures Applied at I-65 Exit 208

The average number of WWD incidents was reduced during the fourth and fifth after periods after the new DNE/One-Way signs were installed on the channelized island again. The results suggested that the non-traversable channelizing island without any signage might cause driver's confusion and result in more WWD incidents during the daytime. The implementation of the additional signs is essential to reduce driver's confusion. Furthermore, the repainted double yellow line on the crossroad and the repainted stop bar can also help guiding the drivers to the right way. Overall, the number of WWD incidents was reduced from 5.5 per day in the before period to an average of 1.7 per day during the after periods 2, 4 and 5 when all the low-cost countermeasures were in place.

3.3 WWD Distance

Additional analysis was conducted to evaluate the effectiveness of WW-related TCDs by measuring the distance of the WW driver traveled on the WW before taking corrective action. As shown in Figure 6, at I-65 Exit 284 SB, the first WW sign paired with WW arrows are located at 100 ft from the stop bar at the off-ramp terminal. Additionally, a second WW sign was located at 200 ft from the stop bar on the off-ramp. At I-65 Exit 208 SB, the first pair of WW arrows were located at 50 ft and one pair of WW signs were located at 250 ft from the stop bar on the off-ramp.

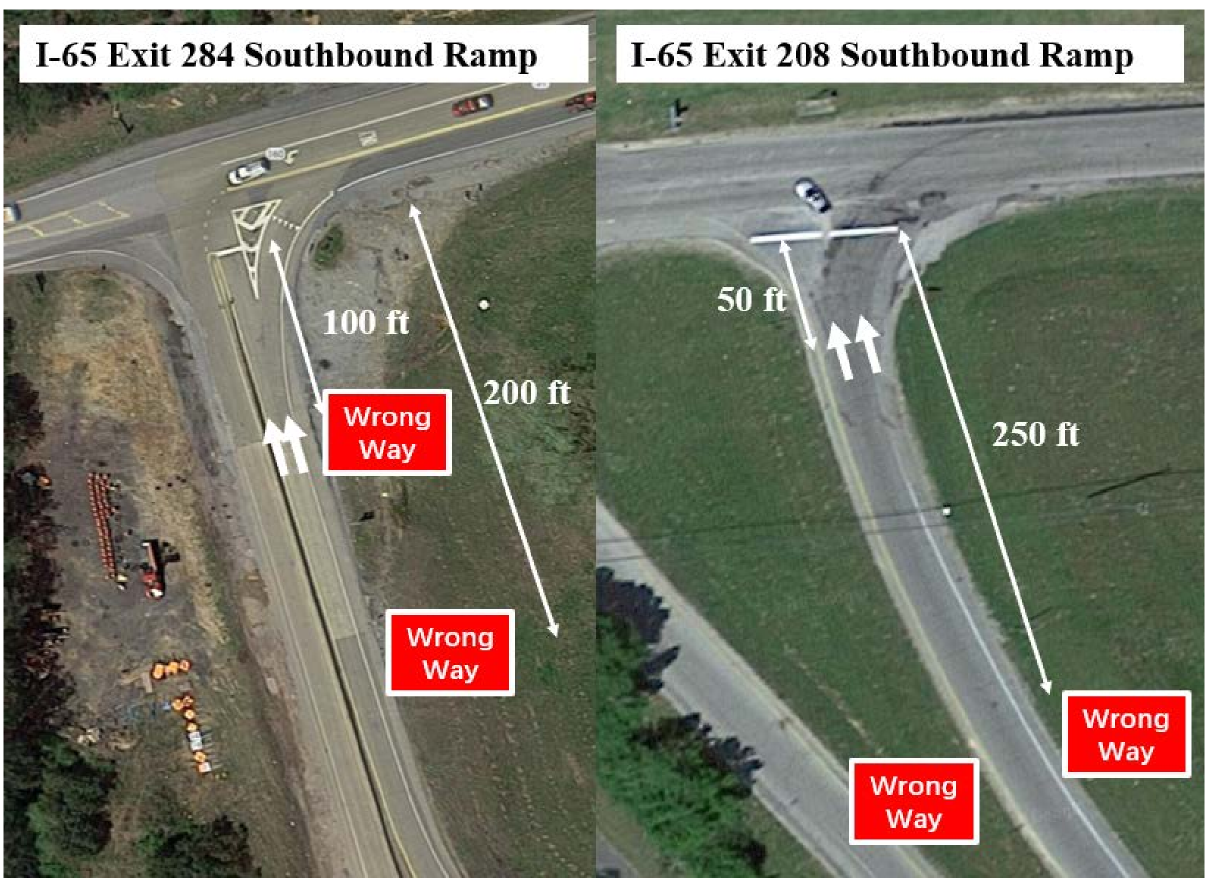


Figure 6. Locations of WW Signs and WW Arrow at Two Study Sites

Table 9 summarizes the driving distance in the wrong direction along the off-ramps by all the WW drivers at the two study sites. While measuring the WWD distance, only the first WW vehicle was considered if there were two or more vehicles entering the WW together because the following vehicles could be stopped by the front vehicle instead of the countermeasures. At I-65 Exit 284 SB off-ramp, 42% of WW drivers realized that they were driving WW and turned around in less than 20 ft onto the off-ramp. Another 29% of WW drivers turned around in less than 100 ft before passing the first WW sign and WW arrows. There were 21% of WW drivers that drove past the first WW sign and turned around before the second WW sign, which is located at approximately 200 ft onto the off-ramp. Only 9% of WW drivers passed both WW signs and stopped after they encountered right-way vehicles on the off-ramp. At I-65 Exit 208, the majority of the drivers (84%) turned around before the first set of WW arrows, which is located at 50 ft from the stop bar on the off-ramp. There were 12% of WW drivers drove past the WW arrow and stopped before the WW signs implemented on the roadside. Additionally, only 3% of WW drivers passed both WW arrows and WW sign and turned around after going the WW for more than 200 ft. The data analysis suggests that placing WW arrows and WW signs closer to the stop bar of the off-ramp can reduce the average WWD distances. The second pair of WW signs is necessary since the study found that they stopped approximately 20% of WW drivers.

Table 9. WWD Distances

I-65 Exit 284 SB Ramp			I-65 Exit 208 SB Ramp		
WWD Distance	**Number of WWD**	**Percent**	**WWD Distance**	**Number of WWD**	**Percent**
20 ft (Impacted by DNE sign or stop bar)	32	42%	**20 ft (Impacted by DNE sign or stop bar)**	22	37%
100 ft (Impacted by 1st WW sign or WW arrows)	22	29%	**50 ft (Impacted by WW arrows)**	28	47%
200 ft (Impacted by 2nd WW sign)	16	21%	**150 ft (Impacted by WW sign)**	7	12%
More than 200 ft. (Stopped by right-way vehicles)	7	9%	**More than 200 ft (Stopped by right way vehicles)**	2	3%
Total	77	100%	**Total**	57	100%

3.4 Summary

Low-cost countermeasures, such as DNE, WW sign, WW pavement marking, and channelizing island, if used properly, can effectively reduce WWD incidents and reduce WWD distance on off-ramps, therefore reduce the risk and severity of WWD crashes.

The results of the case study at I-65 Exit 284 SB suggested that the new pavement markings (double yellow line and left-turn skip strips on crossroad, and yield line and stop bar on off-ramp) resulted in an overall 62% reduction in the number of WWD incidents, and 73% reduction at night. Further analysis showed that the drivers' compliance with the new solid double yellow line during the night is significantly higher than daytime. More than 70% of the drivers crossed the new solid double yellow line to turn left onto the on-ramp during the daytime. This implies that the driver's incompliance at this location may result in the double yellow line fading quicker than normal use. This study concluded that pavement markings have a significant impact on WWD incidents and recommended that agencies should consider regular maintenance to keep the double yellow line and left turn skip strips in good condition.

The results of the case study at I-65 Exit 208 SB showed that the frequency of WWD incidents increased by 64% after installing a raised channelizing island only, especially during the daytime. The study suggests that the channelizing island without proper pavement markings and signs might cause more confusion and lead to more WWD incidents. According to the researcher's observation from videos, the absence of stop bars at the off-ramp terminal may have caused driver confusion and contributed to the increased frequency of WWD events. After the DNE and One-Way signs were implemented on the channelized island and other pavement markings were improved, the frequency of a WWD incident was significantly decreased (from average 5.5 per day to 1.7 per day).

The analysis of WWD distance at the two study sites suggested that a large percentage (70-80%) of WW drivers were able to make corrective turnarounds before the first pair of WW signs. However, the second pair of WW signs should still be considered since there were approximately 20-30% WWD vehicles that drove past the first pair of WW signs. The data analysis for I-65 Exit 208 revealed that approximately 86% of the WW drivers made a corrective turn-around maneuver right before the WW arrows, which implies that the WW arrow is very effective in deterring WWD. Only 2% of WW drivers drove for more than 200 ft and passed all the WW signs and WW arrows on the off-ramp. Apparently, advanced TCDs or ITS technologies should be considered for preventing those 2% of WW drivers from entering the freeway mainline.

The study results indicated that the low-cost countermeasures can reduce a large portion of WWD incidents. It also suggests that it is important to standardize the mounting locations for WW arrows and WW signs. The study recommends that WW arrows should be installed less than 100 ft from ramp terminals to reduce WWD distance and the first set of WW sign should be installed less than 200 ft from ramp terminals.

After all of the low-cost countermeasures that were implemented at these two sites, there were still approximately 2-3 WWD incidents per day at these two locations. The next chapter contains the evaluation results of a new TCD, called directional rumple strips (DRS), on WWD incidents. The WWD incident data showed that a large percentage of WWD vehicles are commercial trucks. An in-person survey was conducted to assess truck driver needs on WWD countermeasures. The results of the survey were summarized in Chapter 5.

4. EFFECTS OF DIRECTIONAL RUMBLE STRIPS ON DETERRING WWD

A recent study (Zhou et al. 2018), entitled "Directional Rumble Strips (DRS) for Reducing Wrong-Way-Driving Freeway Entries," developed and tested five DRS designs (named A to E) with various configurations (e.g., A1, A2…). Recommendations were made to implement three DRS design patterns in the field, which were Pattern D3 (one configuration of Pattern D), Pattern C, and Pattern E.1 (a variant of Pattern E). The DRS aims at reducing WWD incident frequency and severity, and at the same time reducing right-way (RW) vehicles' speeds on freeway off-ramps. The objective of this study was to evaluate the safety effectiveness of three DRS patterns through the field implementation. SB off-ramps at Exits 208 and 284 on I-65 in Alabama were selected for field implementation based on the prediction model results (Zhou and Atiquzzaman 2019) and the number of WWD incidents observed. Before and after studies were conducted to evaluate effects of DRS patterns on WWD incidents. Field driving tests were also conducted to collect data of sound and vibrations caused by DRS at various speed categories for both RW and WW directions. Time-series and spectrum analysis were employed to analyze sound and vibration data, respectively.

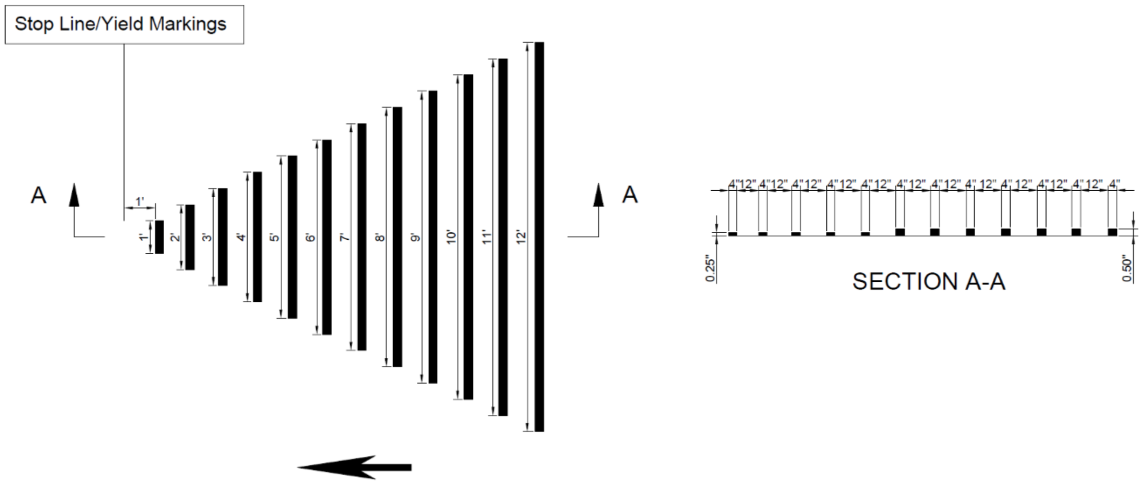
4.1 DRS Pattern Design

Figure 7.a shows Pattern D3 modified based on the advance warning pavement markings for speed humps (see 3B-31 in the MUTCD), which has a triangle appearance, as the length of the strip gradually increases from 1 to 12 ft. Strips with lengths from 1 to 5 ft have 0.25 inch in thickness. The remaining strips have the same thickness of 0.5 inch. Pattern D3 was designed to be installed immediately after stop bars or yield lines on off-ramps.

Pattern C (Figure 7.b) is similar to the transverse rumble strips (TRS) but has various spacings. Three groups of strips with spacings of 1, 2, and 5 ft, respectively, were placed apart with 100 and 50 ft spacing. All the strips have the same thickness of 0.25 in. Due to different lane widths, strips have unequal lengths at two sites, which were 7 ft at Exit 208 and 4.5 ft at Exit 284. A 2-ft center gap is left in the middle of the lane to allow motorcycles and emergency vehicles to bypass the strips. They can utilize the gaps to pass the DRS without experiencing undesirable sound and vibrations. To not overlap with WW arrows, Pattern C was placed 3 ft behind the dual WW arrows at both sites.

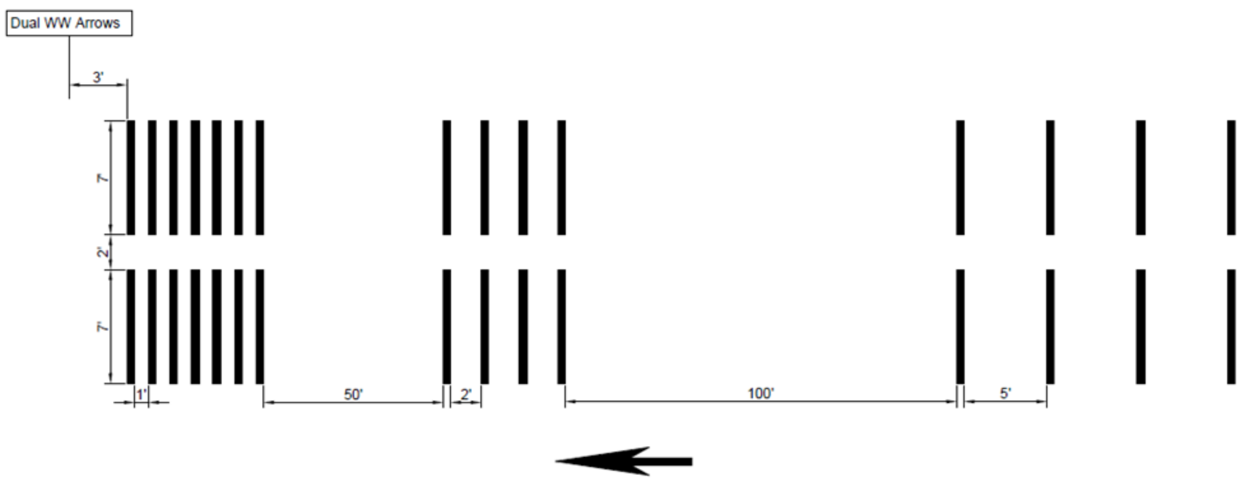
Pattern E.1 (Figure 7.c) was designed to have double strips on the inside of the RW travel lane for elevated sound and vibrations for WW drivers. Spacing between the strips was 4 ft on the RW driver side and 2 ft on the WW driver's side. A 2-ft center gap was also left in the middle of the lane to serve motorcycles and emergency vehicles. Pattern E.1 was installed 30 ft ahead of the advisory ramp speed sign. At that point, RW drivers were able to clearly see the advisory speed sign and horizontal curve ahead.

(a)



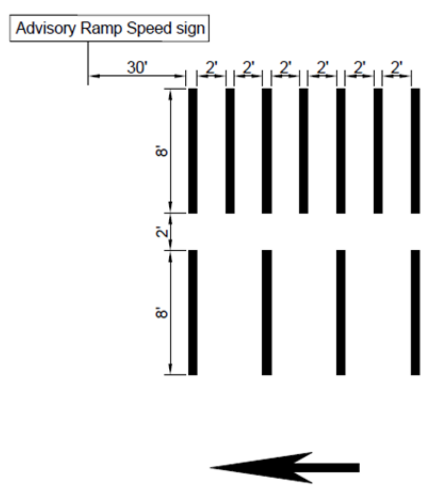
Note: 1) Not to scale; 2) ← = RW traffic flow.

(b)



Note: 1) Strips have equal thickness of 0.25" and width of 4"; 2) Strips have different lengths at two sites (Exit 208: 7'; Exit 284: 4.5'); 3) Not to scale; 4) ← = RW traffic flow.

(c)

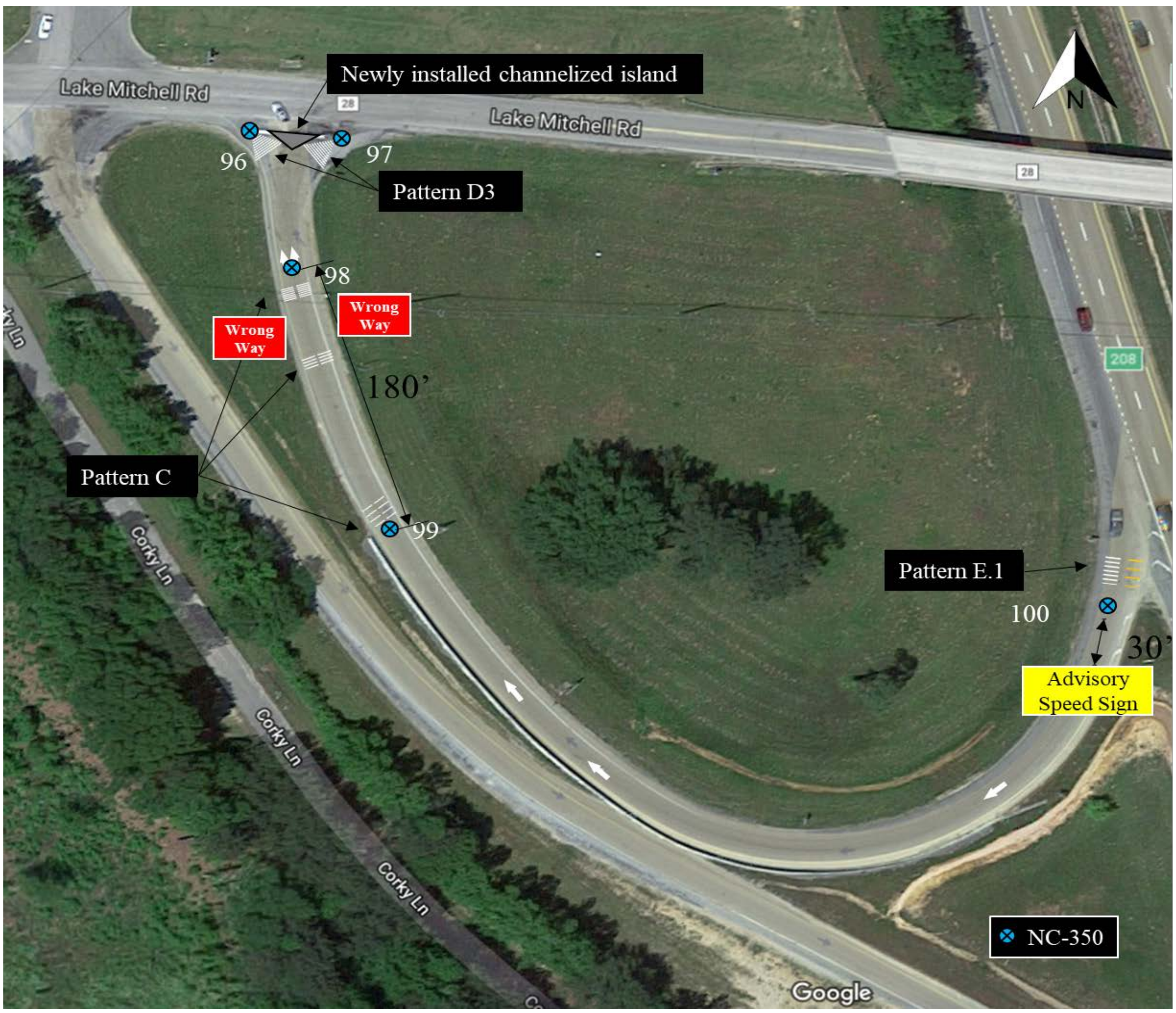


Note: 1) Strips have equal thickness of 0.25" and width of 4"; 2) Not to scale; 3) ← = RW traffic flow.

Figure 7. DRS Pattern Designs: (a) Pattern D3, (b) Pattern C, and (c) Pattern E.1

4.2 Field Implementation

Figure 8 shows the existing TCDs, and proposed locations for DRS and magnetic sensors for collecting traffic volumes and speed data on SB off-ramps at Exits 208 (Figure 8.a) and 284 (Figure 8.b) on I-65 in Alabama. Three DRS patterns were installed by a contractor in December 2018. Figure 9 illustrates field photos of DRS. Pattern D3 was positioned 1 foot after the stop bars or yield lines on the off-ramps at two study sites. It also acts as an enhanced lane-use arrow due to the triangle shape. To not overlap with the existing WW arrows, Pattern C was placed 3 ft behind the dual WW arrows at both sites. A 2-ft center gap was left in the middle of Pattern C to allow motorcycles and emergency vehicles to bypass the strips. Pattern E.1 was designed to have double strips on the driver side in the WW direction. Pattern E.1 was installed 30 ft ahead of the advisory ramp speed sign. Similar to Pattern C, a 2-ft center gap was also left in the middle of the strips to serve motorcycles and emergency vehicles.



(a)

(b)

Figure 8. Existing TCDs and Magnetic Sensors Deployments on Off-Ramps: (a) Exit 208 and (b) Exit 284 on I-65

(a) Pattern D3 (right way)

(b) Pattern D3 (wrong way)

(c) Pattern C (1-ft spacing)

(d) Pattern C (2-ft spacing)

(e) Pattern C (5-ft spacing)

(f) Pattern E.1 (right way)

(g) Pattern E.1 (wrong way)

Figure 9. Field Photos of DRS

4.3 Data Collection

Portable traffic cameras were used to monitor the WWD incidents and driver behavior. They were mounted at a traffic sign post on the opposite side of the crossroad at the ramp terminals. The cameras have a wide viewing angle of 170 degrees to accommodate the entire off-ramp. They can record color videos with a resolution of 720P for up to 72 hours when fully charged. The speed data were collected by magnetic sensors called NC-350 BlueStar Portable Traffic Analyzer (NC-350). Unlike other speed-measurement equipment, such as radar guns and tube counters, the NC-350 can provide individual vehicle data, including speed, direction, length, headway, etc. A NC-350 battery can last up to 21 days. Additionally, the sealed design of NC-350 made it robust against moisture and pressure. Protective covers were used to cover and secure the sensors. In-vehicle sound and vibration were measured by using a full-size passenger car (2018 Nissan Altima). The acoustical signature was recorded by an EXTECH HD600 Sound Level Meter, which collected 10 decibel readings every second. The vibration data was recorded using a Measurement Specialists 35201A accelerometer, which recorded 100 samples per second. This device measured acceleration rates along the longitudinal, lateral, and gravitational axes. A total of nine magnetic speed sensors (NC-350), which were labeled following their device serial numbers from #96 to #104, were used to collect traffic speeds on off-ramps. At Exit 208 (Figure 8.a), sensors #96 and #97 were installed 1 foot in front of the two stop bars. Sensor #98 was positioned right behind the dual WW arrows. Sensor #99 was placed near the end of the concrete barrier, about 180 ft away from #98. Sensor #100 was installed 30 ft before the advisory ramp speed sign. At Exit 284 (Figure 8.b), sensor #101 was placed before the yield line. Sensor #102 was installed immediately behind the dual WW arrows. Sensor #103 was placed 180 ft away from #102 to measure speeds of vehicles exiting/entering the ramp curve. As with Exit 208, sensor #104 was also installed 30 ft before the advisory ramp speed sign to measure speeds of vehicles departing from freeway mainlines.

Table 10 summarizes the study periods and schedule of the DRS implementations. DRS were installed by a contractor (Ozark Striping, Inc) in Alabama. The material of the strips was thermoplastics. The before weeks (W0-4 to W0-1) served as the control group. W0-4, W0-3, and W0-2 are the monitoring periods after the low-cost countermeasures were implemented as summarized in Chapter 3. They were considered as before periods for the DRS study in this Chapter. Starting from the first after week (W1), one new DRS pattern was installed at the beginning of each week. Speed data and traffic volumes were recorded by NC-350 from W0-1 to W3 for the four weeks. W4-W10 are additional after periods randomly selected to monitor WWD incidents. Video data was recorded during each period. According to the district administrators, no new construction was conducted at Exit 208 during all study periods for this project, except for regular maintenance. However, DRS were removed after W5 due to a resurfacing project at Exit 284. It should be noted that W9 and W10 were monitored during the COVID-19 pandemic. Reduced traffic volumes have been reported by traffic agencies, which have also been verified by the video data.

Table 10. DRS Field Implementation Schemes

Schedule		DRS Pattern Installed			Traffic Volume[a]		Video Monitoring
Phase	Time	E.1	C	D3	Exit 208	Exit 284	
Before	W0-4[b]						48 hours
	W0-3[b]						48 hours
	W0-2[b]						120 hours
	W0-1				1,347	1,127	72 hours
After	W1	×			1,291	1,180	72 hours
	W2	×	×		1,299	1,195	72 hours
	W3	×	×	×	1,379	1,208	72 hours
	W4	×	×	×	-	-	72 hours
	W5~W10[c]	×	×	×	-	-	72 hours

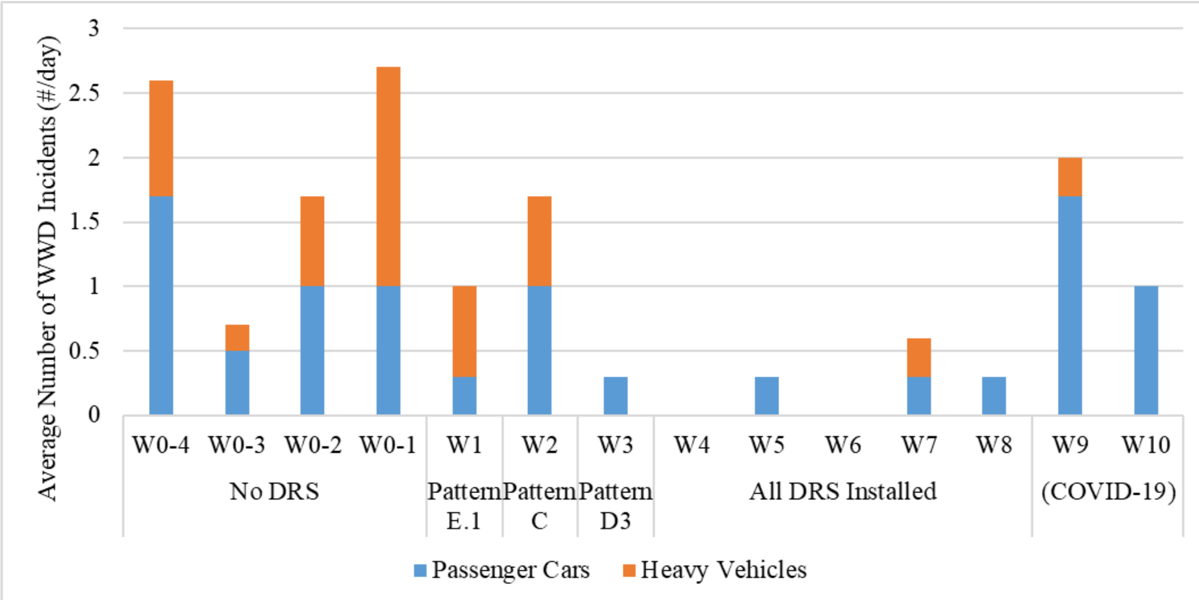
Note:
[a]Average Daily Traffic Volume from NC-350; Reference AADT: Exit 208 = 1,550; Exit 284 = 1,260 (Source: 2017 Alabama Traffic Data).
[b]Data used for low-cost countermeasures evaluation in Chapter 3. W0-4 = After Period 2; W0-3 = After Period 4; W0-2 = After Period 5. WWD incidents occurring while raining were excluded.
[c]DRS removed at Exit 284.

4.4 Results

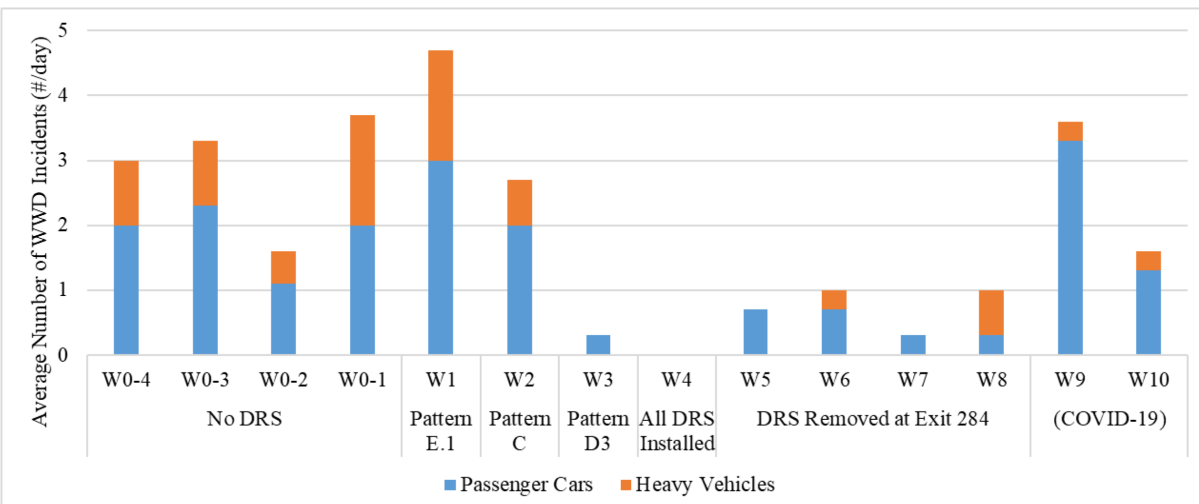
4.4.1 Analysis of WWD Incidents

Figure 10 shows the changes in the number of WWD incidents per day before and after DRS installation at the two study locations. Overall, there is a decreasing trend in the number of WWD incidents per day after DRS installation. However, the WWD incident frequency at Exit 284 has increased after DRS were removed due to a resurfacing project. The study also found that traffic volume has a significant impact on WWD incidents. The frequency of WWD incidents at both sites increased during the after periods when the traffic volume dropped due to COVID-19.

At Exit 208 (Figure 10.a), the frequency of WWD incidents was reduced from 1.9 per day (mean of W0-1, W0-2, W0-3, and W0-4) to near zero after installing all the DRS patterns. Additionally, a large number of heavy vehicles were involved in WWD incidents before DRS installation. No heavy vehicles were found to enter the off-ramp during the after periods. The WWD incident frequency increased during the COVID-19 pandemic periods (W9 and W10). At Exit 284, the frequency of WWD incidents was reduced from 3.3 to 0.2 per day after the implementation of DRS Pattern D3, then increased to 1.4 per day after all the DRS were removed. The reason that WWD incident frequency did not increase to the before condition might be that a resurfacing project provided drivers with better visibility of the on-ramp and setups of work zone may slow the potential WW drivers (left-turns on crossroad). Similarly, the lower traffic volume caused by COVID-19 resulted in the increased frequency of WWD incidents.



(a) Exit 208



(b) Exit 284

Figure 10. Changes in the Number of WWD Incidents before and after DRS Installation: (a) Exit 208 and (b) Exit 284

Table 11. Statistical Analysis of Frequency of WWD Incidents

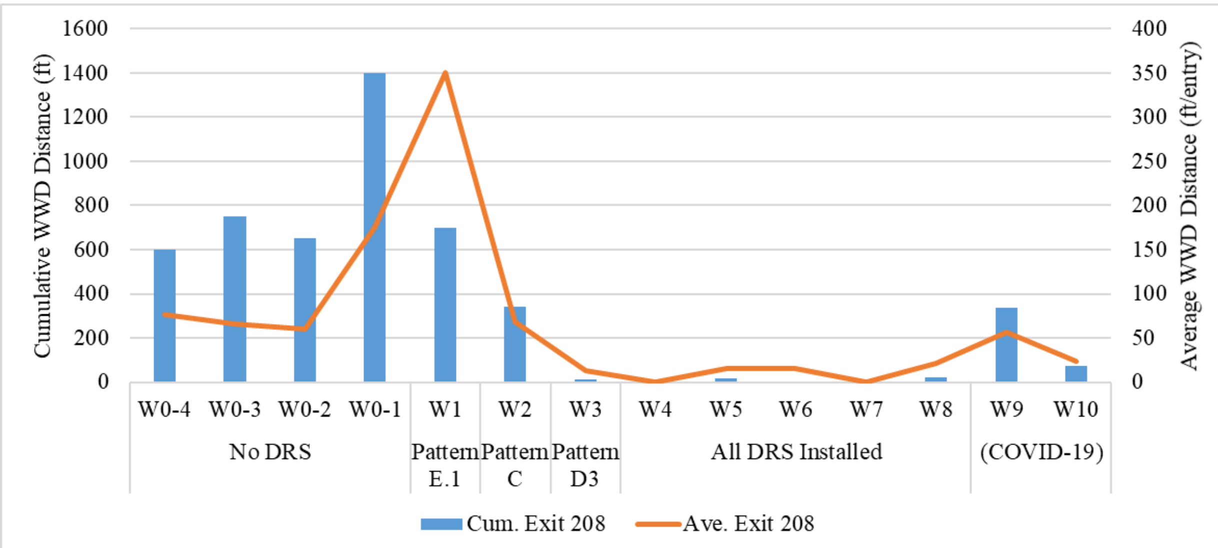
Studies	**Comparison Group 1**		**Comparison Group 2**		***t*-stat**	***p*-value**
	Phase	**Mean (per day)**	**Phase**	**Mean (per day)**		
Before-and-After[a]	**Exit 208 Before DRS Implementation (W0-4 ~ W0-1)**	1.9	**Exit 208 After DRS Implementation (W3 ~ W10)**	0.7	2.95	0.04
	Exit 284 Before DRS Implementation (W0-4 ~ W0-1)	3.3	**Exit 284 After DRS Implementation (W3 ~ W4)**	0.2	13.06	< 0.01
	Exit 284 After DRS Implementation (W3 ~ W4)	0.2	**Exit 284 DRS Removed from the Field (W5 ~ W10)**	1.4	-2.36	0.03
	Exit 284 Before DRS Implementation (W0-4 ~ W0-1)	3.3	**Exit 284 DRS Removed from the Field (W5 ~ W10)**	1.4	3.66	< 0.01
Cross-Sectional[b]	**Exit 208 DRS Remain in the Field (W5 ~ W10)**	0.7	**Exit 284 DRS Removed from the Field (W5 ~ W10)**	1.4	-2.45	0.03

Note: [a]*t*-tests at significance level of 0.05; [b]Paried *t*-tests at significance level of 0.05.

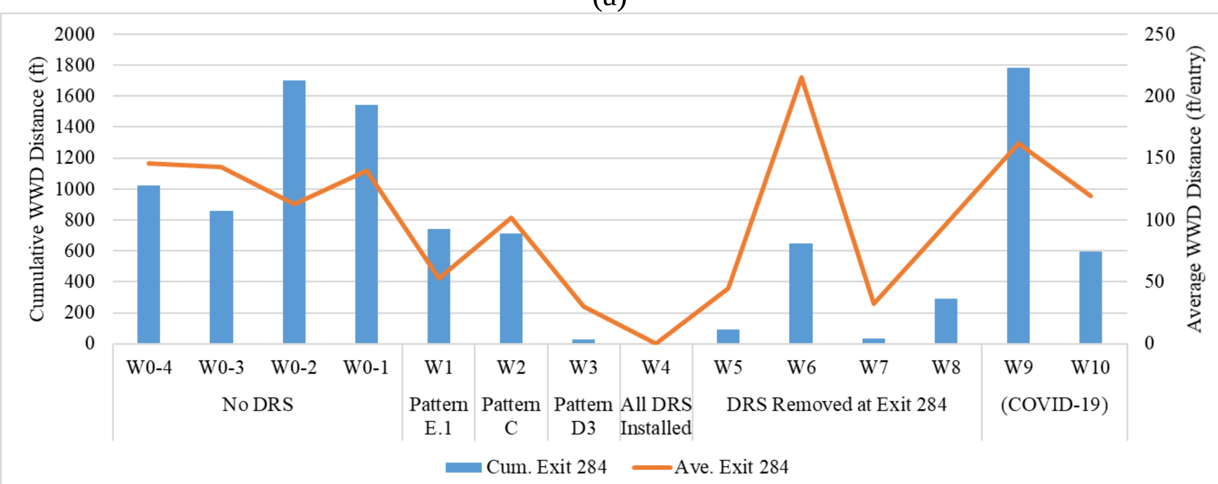
Table 11 summarizes the statistical results of frequency of WWD incidents. *T*-tests with a significance level of 0.05 were used for before-and-after comparisons while paired *t*-tests with a significance level of 0.05 were conducted for the cross-sectional comparisons. Based on the *p*-values, the frequency of WWD incidents were significantly lower after DRS implementation than before at both locations (Exit 208: *p*-value = 0.04; Exit 284: *p*-value < 0.01). This indicates that DRS can reduce the frequency of WWD incidents. At Exit 284, the frequency of WWD incidents significantly increased after removing DRS (*p*-value = 0.03). However, due to the resurfacing project, this frequency didn't increase to the before condition (*p*-value < 0.01). As a result of removing DRS (W5-W10), the frequencies of WWD incidents at two locations are statistically different (*p*-value = 0.03), where the frequency at Exit 284 is higher than Exit 208.

Figure 11 presents the changes in WWD distances before and after DRS installation. The cumulative and average WWD distance shows a decreasing trend after DRS installation at both locations. Additionally, an increasing trend was observed at Exit 284 after DRS were removed. For WWD incidents occurring at Exit 208 (Figure 11.a), the average WWD distance was more than 50 ft per entry before DRS installation. All WW drivers stopped and self-corrected after going the WW in less than 20 ft after all the DRS installation. The average WWD distance slightly increased due to the low volume during the COVID-19 pandemic period. At Exit 284 (Figure 11.b), the average WWD distance was roughly more than 100 ft per entry. It was reduced to below 30 ft per entry with the installation of DRS. According to video data, the WW drivers quickly stopped and self-corrected after driving over DRS Pattern D3. After DRS were removed, average WWD distances were found to be close to the before condition.

Figure 12 compares the average WWD distance between Exit 208 with DRS and Exit 284 without DRS. The average WWD distance is approximately four times longer at Exit 284 than Exit 208 during the entire six after periods.



(a)



(b)

Figure 11. Changes in WWD Distances before and after DRS Installation: (a) Exit 208 and (b) Exit 284

Figure 12. Cross-Sectional Comparison of Average WWD Distance

Table 12 summarizes the statistical results of comparison of WWD distance between the different before and after periods. *T*-tests with a significance level of 0.05 were used. Based on the *p*-values, the WWD distances were significantly lower after DRS implementation at both locations (Exit 208: *p*-value = 0.02; Exit 284: *p*-value < 0.01). This implies that DRS can reduce the WWD distance. At Exit 284, the WWD distance significantly increased after removing DRS (*p*-value < 0.01), which also shows no statistical difference with the before condition (*p*-value = 0.45). According to the cross-sectional comparisons between Exit 208 and Exit 284 after removing DRS, the WWD distances at two locations are statistically different (*p*-value = 0.01), where the average distance at Exit 284 is significantly higher than Exit 208. The results prove that DRS can effectively reduce WWD distance.

Table 12. Statistical Analysis of WWD Distance

Studies	Comparison Group 1		Comparison Group 2		*t*-stat	*p*-value
	Phase	Mean (ft/entry)	Phase	Mean (ft/entry)		
Before-and-After[a]	Exit 208 Before DRS Implementation (W0-4 ~ W0-1)	76	Exit 208 After DRS Implementation (W3 ~ W10)	30	2.21	0.02
	Exit 284 Before DRS Implementation (W0-4 ~ W0-1)	121	Exit 284 After DRS Implementation (W3 ~ W4)	15	3.57	< 0.01
	Exit 284 After DRS Implementation (W3 ~ W4)	15	Exit 284 DRS Removed from the Field (W5 ~ W10)	126	~3.09	< 0.01
	Exit 284 Before DRS Implementation (W0-4 ~ W0-1)	121	Exit 284 DRS Removed from the Field (W5 ~ W10)	126	-0.12	0.45
Cross-Sectional[a]	Exit 208 DRS Remain in the Field (W5 ~ W10)	34	Exit 284 DRS Removed from the Field (W5 ~ W10)	126	-2.74	0.01

Note: [a]*t*-tests at significance level of 0.05.

4.4.2 Interior Sound Caused by DRS

Interior sound data were collected through field driving tests when the ramp was temporarily closed by ALDOT regional engineers. The field driving tests were conducted at Exit 208 on I-65. Both RW and WW interior sound data were acquired under seven speed categories, including 10, 15, 20, 25, 30, 35, and 40 mph. To gather the RW sound data, one researcher drove a full-size passenger car from the deceleration lane to the off-ramp terminal on the closed ramp, then drove in the reverse direction to obtain the WW sound data.

The time-series analysis was applied to obtain an understanding of sound level change over the entire trip, including the peaks when vehicles pass the DRS. *T*-tests at the significance level of 0.05 were also conducted to discern significant differences between the average RW and WW sound levels.

Pattern E.1

According to the speed data collected by speed sensors, the average RW speed was 30 mph and average WWD speed was 35 mph at the location where Pattern E.1 was implemented. Figure 13 presents the internal sound level when driving on Pattern E.1 in both RW and WW directions.

This pattern generated a 15 dBA louder sound for RW drivers and 20 dBA more for WW drivers than in the ambient conditions. The mean value of WW sound was 72 dBA, which was almost 5 dBA higher than the RW mean value (67 dBA). The *p*-value of the *t*-test (significance level = 0.05) was 0.012, which indicated that average RW and WW sound levels were significantly different.

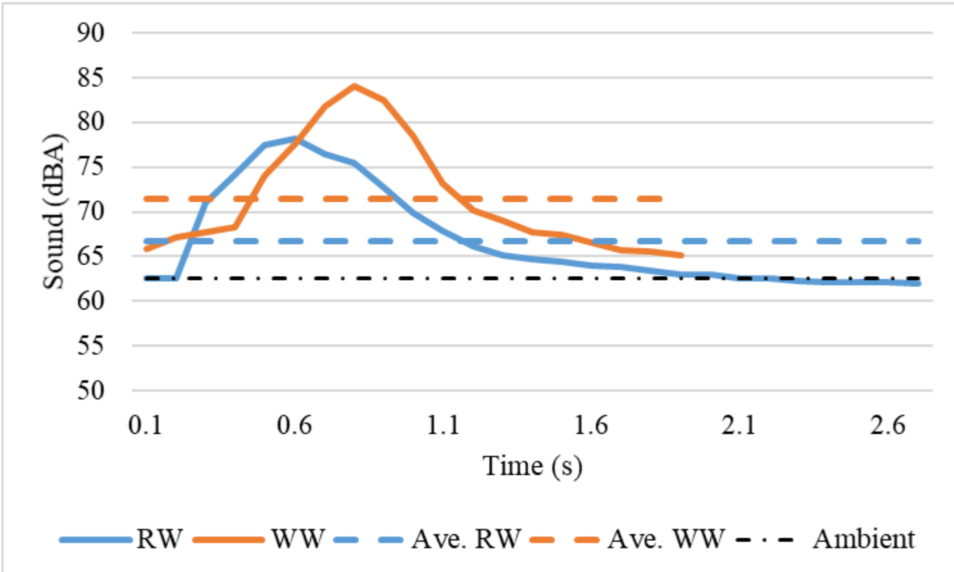


Figure 13. RW and WW Sound by Pattern E.1

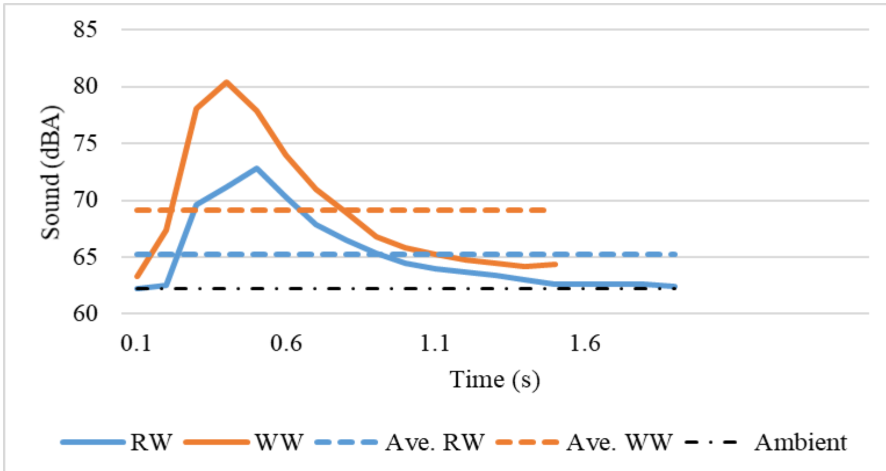
Pattern C

Figure 14 shows the RW and WW sound level on Pattern C when the average RW speed was 30 mph and average WWD speed was 35 mph. As shown in Figure 14.a, RW drivers perceived a maximum of 10 dBA louder sound than in ambient conditions, while WW drivers perceived 17 dBA louder sound when driving on the strips of 5-ft spacings. Moreover, average sounds for the RW drivers and WW drivers are 65 dBA and 69 dBA, respectively. A *p*-value of 0.03 implied that a significant difference existed between the average RW and WW sound levels.

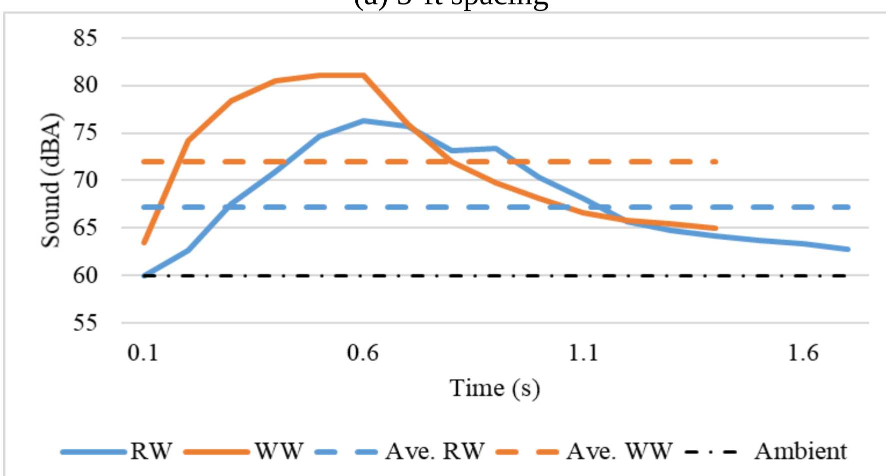
Figure 14.b presents the RW and WW sound generated by the strips of 2-ft spacing. The average RW speed was 25 mph and WWD 30 mph. Compared with the ambient condition, the strips of 2-ft spacing produced a maximum 15 dBA louder sound for RW drivers and 17 dBA for WW drivers. The average sound level (72 dBA) for WW drivers is 5 dBA more than average sound (67 dBA) for RW drivers. The *t*-test results revealed that the average WW sound level was significantly different from the RW with a *p*-value of 0.03.

Figure 14.c shows the RW and WW sound produced by 1-ft spacing strips of Pattern C. The speed sensors recorded an average speed of 20 mph for RW drivers travelling on these strips, while WWD were 35 mph. In comparison with the ambient status, a maximum of 17 dBA louder sound was caused by strips for RW drivers and 20 dBA for WW drivers. Average sound level (71 dBA) for WW drivers is 5-dBA more than the sound level (66 dBA) perceived by RW drivers.

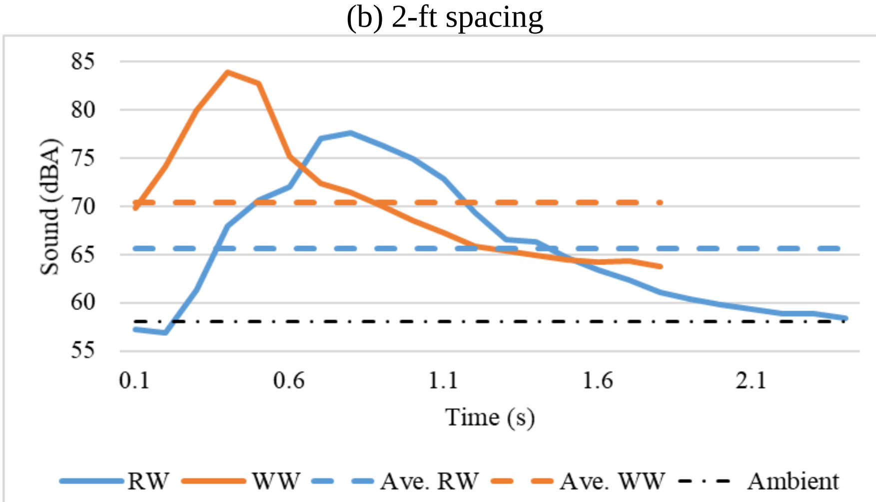
A *p*-value of 0.02 manifested the significant difference between the average RW and WW sound levels.



(a) 5-ft spacing



(b) 2-ft spacing



(c) 1-ft spacing

Figure 14. RW and WW Sound by Pattern C

Pattern D3

Figure 15 demonstrates the RW and WW sound levels when a vehicle passes the Pattern D3. The average RW speed was 10 mph and average WW speed was 25 mph based on the data collected by speed sensors in the field. Compared with the ambient condition, RW drivers were able to obtain a 13 dBA louder sound at most while WW drivers would perceive a maximum 20 dBA more. Average sound level (71 dBA) for WW drivers is 13 dBA more than the average sound level (58 dBA) for RW drivers. The *t*-test results showed that the average RW and WW sound levels were significantly different with a *p*-value of less than 0.01.

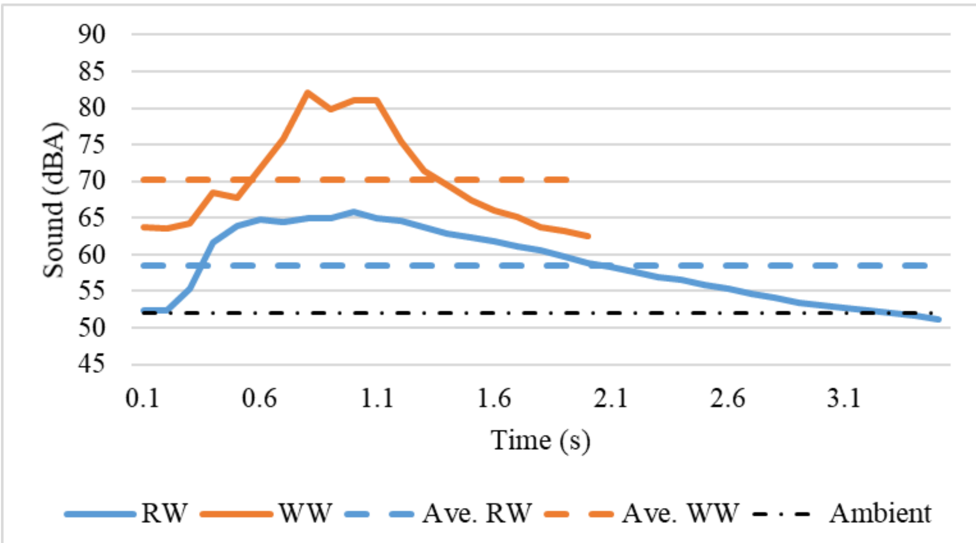


Figure 15. RW and WW Sound by Pattern D3

4.4.3 Exterior Sound Caused by DRS

Table 13 summarizes the exterior sound levels generated by the DRS. At Exit 208, the exterior sound level on the roadside next to Pattern E.1 ranged from 55 to 75 dBA at ambient condition. Because it was close to the freeway mainline, the maximum sound level of 75 dBA happend when a large platoon of mainline vehicles passed by. The exterior sound level increased to 68-79 dBA when a vehicle travelled on Pattern E.1. By averaging the sound levels, it was found that Pattern E.1 can generate an average of an extra 9 dBA sound to the environment.

Pattern C was located farther from the freeway mainlines. The ambient exterior sound level ranged from 55 to 65 dBA. The reduced spacings of strips led to the increasing sound levels generated by different strip groups. An additional 3 dBA, 5dBA, and 10 dBA sound were generated by the 5-ft spacing strips, the 2-ft strips, and 1-ft strips, respectively.

The ambient sound near the Pattern D3 was a bit louder than Pattern C because it was located near the traffic on the crossroad. However, the sound increment caused by Pattern D3 was negligible because vehicles typically made complete stops at the stop bar and the exterior sound mainly came from the idling engine noise.

Likewise, exterior sound results were similar at Exit 284, except for the overall louder ambient sound due to the larger traffic volumes. To summarize, Pattern E.1 can produce 9 dBA extra sound to the environment. Pattern C generated almost 10 dBA additional sound by the 1-ft spacing strips, 5 dBA by the 2-ft ones, and 3 dBA by the 5-ft ones. The exterior sound impact of Pattern D3 was negligible.

Table 13. Exterior Sound Levels Caused by the DRS

Location	Pattern		Ambient (dBA)	Vehicle (dBA)	Mean Increment (dBA)
Exit 208 I-65, AL	**E.1**		55-75	68-79	8.9
	C	**5-ft**	55-65	58-68	3.2
		2-ft		60-70	5.1
		1-ft		65-74	9.7
	D3		55-67	Engine Noise	Negligible
Exit 284 I-65, AL	**E.1**		62-77	70-77	8.5
	C	**5-ft**	60-67	62-70	2.9
		2-ft		66-72	5.6
		1-ft		70-75	9.2
	D3		65-70	Engine Noise	Negligible

4.4.4 Interior Vibration Caused by DRS

Interior vibration data was also acquired from the same field driving tests for measuring interior sound at Exit 208 on I-65 for both RW and WW directions. The RW vibration data was collected from driving from the deceleration lane on the freeway mainline to the off-ramp terminal. The WW vibration data was obtained from driving in the reverse direction on the closed ramp.

A spectrum analysis was applied for vibration data analysis because different vibration patterns can be expressed similarly in the time series. Fast Fourier transform (FFT), which is a common algorithm to compute the spectrum, was employed to measure vibration amplitudes as a function of frequency. FFT converted the original vibration data from the time domain to the frequency domain. Nonstandard vibrations can be treated as a combination of various vibrations with different frequencies and amplitudes. The *X*-axis in the FFT plot stands for frequencies ranging from low to high, while the *Y*-axis shows the amplitude associated with each frequency.

Equation 1 presents the procedure of dividing a nonstandard vibration signal into a list of standard vibration signals (i.e., sine and cosine signals). In this study, the vibration signals caused by the DRS can be presented as *f*(*x*), which equals to the sum of various standard signals with different phases *kx* (i.e., 1/2π, π, 3/2π…) and the halved offset (a_0):

$$f(x) = \frac{a_0}{2} + \sum_{k=1}^{n} [a_k \cos(kx) + b_k \sin(kx)], \tag{1}$$

where

- *f*(*x*) is the original signal;
- a_0 is the offset phase;
- a_k and b_k are the amplitudes of associated standard signals; and
- *kx* is the multiple of 1/2 π (e.g., 1/2π, π, 3/2π…).

By using the following equation, the root-mean-square (RMS) is used to estimate the amount of vibration generated by DRS.

$$RMS = \sqrt{\frac{1}{n}\sum_{i} {x_i}^2} \tag{2}$$

where x_i is the collected vibration data and *n* is the total number of data points.

Pattern E.1

RMS amplitude of WW vibrations was 0.106 *g*, which was 0.027 *g* higher than the RW direction (0.079 *g*). The *p*-value from the *f*-test at the significance level of 0.05 was 0.00, which showed that the variances of RW and WW vibrations were significantly different. Figure 16 presents the spectrums of the vibrations generated by Pattern E.1 in RW and WW directions. The RW vibrations had peaks of 2 and 13 Hz, while the WW direction had peak vibrations at 2, 16, 32, and 47 Hz. In short, WW drivers can perceive more severe vibrations in terms of higher amplitudes and frequencies.

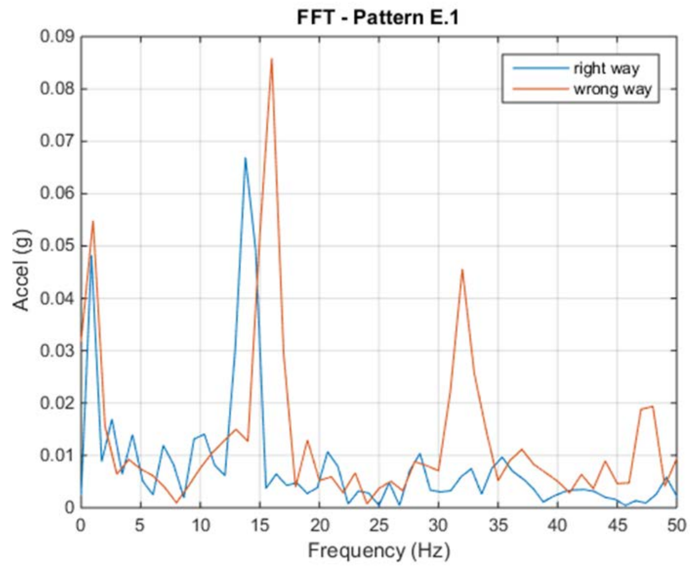


Figure 16. Spectrums of Vibrations by Pattern E.1

Pattern C

Vibration data were collected when driving at a constant speed of 35 mph on all three groups of Pattern C in the WW direction. However, RW drivers had decreased average speeds of 30, 25, and 20 mph at the strips of 5-ft, 2-ft, and 1-ft spacings, respectively.

Consequently, WW drivers were able to perceive RMS amplitude of vibrations equivalent to 0.054 *g*, compared with 0.041 *g* for RW drivers when passing the strips of 5-ft spacings. The RW and WW vibrations were significantly different in variances according to the *p*-value of 0.00 from the *f*-test. As shown in Figure 17.a, vibrations for RW drivers had peaks of 3, 13, 21, and 35 Hz, while WW vibrations saw peaks of 2, 5, 13, 33, and 37 Hz. Visually, the peaks from RW and WW vibrations were alike. However, WW vibration peaks had higher amplitudes.

The RMS WW vibration (0.117 *g)* was 0.04 *g* more than the RW one (0.077 *g*) by the 2-ft spacing strips. The *f*-test result also showed the significant difference between the variances of RW and WW vibrations. The spectrums of RW and WW vibrations produced by these strips are presented in Figure 17.b. RW vibrations had peaks of 13 and 35 Hz, while peaks occurred at 17 and 35 Hz in the WW direction. The amplitude of the 13 Hz RW peak was almost 0.02 *g* higher than the 17 Hz WW peak, while amplitudes of the 35 Hz WW peak were more than twice as high as the RW one.

For the 1-ft spacing strips, the RMS WW vibration (0.121 *g)* was 0.023 *g* higher than RW vibrations (0.098 *g)*. A *p*-value of 0.02 from the *f*-test revealed a significant difference between RW and WW vibrations in variances. Figure 17.c exposed the spectrums of RW and WW vibrations. The RW vibration had only one peak of 14 Hz, while WW had two peaks of 17 and 36 Hz.

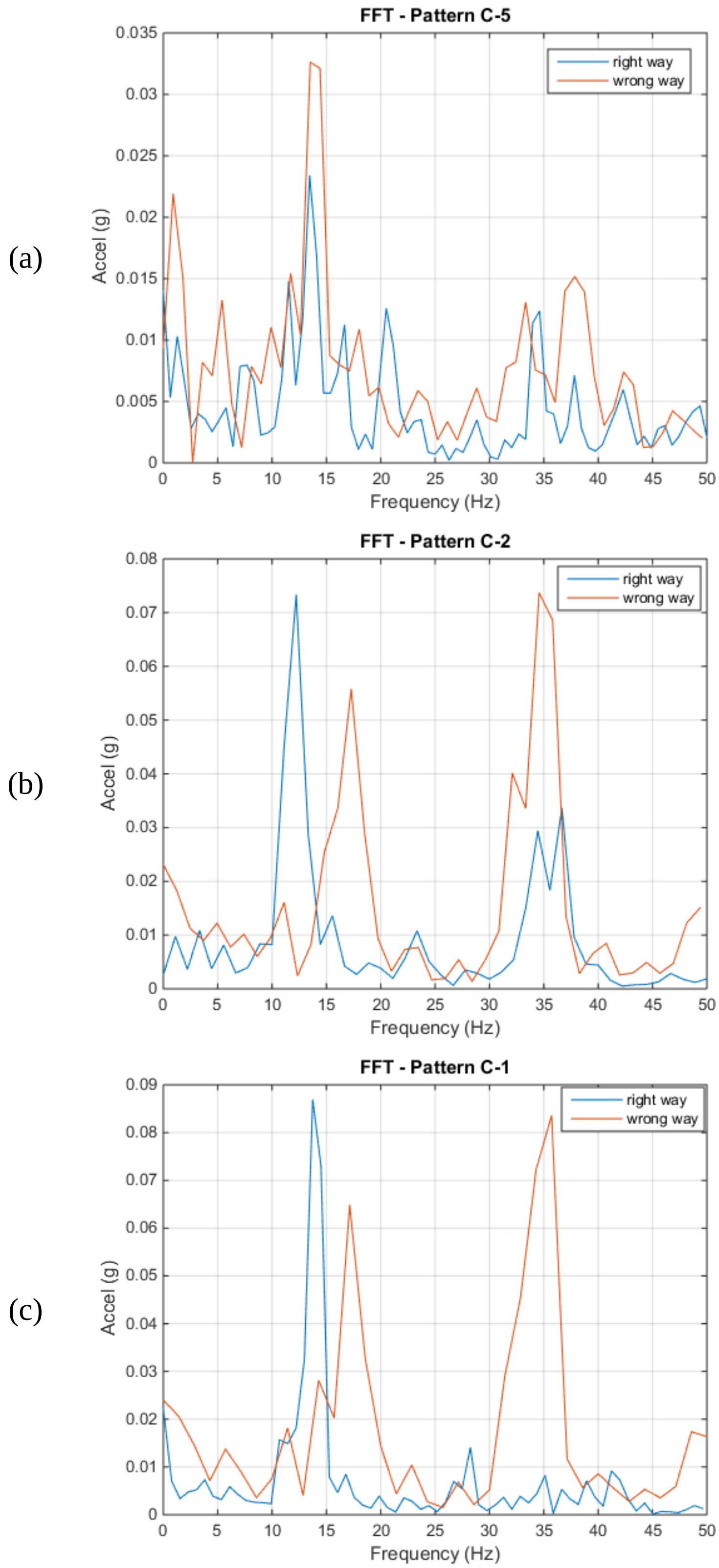


Figure 17. Spectrums of Vibrations by Pattern C: (a) 5 ft; (b) 2 ft; (c) 1 ft

Pattern D3

The vibration data by the Pattern D3 were collected at the average RW speed of 10 mph and the average WW speed of 25 mph. Consequently, the vibrations collected for WW and RW are 0.089 *g* and 0.044 *g*, respectively. As shown in Figure 18, vibrations for RW drivers had two peaks of 1 and 7 Hz, while WW drivers obtained three vibration peaks of 1, 12, and 35 Hz. Briefly, WW drivers can perceive twice the vibrations amplitude as RW, as well as more peaks with higher frequencies.

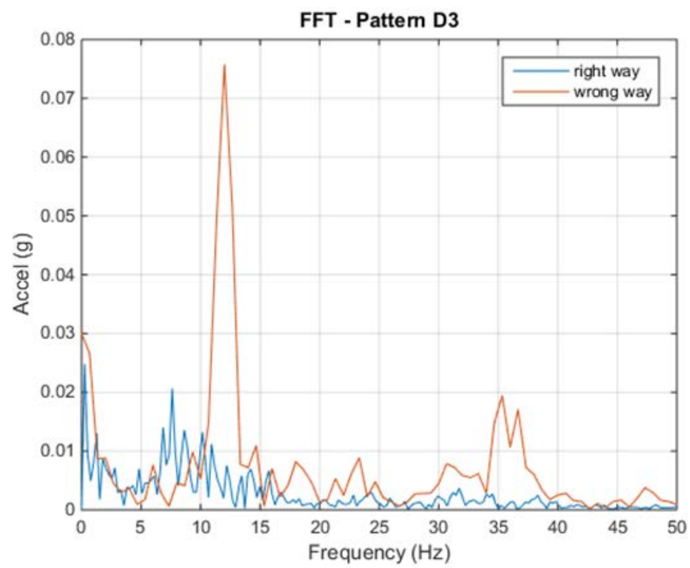


Figure 18. RW and WW Spectrums of Pattern D3

4.4.5 Speed Impacts on RW Vehicles by DRS

Since DRS mostly affects traffic speed by passenger car in the free-flow condition, the raw speed data need to be filtered and cleaned before analysis. Vehicle speed (mph), vehicle length (ft), and time headway (s) were first examined. First, boxplot outlier filters were utilized to filter the speed data that are more than the upper limit or less than the lower limit. For a normal distribution (α= 0.05), 0.7% of the data were fitered as the outliers. Equations 2 to 4 show the calculations of upper and lower limits. Other filters were also applied to further process the data. According to *Reference.com* (IAC Publishing, LLC 2019), the average length of passenger cars ranges from 14.4 to 16.4 ft in America. Thus, a filter was set to search records between 14 and 17 ft. To eliminate the effects of slow leading vehicles on speeds, headways greater than 2 s were selected. The 2-s time headway will ensure that the vehicle speeds were measured for the free-flow condition. Overall, approximately 70% of speed data remained for analysis after the filtering and cleaning process.

$$interquartile\ range\ (IQR)\ =\ upper\ quartile\ (Q3) - lower\ quartile\ (Q1) \tag{2}$$

$$lower\ limit\ =\ Q1 - 1.5 \times IQR \tag{3}$$

$$upper\ limit\ =\ Q3\ +\ 1.5 \times IQR \tag{4}$$

where

- First quartile (Q_1 / 25th percentile), also known as the lower quartile $q_n(0.25)$, is the median of the lower half of the dataset.
- Third quartile (Q_3 / 75th percentile), also known as the upper quartile $q_n(0.75)$, is the median of the upper half of the dataset.
- Interquartile range (IQR) is the distance between the upper and lower quartiles.

Descriptive statistics such as maximum, 85th percentile, mean, minimum, and variance [or standard deviation (SD)] were first analyzed. To compare the average speeds, *z*-tests were employed. As the speed distributions were normal, both *z*- (when variances were known) and *t*-tests can be applied. *Z*-tests were used when the sample size was large (i.e., greater than 30), while *t*-tests were utilized with small sample sizes. The significance level of *z*-tests used in this study was 0.05. Moreover, the speed variance was investigated to measure driver adoption of DRS. *F*-tests with the significance level of 0.05 were applied to compare the before and after speed variances.

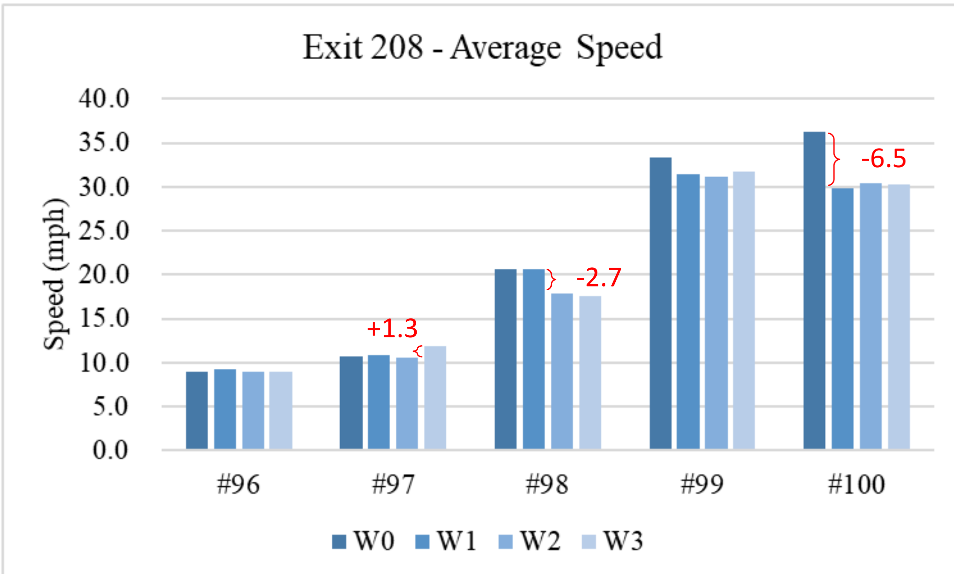
Average Speeds

A comparison between the average speed before and after each DRS implementation was conducted to examine if the DRS pattern has an impact on average speed, especially on the average speed before the posted advisory speed sign (25 mph at Exit 208 and 30 mph at Exit 284). The *z*-tests were used for statistical significance at the confidence level of 0.05. Figure 19 shows the average speed in four weeks (W0=before DRS, W1=Pattern E.1, W2=Pattern C, W3=Pattern D3).

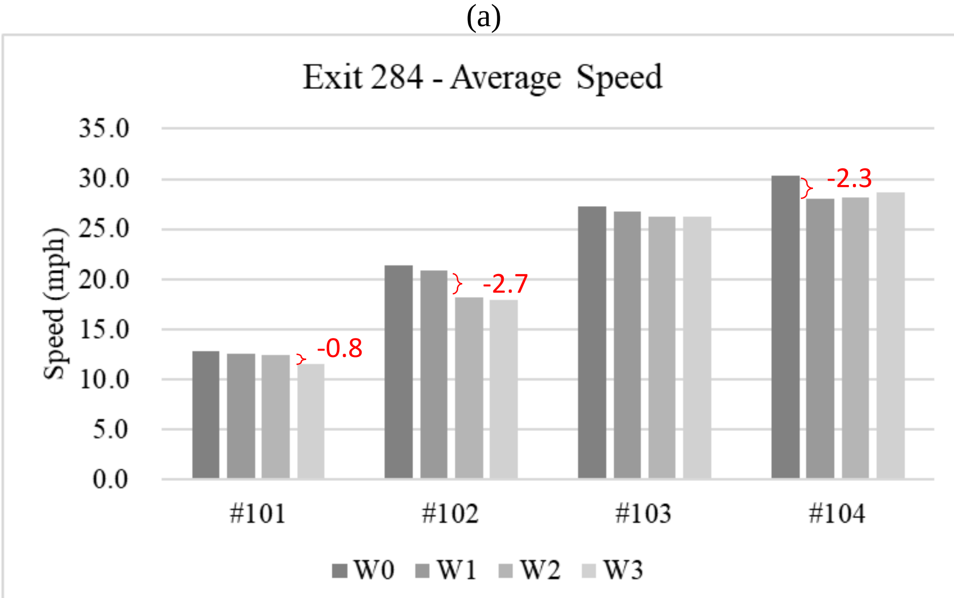
As shown in Figure 19.a, the average speed from sensor #100 located right before the advisory ramp speed limit sign (25 mph) significantly decreased by 6.5 mph (from 36.3 to 29.8 mph) at Exit 208 after the installation of Pattern E.1. While at Exit 284 (Figure 19.b), a reduction of 2.3 mph (from 30.3 to 28 mph) in the average speed from sensor #104 was observed after implementing Pattern E.1. The reason for the smaller amount of speed reduction at Exit 284 is that the average speed in the before period was already very close to the posted advisory speed sign. Moreover, it was found that 94% of vehicles exceeded the advisory ramp speed limit at Exit 208 in the before period. This percentage was reduced to 83% after installing Pattern E.1. A similar trend was found at Exit 284. The percentage of vehicles over the advisory ramp speed limit decreased from 45% to 30% at Exit 284. This finding implied that Pattern E.1 can reduce RW traffic speed before they enter the ramp curve segment. The advisory speed at Exit 208 seems too low given the factor that average speed during the before condition is about 36.3 mph. The DRS pattern E.1 can reduce it to 29.8 mph; however, that is still about 5 mph above the advisory speed.

The data analysis suggests to increase the advisory speed to 30 mph for better driver compliance and being more consistent with other similar locations such as Exit 284.

Significant changes can be observed in average speeds collected from sensors #98 and #102 immediately after Pattern C at Exits 208 and 284. The same average speed reduction of 2.7 mph was estimated for both locations, as shown in Figure 19. The average speeds collected by sensors # 99 and #103 before the Pattern C were also reduced after Pattern E.1 was implemented in W1.



(a)



(b)

Figure 19. Average Speeds on SB Off-Ramps at Exits (a) 208 and (b) 284 on I-65

At Exit 208 (Figure 19.a), the average right-turn speed slightly increased by 1.3 mph at sensor #97 located after the stop bar after implementing Pattern D3, while there was no significant change in average speed for left turns from sensor #96 located before the stop bar. The possible reason is that more right-turning vehicles stopped on Pattern D3 before the stop bar and then accelerated to merge with the crossroad traffic. The average speed before the yield line (sensor #101 in Figure 19.b) was reduced by 0.8 mph at Exit 284 after implementing DRS Pattern D3.

85th Percentile Speeds

The 85th percentile speed is defined as the speed higher than 85 percent of drivers. In this study, the speed more than the 85th percentile speed represents aggressive driving speed. The MUTCD recommends that the speed limit is within 5 mph of the 85th percentile speed of free-flowing traffic. Adjustments can be made if there are horizontal and vertical curves (possible limited sight distance). In this study, 85th percentile speeds at sensors #100 at Exit 208 and #99 at Exit 284 were estimated to compare with the posted advisory speed.

The data analysis suggested that 85th percentile speeds followed the same patterns of the average speeds in terms of significant changes after certain DRS patterns being installed. The 85th percentile speed at sensor #100 was reduced to 35 from 44 mph after implementing Pattern E.1 at Exit 208. The 85th percentile speed was reduced to around 35 mph from 39 mph at sensor #99 at 284. The results indicated that the 85 percentile speed can be reduced by 4 to 9 mph by Pattern E.1. To assess the impact of Pattern E.1 on aggressive driving, the speed characteristics of the upper 15th percentile speeds are studied. Table 14 summarized the characteristics of the upper 15th percentile speeds when vehicles approached and exited the ramp curve segment, including maximum, minimum, mean, and SD during the four week study periods. With *p*-values less than 0.05 from *z*- and *f*-tests at the significance level of 0.05, their means and SDs proved to have significant decreases. No significant difference of the 85th percentile speed was observed at other locations (sensor #104 and sensor #103) because the initial 85th speed was close to the speed limit.

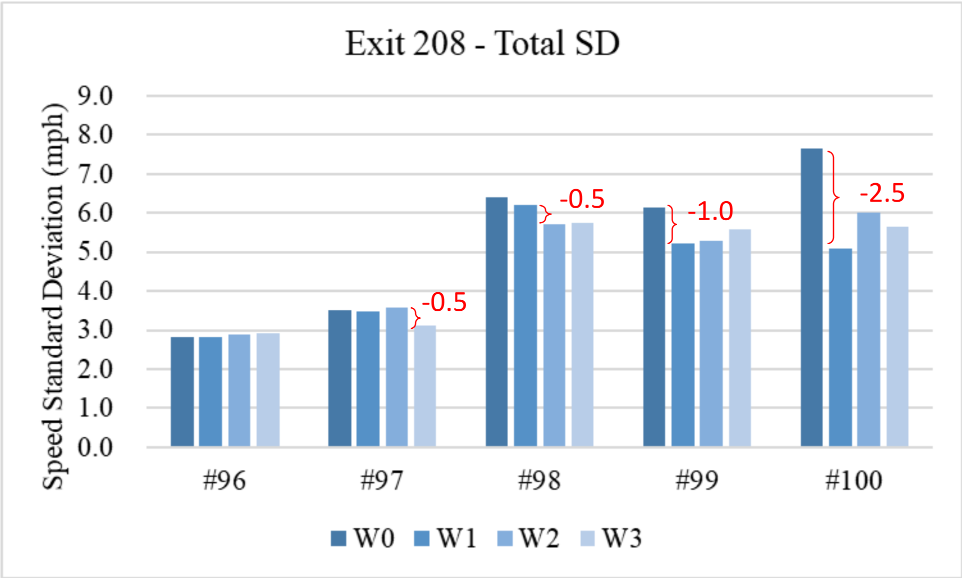
Table 14. Speed Characteristics of Upper 15th Percentile Speeds

Location	**Sensor #99**				**Sensor #100**			
Characteristics (Unit: mph)	**W0**	**W1**	**W2**	**W3**	**W0**	**W1**	**W2**	**W3**
Max	51.0	45.0	45.0	48.0	58.0	44.0	47.0	46.0
Mean	43.0*	40.1*	39.5	40.7	49.7*	38.7*	41.5	40.4
Min	40.0	38.0	37.0	38.0	45.0	36.0	38.0	37.0
SD	3.1*	1.9*	2.3	2.6	4.0*	2.3*	3.0	2.8

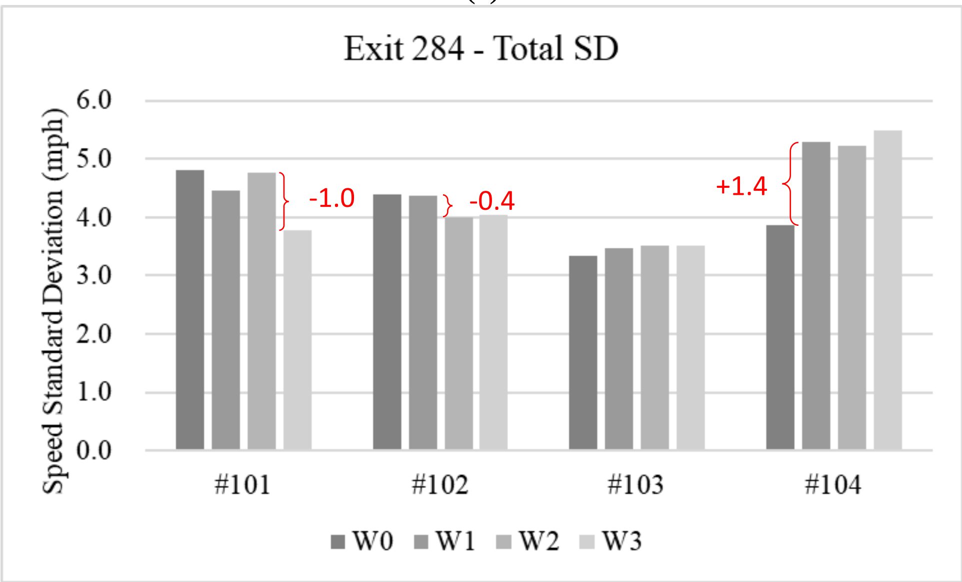
Note: * Significant difference based on *z*-tests at the significance level of 0.05

Speed Standard Deviations

Figure 20 presents the SDs of speed along the off-ramps from W0 to W3 at the two study locations. At Exit 208 (Figure 20.a), the SDs at four of the five locations showed a declining trend after implementing DRS. In the W1 period after implementing Pattern E.1, SDs of speed from sensors #100 and #99 significantly decreased by 2.5 and 1.0 mph, respectively. From W1 to W2, the SDs of speed from sensor #98 was significantly reduced by 0.5 mph after installation of Pattern C. Further, Pattern D3 led to a decrease of 0.5 mph in SDs for right-turn speed at the stop bar (sensor #97). There was no significant change in SDs for the left-turning speed at the stop bar (sensor #96).



(a)



(b)

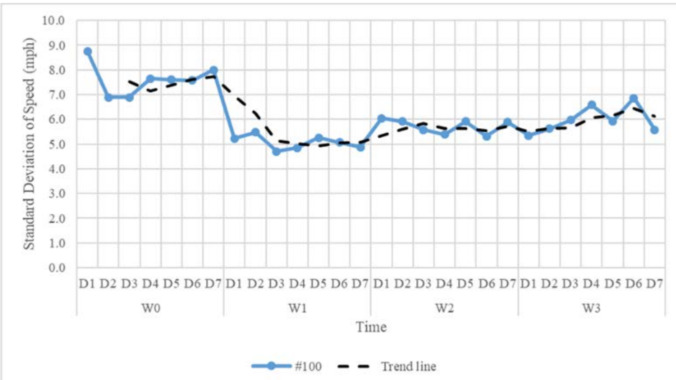
Figure 20. Speed Standard Deviations on SB Off-Ramps at Exits (a) 208 and (b) 284 on I-65

At Exit 284 (Figure 20.b), Pattern D3 led to a decrease of 1.0 mph in the SDs for right-turn speeds at the yield line (sensor #101). Pattern C reduced 0.4 mph in the SDs of speed in middle of the ramp (sensor #102). However, SDs of speed from sensor #104 significantly increased by 1.4

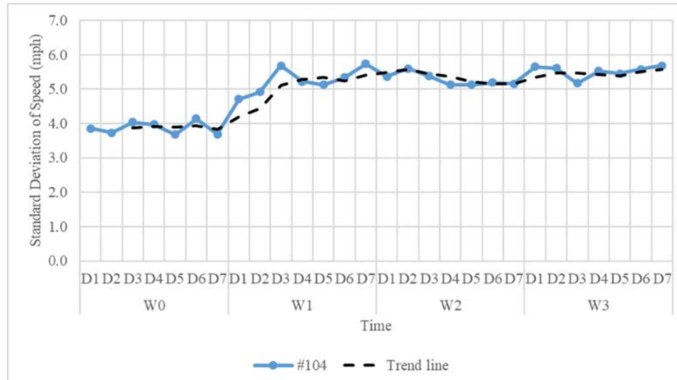
mph after installing Pattern E.1, and remained that level in the W2 and W3 periods. The possible reason is that the average speed of this location was already close to the posted speed limit. Some drivers further reduced their speeds after implementing the DRS.

Driver Adoption

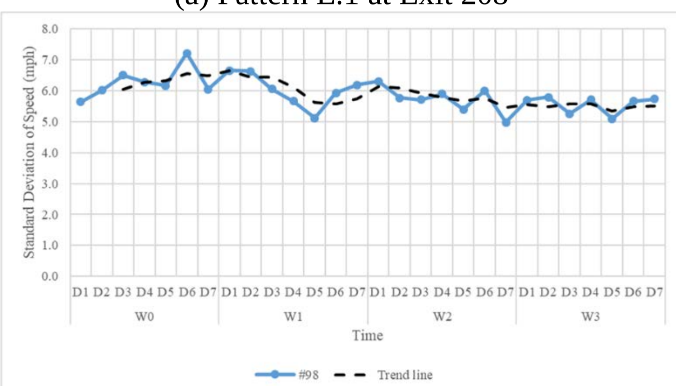
In this study, the trends of daily changes in speed SDs were used to evaluate the driver adoption of a certain DRS pattern. Figure 21 presents the trends of the driver adoption process.



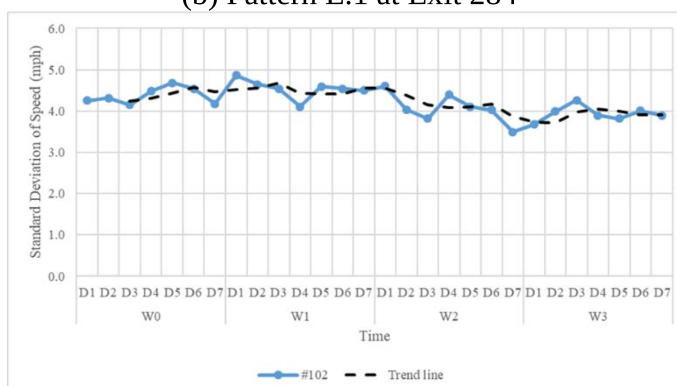
(a) Pattern E.1 at Exit 208



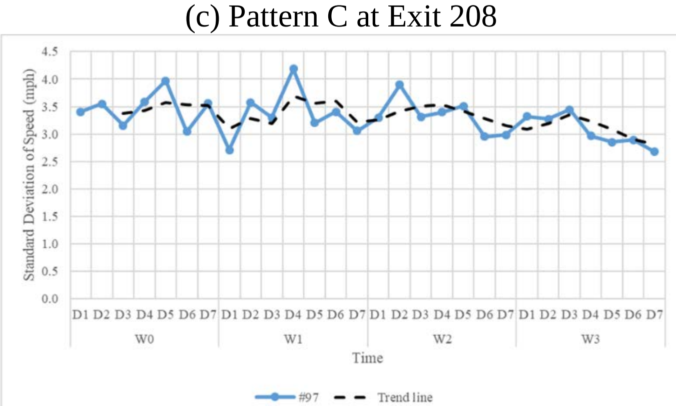
(b) Pattern E.1 at Exit 284



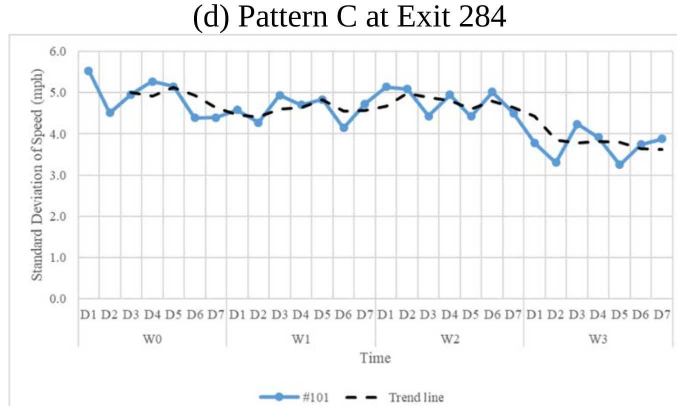
(c) Pattern C at Exit 208



(d) Pattern C at Exit 284



(e) Pattern D3 at Exit 208



(f) Pattern D3 at Exit 284

Note: Solid line = recorded speed SD; Dashed line = 2-day moving average

Figure 21. Driver Adoption of DRS Patterns

Speed SDs at each location were estimated for each day for four weeks (W0 to W3). The simple moving average method (Interval = 2 days) was applied to track the trend. At Exit 208 (Figure 21.a), an immediate drop of the speed SD was observed on the first day of W1 when Pattern E.1 was installed. It took two days for the speed SD to become stable around 5-6 mph. In contrast, an increasing trend was found from Day 1 (D1) to Day 3 (D3) during the frist week after implementing Pattern E.1 at Exit 284 (Figure 21.b). The speed SD then stabilized between 5 and 6 mph.

As presented in Figures 21.c and 21.d, the SDs of speed at Pattern C gradually decreased after an increase on the D1 of the W2. The speed SDs then had a declining trend since the D2 of the W2. The data collected during the 3-hour DRS installation was removed. Pattern D3 also helped reduce the speed SDs at both stop and yield-controlled ramp terminals. As presented in Figure 21.e, the decreasing trend of the speed SD for right-turn vehicles started after three days in the W3 at Exit 208. It indicated that more drivers made complete stops, which resulted in smaller speed differences. Figure 21.f illustrates the trend of the SDs for right-turn speed under the yield sign control. The trend suggests that Pattern D3 can reduce the average speed SD from 5 mph to below 4 mph.

4.4.6 Other Findings

Left-Turn Confusion at Stop-Controlled Off-Ramp Terminals

The video camera captured that the new channelization island confused some left-turn drivers at the off-ramp terminal at Exit 208 on I-65. As shown in Figure 22, a driver entered a right-turn lane to turn left. The driver may mistakenly consider the new island as a right-in/right-out channelization design. Thus, there was a concern that some drivers did not fully understand the purpose of the channelized island at the off-ramp terminal.

(a) (b) (c)

Figure 22. Left-Turn Confusion Captured at Exit 208 on I-65

A hundred free-flow vehicles were sampled from videos that were recorded during random nonpeak hours on each weekend. Videos taken during daytime or nighttime were both considered.

Nearly 23% to 28% of left-turn vehicles were confused by the new channelization island before installation of Pattern D3. After the implementation of Pattern D3 (W3), the percentage was roughly reduced by half (12%). This indicated that the arrow shape of Pattern D3 can serve as a lane use arrow that helped guide left-turning vehicles to stay in the correct lane.

Utilization of the Center Gaps

Considering the complaints from motorcyclists on TRS based on past studies, a 2-ft gap in the middle of Patterns E.1 and C was designed to allow motorcyclists to pass the strips without hitting them. As observed in the videos (Figure 23), motorcyclists utilized the center gap to pass Patterns E.1 and C.

Figure 23. Motorcycle Using the Center Gaps to Pass DRS Pattern C

4.5 Guidelines for DRS Implementation

The DRS is a relatively new TCD that can be implemented on off-ramps to reduce WWD frequency and distance. Currently, there is no standard or guideline for implementing this device. This study found that DRS has advantages in alerting WW drivers by providing WW drivers with elevated interior sound and vibrations. The results also prove that DRS can reduce both frequencies and travel distances of WWD incidents. Figure 24 illustrates the recommended guidance on implementing DRS with other WW-related signs and pavement markings on off-ramps based on the results of this study.

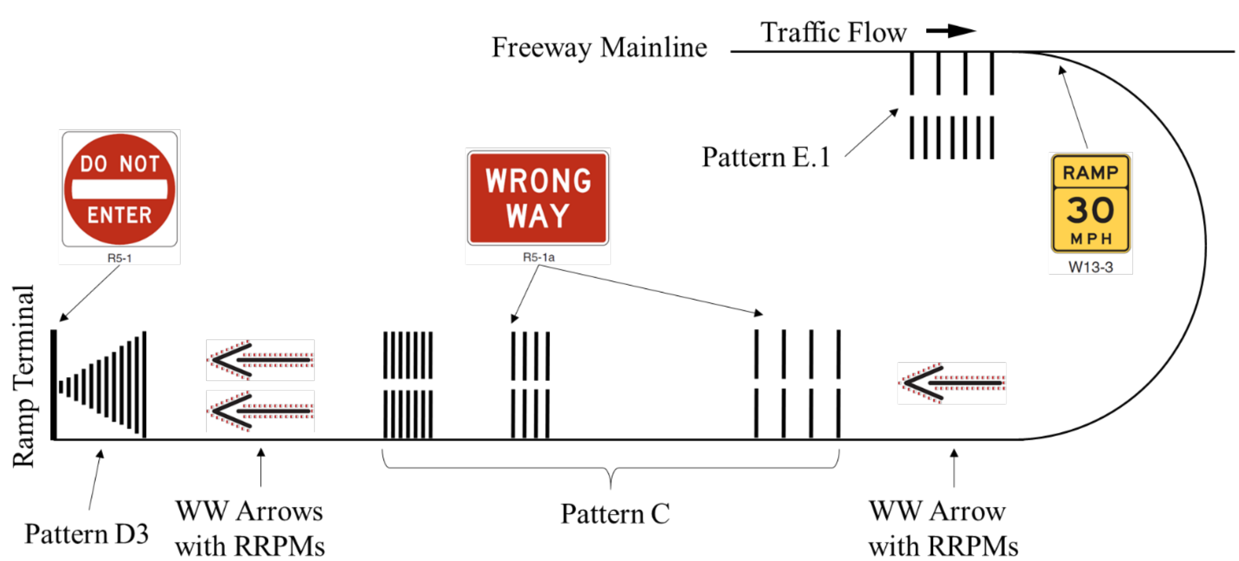


Figure 24. Recommended DRS Deployments with Relevant Signs and Pavement Markings

Pattern E.1 is recommended to be installed ahead of the advisory ramp speed sign in advance of the sharp horizontal ramp curve. The distance between Pattern E.1 and the advisory ramp speed sign shall be considered based on the sight distance study and engineering judgment. For example, 30 ft was employed in this study that can provide a good sight distance for drivers to see the advisory ramp speed limit signs and the horizontal curve when passing the DRS.

Pattern C is recommended to be installed at the long straight off-ramp segment between the ramp gore area and terminal. It can alert RW drivers of a need to slow down/stop or to other upcoming changes. It will also alert WW drivers via sound and vibrations to pay attention to WW signs on the roadside. Therefore, it is recommended to have WW signs placed ahead of Pattern C. Furthermore, the placement of Pattern C should not be overlapping with WW arrows or other lane use pavement markings. Based on this study, it can be placed between two sets of WW arrows.

It is recommended to deploy Pattern D3 near stop bars at the off-ramp terminals. This pattern is effective in terms of reducing WW entries by alerting WW drivers with louder sound and more severe vibrations and a clear visual cue. It can work in collaboration with DNE signs.

The strips should not be attached to other pavement markings such as stop bars or yield lines. In this study, the 1-ft strip of this pattern was installed 1 ft behind the stop bars and the yield line. As described in MUTCD Section 3B.13, retroreflective markers may be used to supplement wide lateral line markings (e.g., stop bar) and WW arrows. Similarly, red retroreflective paint can be applied onto the WW side of Pattern D3.

4.6 Summary

Before-and-after studies were conducted to evaluate the effectiveness of these patterns of DRS based on the WWD frequency and distance, RW vehicle speeds, and other driver behavior changes. Both numbers of WWD incidents and WWD distances had a significant reduction after implementing all the DRS patterns. Each pattern can play its own role in reducing WWD incidents and RW driving speed to meet its design purpose. Though the critical event was rare (e.g., WW vehicles drove all the way to the freeway), one WW vehicle was recorded to stop on the ramp curve by Pattern E.1. Further evaluation is required to test its effectiveness in countering WWD incidents, especially for impaired drivers because most of normal drivers can self-correct before they reach the Pattern E.1. Pattern C reduced both the WWD frequencies and average WWD traveling distances almost by half. Pattern D3 was considered the most effective one for preventing vehicles from entering the off-ramps from crossroads. After implementing Pattern D3, WWD frequencies and distances were reduced to near zero. The after data showed that no WW vehicles traveled farther than the latest implemented DRS pattern in this study.

The before-and-after speed analysis suggested that all three Patterns can reduce RW traffic average speed and most of their SD values. Pattern E.1 can reduce the average speed by 2.3 to 6.5 mph depending on the difference between the advisory speed and operational speeds. When the operational average speed was about 10 mph over the advisory speed, the Pattern E.1 can also reduce speed SD by 2.5 mph at Exit 208. At Exit 284, where the operational speed is close to the speed limit, adding Pattern E.1 slightly increased the speed SD by 1.4 mph. The results from both locations showed that the average speeds and speed SDs decreased by 2.7 and 0.5 mph, respectively, due to the implementation of Pattern C. Pattern D3 helped lower the speed SDs by 0.5 and 1.0 mph at the stopped and yield-controlled terminals, respectively. The trends of changes in speed SDs indicated that two to three days were needed for drivers to get familiar with these new TCDs. Speed comparisons between daytime and nighttime illustrated that Pattern C can reduce the speed SD by 5% more during the nighttime than the daytime.

While all the DRS patterns generated enough interior sound to alert drivers, WW drivers would perceive louder sound in effect by all three patterns (12 dBA by Pattern D3, 5 dBA by Patterns C and E.1). The exterior sound increasements caused by the DRS suggested that Pattern C and Pattern E.1 can produce a maximum of 10 dBA and 9 dBA additional noises, respectively. However, extra exterior noises caused by Pattern D3 were negligible. After denoising the vibration data, all the patterns were proved to generate higher frequencies of vibrations for WW drivers.

Pattern D3 can produce 0.045 *g* more vibrations for WW drivers, while Pattern C generated at least 0.011 *g* more and Pattern E.1 0.027 *g* more.

5. ASSESSMENT OF NEEDS AND PREFERENCES FOR WWD COUNTERMEASURES

Compared with passenger vehicles, trucks typically cause more severe results when driving the WW due to their large size and limited space of off-ramps for self-correction. Alarmingly, based on 504 hours of the video data collected from the SB off-ramp terminal at I-65 Exit 208 in Alabama, 25 out of 69 WW drivers were truck drivers. In other words, approximately 36% of WWD incidents involved truck drivers entering off-ramps from the crossroad at this interchange terminal, where a truck station is located less than 1,000 ft away. Figure 25 shows a semi-truck making a left turn from the crossroad and entering the off-ramp at the I-65 Exit 208.

Figure 25. A WWD Incident by a Truck at I-65 Exit 208, Alabama

Considering the frequency and severity of truck WWD incidents, it is necessary to understand the factors that contribute to these types of incidents and to identify the corresponding countermeasures. The literature review results indicated that most of the previous studies aimed to identify the contributing factors for WWD based on crash data analysis and simulation results. However, the truck drivers' needs for mitigating WWD incidents have not been fully addressed. The objective of this part is to assess the needs and preferences for WWD countermeasures at freeway ramp terminals for truck drivers. To achieve this goal, a survey-based study was conducted at a truck station near I-65 Exit 208 in Alabama. To supplement the survey in Alabama, another survey was conducted at a truck rest area near I-85 Exit 147 in Georgia where a large number of WWD incidents were recorded. An in-person interview was performed to ensure each truck driver fully understood the questionnaire and obtained more information through the communication. One hundred and fifteen completed questionnaires were collected for this study. A thorough analysis via survey was conducted to identify truck drivers' needs and suggestions for reducing

WWD incidents at off-ramp terminals. The video analysis was conducted prior to the survey to summarize the characteristics of WWD incidents by truck drivers to supplement the survey results.

5.1 Characteristics of WWD Incidents by Truck Drivers

To understand the characteristics of WWD incidents by truck drivers, video data were collected at the Exit 208 SB off-ramp terminal in Alabama. A total of 504 hours of video data was recorded by a portable traffic monitoring camera. After that, the researchers reviewed the video data manually to identify WWD incidents caused by truck drivers. When a truck WWD incident was identified, the short video clips were saved to record the related information, such as the time of the day, reaction time, turn around time, driving distance, potentially effective TCDs, conflicting with RW vehicles, property damage only (PDO) crashes, lighting conditions, weather, etc.

Table 15 summarizes the detailed information about each of the 25 WWD incidents caused by truck drivers. Three of them resulted in PDO crashes when the truck driver backed up to correct their path and ended up hitting the DNE and One-Way signs on the channelizing island implemented on the exit ramp. Considering the size of the truck and the limited width of the off-ramp, truck drivers could hardly see the roadside signs and raised channelized island, especially at nighttime. General characteristics of WWD incidents by truck drivers are summarized as below:

- Truck WWD incidents had almost the same distribution in daytime and nighttime. Among these 25 WWD incidents, 12 occurred in the daytime and 13 at nighttime. As for weather conditions, 24 out of 25 truck WWD incidents occurred in clear weather conditions, while only one case happened during a rainy day.
- According to the video data analysis, the average reaction time (the time from the truck driver going the WW to a complete stop) for the truck drivers is 5.8 seconds. All the WW truck drivers reacted to correct their ways. Forty percent of the truck drivers (10 out of 25) realized they were driving the WW immediately after crossing the stop bar on the off-ramp. Additionally, 11 out of 25 truck drivers (44%) were stopped by the first pair of WW pavement arrows on the exit ramp, where a pair of WW signs were also implemented on the roadside. The effectiveness of the signs and pavement markings to deter WWD for truck drivers has been investigated in Chapter three. Four truck drivers (16%) traveled more than 100 ft until they realized they were going the WW when they saw the second pair of WW signs located approximately 150 ft in front of them.
- Based on the analysis of WWD videos, the time spent by WW truck drivers for self-correction varied from 8 to 191 seconds, with an average of 42.3 seconds. Forty-eight percent of them encountered RW vehicles before they turned around. Since there's only one lane on the exit ramp, the lane width is not wide enough for truck drivers to make a U-turn. The most common way for self-correcting WWD is backing up to the crossroad.

Based on the information obtained from WWD incident video data, it was found that the frequency of the WWD incidents caused by truck drivers were higher than expected. The WWD incidents caused by truck drivers will more likely result in a crash due to the longer time used for self-correction. The result reveals the seriousness of the problem and demonstrates the necessity of this study.

Table 15. Summary of Truck WWD Incidents

Time	Reaction Time (s)	Turn Around Time (s)	Way to Turn Around	Travel Distance	Potentially Effective TCDs	PDO Crash?	Conflicting with RW Drivers?	Lighting	Weather
12:35 AM	4.4	15.5	Backup	20 ft - 50 ft	WW Arrow	N	N	Night	Sunny
7:55 PM	6.1	17.8	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	Y	Dusk	Sunny
9:48 PM	3.6	15.4	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	N	Night	Sunny
4:49 AM	7.2	19.9	Backup	20 ft - 50 ft	WW Arrow	N	N	Night	Sunny
5:17 PM	4.5	28.2	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	N	Daylight	Cloudy
10:29 AM	7.2	45.5	Backup	20 ft - 50 ft	WW Arrow	N	Y	Daylight	Sunny
1:39 PM	4.5	23.2	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	Y	Daylight	Sunny
6:28 AM	3.8	13.8	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	N	Dawn	Sunny
9:59 AM	5.3	22.5	Backup	20 ft - 50 ft	WW Arrow	N	N	Daylight	Sunny
4:58 AM	5.6	65.3	Backup	20 ft - 50 ft	WW Arrow	N	Y	Night	Sunny
1:39 PM	4.5	23.2	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	N	Daylight	Sunny
9:42 PM	4.8	49.9	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	N	Night	Sunny
4:46 AM	5.4	15	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	N	Night	Sunny
5:01 AM	7.4	43.4	Backup	20 ft - 50 ft	WW Arrow	N	N	Night	Sunny
5:31 AM	7.9	19.6	Backup	20 ft - 50 ft	WW Arrow	N	Y	Night	Sunny
6:01 AM	7.9	63.1	Backup	100 ft -250 ft	WW signs	N	Y	Night	Sunny
8:25 AM	10.3	82.3	Backup	100 ft -250 ft	WW signs	N	Y	Daylight	Sunny
9:54 AM	6	20.9	Backup	20 ft - 50 ft	WW Arrow	N	N	Daylight	Sunny
7:28 PM	7.3	27	Backup	20 ft - 50 ft	WW Arrow	N	N	Night	Sunny
1:28 PM	7.5	191.1	Backup	More than 250 ft	None	N	Y	Daylight	Rain
11:10 PM	3.1	21.5	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	N	Night	Sunny
8:24 AM	9.5	86.9	Backup	100 ft -250 ft	WW signs	N	Y	Daylight	Sunny
10:32 AM	2.2	7.7	Backup	Less than 20 ft	DNE Sign or Stop Bar	N	Y	Daylight	Sunny
11:44 AM	5.1	122.3	Backup	20 ft - 50 ft	WW Arrow	N	Y	Daylight	Sunny
2:03 AM	5.5	28.5	Backup	20 ft - 50 ft	WW Arrow	Y	Y	Night	Sunny

5.2 Survey Design and Implementation

To understand truck drivers' needs and preferences for WWD countermeasures, this study developed a survey to obtain details about truck drivers' basic information, experiences driving WW, potential reasons for WWD, and preferred countermeasures to deter WWD. A total of 11 questions was included in the final survey. Table 16 lists the survey questions and answer choices. Participants were, in general, allowed to select only one answer for each question for Questions 3, and 7-11. There were no answer choices for Questions 1, 2 and 4; instead, participants were asked to write the answers. As for Questions 5 and 6, participants could select more than one answer that applied. It should be noted that some answers allowed participants to provide additional information after they selected them. These kinds of choices are marked with "*" in Table 16.

The survey was conducted for two days at each of two truck stations to ensure sample size large enough to represent national truck drivers' age distribution. The first survey was conducted at the truck station located near Exit 208 on I-65 in Alabama; the second survey was conducted at another truck station, which is located near Exit 147 on I-85 in Georgia. The truck drivers were randomly selected at truck stations. Each valid survey takes around 10 to 15 minutes to ensure they fully understood the background and completed all the questions. After that, some truck drivers are willing to provide additional information based on their interests and experiences. The order of answer choice in Questions 5 and 6 were changed at the second location to reduce the bias.

Table 16. Survey Questions and Answer Choices

Question Numbers	Question Description	Answer Choice
1	What is your age and how long have you driven a truck?	N/A
2	Have you ever entered off-ramps unintentionally (as shown in the video)?	N/A
3	What is the time of day when you drove the wrong way?	Daytime
		Nighttime
		Can't remember
		I never drive the wrong way
4	How long was your training time to become a truck driver?	N/A
5	What is/are the reason(s) that caused you to drive the wrong way?	Unfamiliar road condition
		The off-ramp is too close to the on-ramp
		The off-ramp is too wide
		Bad weather conditions (heavy rain/fog/snow, etc.)

		The signs (WRONG WAY, DO NOT ENTER) are difficult to see and understand
		The faded pavement markings
		Hard to see the on-ramp
		Follow the GPS instruction without thinking
		Others*
6	What kind of countermeasure(s) you think is/are most effective to prevent WWD?	Do Not Enter sign
		WW sign
		One-Way sign
		Pavement WW arrow
		Double yellow line
		Directional rumble strip
		Stop bar at the off-ramp
7	Do you prefer traversable or non-traversable median, which is implemented between on and off-ramp?	Traversable median
		Non-traversable median
		No idea
8	Do you use a navigation app or device while you are driving? (Please provided the name if you choose yes)	Yes*
		No
9	Do you think the navigation app or device you use is accurate?	Yes, it is always accurate
		Sometimes it is accurate but sometimes not
		No, it is not accurate
10	Do you think it is a good idea to provide extra turn-around area on an off-ramp to help WW drivers go in the right direction?	Yes
		No
		No idea
11	Do you know any other locations (off-ramps) with the same problem? If yes, please provide a location.	Yes*
		No

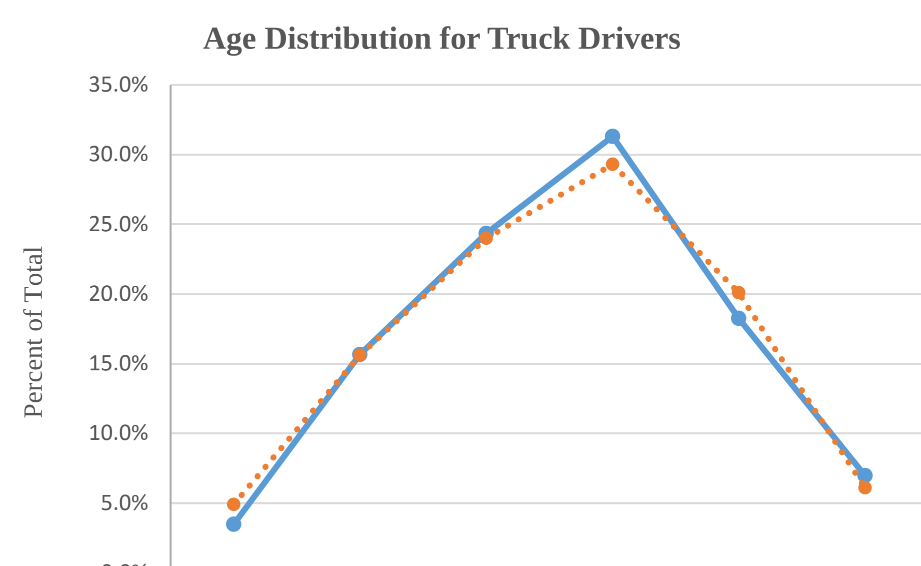
Note: *Need to provide additional information as required.

5.3 Survey Results

A total of 115 questionnaires were completed in good quality for this study. The results are summarized in the following six parts: basic drivers' information, WWD experience, reasons to cause WWD, preferred countermeasures, median and GPS consideration, and other concerns.

5.3.1 Basic Driver Information

As for the general truck driver information, the results reveal that the majority of truck drivers are male. Among the 115 truck drivers, only eight truck drivers are female, which accounts for around 7% of participants. Figure 26 illustrates the age distribution of the survey data and the truck drivers' demographic collected by the American Transportation Research Institute (ATRI) in 2013 (Short, 2014). According to the analysis conducted by ATRI, around 29% of truck drivers fell into the 45- to 54-year-old age group. Additionally, truck drivers within the 20- to 24-year-old age group have lower employment rates compared with older truck drivers who fell into the 65+ age group. The survey data also illustrated similar trends for age group distribution. A t-test was performed to check if there is a significant difference in age distribution between the survey group and the entire population. Since the p-value is less than 0.05 (p-value = 0.5), the results conclude that there is no significant difference between survey age distribution and national trucking employee's age distribution.



	20-24	25-34	35-44	45-54	55-64	65+
Survey Data Distribution	3.5%	15.7%	24.3%	31.3%	18.3%	7.0%
Trucking Employees in 2013	4.9%	15.6%	24.0%	29.3%	20.1%	6.1%

Figure 26. Age Distribution of Participants

5.3.2 WWD Experience

The survey results showed that only 16 truck drivers had driven WW in the past. However, it occupies 14% of total participants. As shown in Figure 27, among these truck drivers with WWD experiences, around 70% of them had WWD incidents during the nighttime. Due to the inadequate sight distance during the nighttime, respondents indicated the need to obtain a better view of ramp terminals. These results are consistent with those of many previous studies that have found the majority of WWD crashes occurred at nighttime.

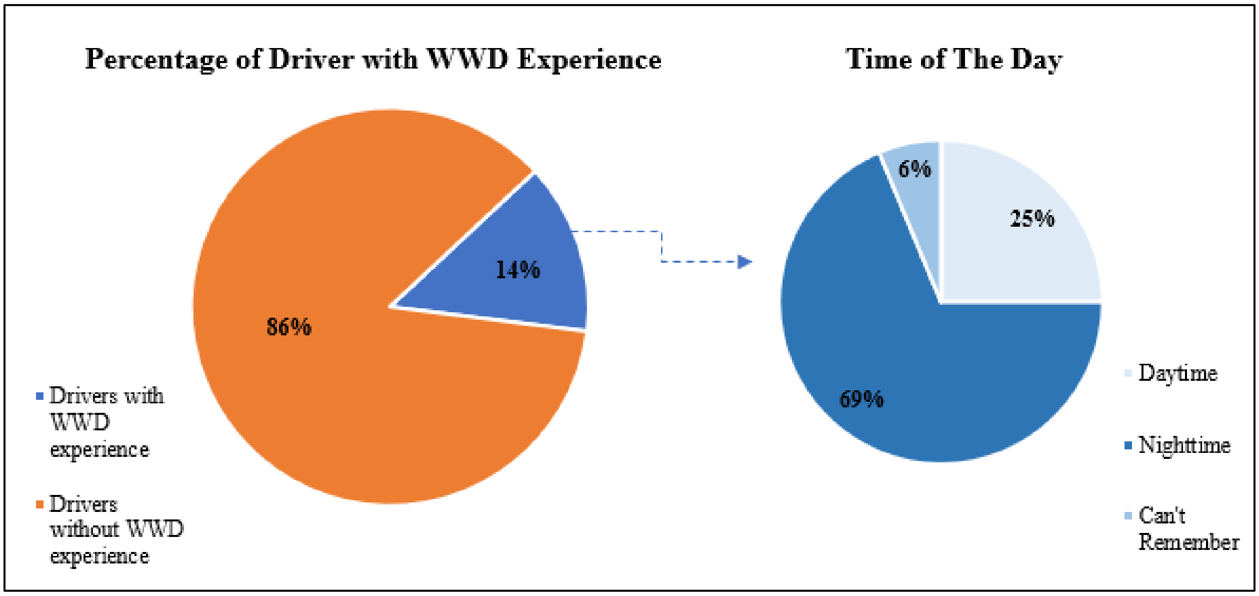


Figure 27. Basic Information for Truck Drivers with WWD Experiences

5.3.3 Contributing Factors to WWD

Table 17 summarizes the results of the potential contributing factors for WWD. In the below output, the percent of cases and percent of responses are displayed. The percent of cases is the percent of respondents saying "yes" for the potential contributing factors. Similarly, percent of responses is the percentage of each response out of the total responses from the given data set, which sums as 100%. The top-three contributing factors selected by truck drivers are "unfamiliar road condition" (35%), "the signs are difficult to see or understand" (28%), and "hard to see the on-ramp" (27%). Among all 32 additional reasons input by respondents, the most frequent answer is that truck drivers did not pay attention to the surrounding conditions. Other reasons such as fatigue and rushing can be regarded as supplemental factors that cause distractions. The results indicated that truck drivers are more likely to choose "truck drivers' issues" than road design issues.

Table 17. Potential Contributing Factors to WWD

Type	Frequency	Percent of Case	Percent of Response
a. Unfamiliar road conditions	40	35%	18%
b. Off-ramp is too close to the on-ramp	13	11%	6%
c. Off-ramp is too wide	2	2%	1%
d. Bad weather condition	22	19%	10%
e. Signs are difficult to see or understand	32	28%	15%
f. Faded pavement markings	22	19%	10%
g. Hard to see the on-ramp	31	27%	14%

h. Follow the GPS instruction without thinking	25	22%	11%
i. Others	32	28%	15%
Summary	219	191%	100%

Survey results suggested the following three recommendations based on truck drivers' needs: (1) improve interchange ramp terminal designs; (2) improve sign and pavement marking visibility; (3) improve the driver's view of the on-ramp.

To improve the design of the ramp terminals and the driver's view of the ramp, it is better to provide truck drivers with a better sight distance. Various countermeasures have been developed to improve roadway design and WW-related TCDs. Figure 28 shows some examples of the current practices that can fulfill truck drivers' needs.

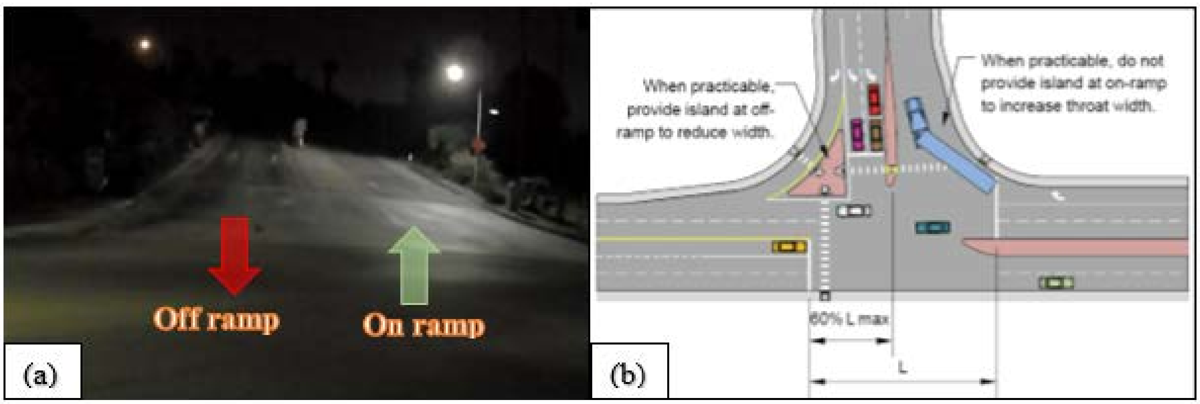


Figure 28. Examples of Current Practices: (a) Brighter on-ramp at CA; (b) Intersection Balance (WSDOT, 2013)

Figure 28.a shows an example of street lighting installed on an on-ramp side in California (CA), which can improve a driver's view of the on-ramp. Moreover, the guideline of the intersection balance provided by Washington DOT (WSDOT) can also improve a driver's view of on-ramps (i.e., parclo interchanges) (WSDOT 2013). Figure 28.b illustrates the guideline that requests that the centerline of the intersection should be located no more than 60% of the entire intersection width from the stop bar of a crossroad.

5.3.4 Preferred Countermeasures

Table 18 summarizes the preferred countermeasure chosen by respondents to mitigate WWD. The results indicated that truck drivers preferred the WW sign (59%), DNE sign (57%), and One-Way sign (31%). The results show that truck drivers might pay more attention to WW signs rather than pavement markings. During the interview, around 85% of respondents said that they would pay more attention to the signs. It was found that the ranking of the four pavement marking countermeasures is much lower than the three WW signs. The WW arrows and DRS received a relatively higher percentage of the cases with 24% and 13%, respectively. The stop bar and double yellow line received 5% and 10% of cases. Some truck drivers explained that it is difficult to see pavement markings during nighttime or in poor weather conditions (e.g., rain, snow). Moreover, they saw faded pavement markings frequently in many places.

Table 18. Truck Drivers' Preferences on the Countermeasures for WWD

Preferred Countermeasures	Frequency	Percent of Case	Percent of Response
Stop Bar	6	5%	3%
DRS	15	13%	7%
WW Pavement Arrow	28	24%	12%
Double Yellow Line	11	10%	5%
One-Way Sign	36	31%	15%
WW Sign	68	59%	29%
DNE	66	57%	29%
Summary	230	199%	100%

Additionally, several recommendations to improve signs' visibility are provided based on respondents' suggestions. First, larger-sized retroflected signs can be applied on the roadside, which will help truck drivers to find the signs and figure out which one is the right way. Next, it is better to implement a WW sign on the roadside rather than on the median of two-way ramps to reduce confusion and make WW signs more effective.

5.3.5 Median Types and GPS Accuracy

Table 19 shows the median preference results from the survey. The results show that 71% of respondents preferred to implement non-traversable medians than traversable medians between on- and off-ramps. Because truck drivers typically have a higher and broader front view than drivers in passenger vehicles, it is believed that a non-traversable median can better help truck drivers to identify on-ramps. However, the height of a non-traversable median might affect drivers' view of an on-ramp, especially for passenger car drivers. Concrete barriers are generally not recommended to be extended to the stop bar of an intersection based on several past studies (Pour-Rouholamin et al., 2015b) because they will block a driver's view of the on-ramp.

Table 19. Median Types of Preference

Type of Median	Percentage of Total
Traversable Median	26%
Non-traversable Median	71%
No Idea	3%

Table 20. Basic Information for the Navigation Device/App Usage

Use GPS or Not	Frequency	Percentage
Yes	86	75%
No	29	25%

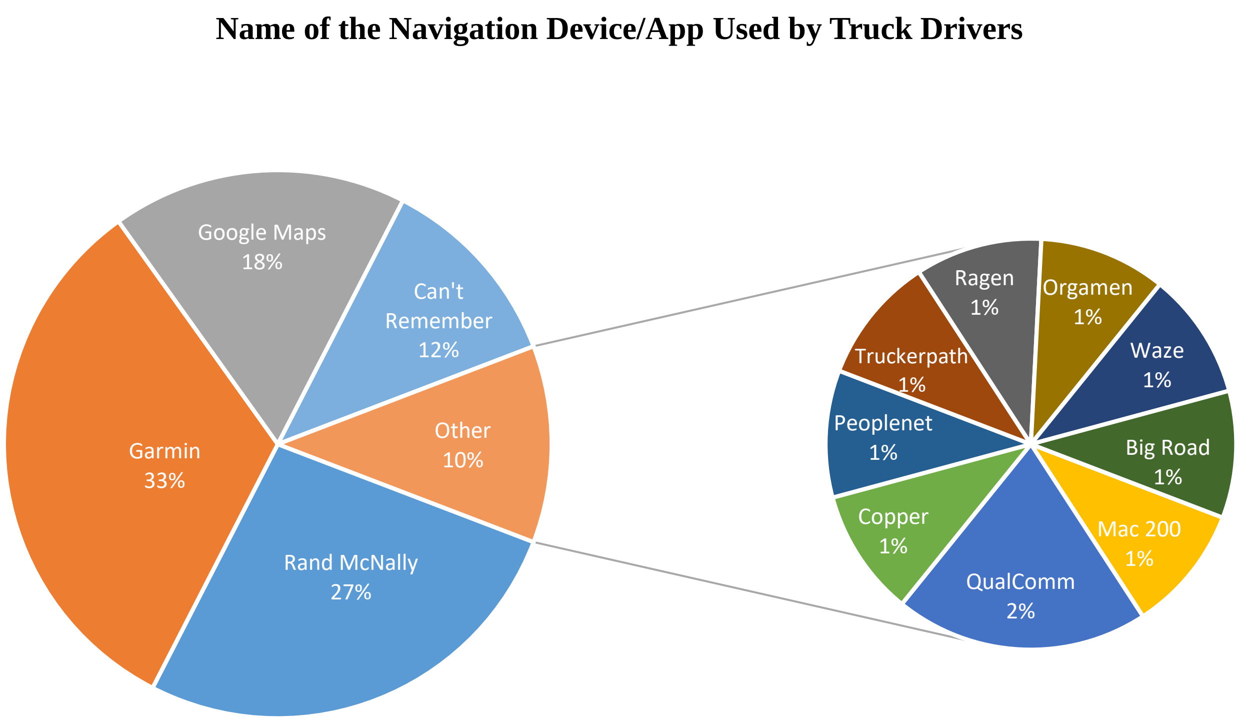


Figure 29. Percent of Different Navigation Device/App Used by Truck Drivers

To better understand the usage of the navigation app/devices, a question was asked about how accurate are navigation devices/APP. As shown in Table 20, the survey results indicate that around 75% of the respondents like to use a navigation app/device. The survey also asked truck drivers to provide the types of navigation device/app. Based on Figure 29, it can be summarized that truck drivers frequently use three main types of device/apps: Garmin (33%), Rand McNally (27%), and Google Maps (18%). Other types of navigation devices/apps accounted for less than 10%.

Table 21. Truck Drivers' Inputs about the Accuracy of Navigation Device/App

Level of Accuracy	Frequency	Percentage of Total
Always Accurate	16	14%
Sometimes Accurate	91	79%
Not Accurate at All	8	7%

Table 21 summarizes the respondents' inputs about the accuracy of the navigation device/app. It can be found that, although there is a higher percentage of respondents using navigation device/apps, 86% of them believe that the navigation devices/apps are not always accurate. The GPS devices sometimes can increase the risk of WWD due to the difficulty in providing correct guidance, especially for the location where the distance between the access point and exit ramp is less than 300 feet (Jalayer et al., 2016). Respondents also mentioned that looking at GPS maps sometimes distracts them by keeping their eyes away from the roadway ahead. Several recommendations were provided based on the truck drivers' needs via GPS devices. First, GPS maps need to be updated more frequently to ensure they are the latest version. More importantly, the implementation of the head-up display (HUD) will reduce distraction and help truck drivers make better decisions by keeping their eyes on the roadway.

5.3.6 Other Concerns

This part contains information like drivers' opinions about the new design to deter WWD. Table 22 shows the results of participants' preference for extra turn-around areas on off-ramps. The results indicated that 63% of participants preferred to add an extra turn-around area on off-ramps. This is because truck drivers need a larger space to make a U-turn if they drive onto the off-ramp. However, more than 25% of truck driver expressed their concerns about it, including cost and a higher number of conflicts.

Table 22. Truck Drivers' Opinions on Extra Turn-Around Area on Off-Ramps

Extra Turn Around Area at the off-ramp	Yes	No	No idea	Total
Frequency	73	32	10	115
Percentage	63%	28%	9%	100%

As an alternative to the turn-around area on an off-ramp, some state DOTs provide an opening before the fork areas for two-way ramp segments, as shown in Figure 30. This gives drivers the chance to correct their way in the last minute without making a U-turn on the off-ramp. Illinois DOT designs an accident investigation site on the off-ramp (Figure 31) which can be used as a turn-around area for WW drivers.

Figure 30. Example of Median Opening Before the Fork Area (I-30 Exit 63, AR) (Source: Google Maps)

Figure 31. Example of Accident Investigation Site in Chicago (I-55 Exit 288 SB) (Source: Google Maps)

5.4 Summary

The objective of this study is to assess the needs and preferences for WWD countermeasures at freeway ramp terminals for truck drivers. A survey questionnaire, which included 11 questions on a driver's basic information, WWD experiences, potential contributing factors, preferred traditional and advanced countermeasures, etc., was designed for this study. The survey was conducted at two truck stations, one in Alabama and one Georgia. Both stations are located close to off-ramp terminals, where recurring WWD incidents by trucks were observed. A total of 115 survey questionnaires were completed through in-person interviews with truck drivers. The results indicated that unfamiliar road conditions, hard-to-see on-ramps, and difficulty to see or understand signs were the three top factors that contributed to WWD by truck drivers. As for WWD countermeasures, the results show that truck drivers prefer WW signs over pavement markings because pavement markings are frequently faded at some locations and hard to see during rain and snow conditions. Other suggestions by truck drivers include better training, larger and highly retroreflective signs, clear view of on-ramps, and usage of non-traversable medians between on- and off-ramps.

6. ACCESS MANAGEMENT STRATEGIES FOR DETERRING WWD ON MULTILANE DIVIDED HIGHWAYS

According to the Federal Highway Adminstration (FHWA), access management (AM) is the proactive management of vehicular access points to land parcels adjacent to all manner of roadways. Good AM promotes safe and efficient use of the transportation network. Therefore, in this chapter, the researchers focused on finding the common types of WW entry points on Alabama divided highways and developed engineering countermeasures from access control and site design perspectives. The field data were collected at ten locations where there were WWD crashes or incidents that occurred over the five years from 2009 to 2013. Video cameras were used to monitor the WWD activities for 48 hours from Friday to Sunday. The WWD activities were analyzed through watching the video data by researchers. Any abnormal vehicle movements were also recorded and analyzed. WWD incidents were observed at four of the ten locations.

To understand the common types of WWD entry points and develop corresponding countermeasures, four case studies were conducted for application of different AM techniques to mitigate WWD issues on divided highways, including (1) provide closer exclusive U-turn median openings for indirect left turns; (2) improve poor front access control, for example, to install a channelized island for right-in/right-out driveways; (3) provide backage road connections for close mixed land use; and (4) improve sight distance for minor-road traffic at unsignalized intersections with large grade difference or wide median widths.

6.1 Four Common Types of WWD Entry Points

6.1.1 Case One: Driveways with a Close Median Opening

Study Location Description

The first study location is a driveway from a Chevron gas station, which is close to an upstream unsignalized intersection of the U.S. 280 and N. College St. in Auburn, AL. Figure 32 shows a Google aerial photo of study location 1. The red arrow shows the direction of WW movements and the blue arrow shows the direction of right-way movements (same for the other three cases). The field data were collected by video cameras from 4:30 p.m. on October 27, 2016 (Friday) to 4:30 p.m. on October 29, 2016 (Sunday).

U.S. 280 is a four-lane divided highway with a wide median width (about 50 ft) at the study location. The terrain is level and drivers have a good sight distance. The speed limit on this segment of the U.S. 280 is high (65 mph). There was no WWD crash history at this site over the past five years. However, a large number of WWD left turn movements were observed from this driveway to make a shortcut to the upstream median opening. There is another median opening for making a U-turn movement located more than 2,000 feet downstream, as shown in Figure 33, the blue arrow shows the potential alternative right turn followed by U-turn movements for the left turns from this driveway. The same arrow markings can be found in the similar figures of the following case studies. The weaving distance (more than 2000 ft) is very long for the downstream median opening to be seen by the driver from the gas station.

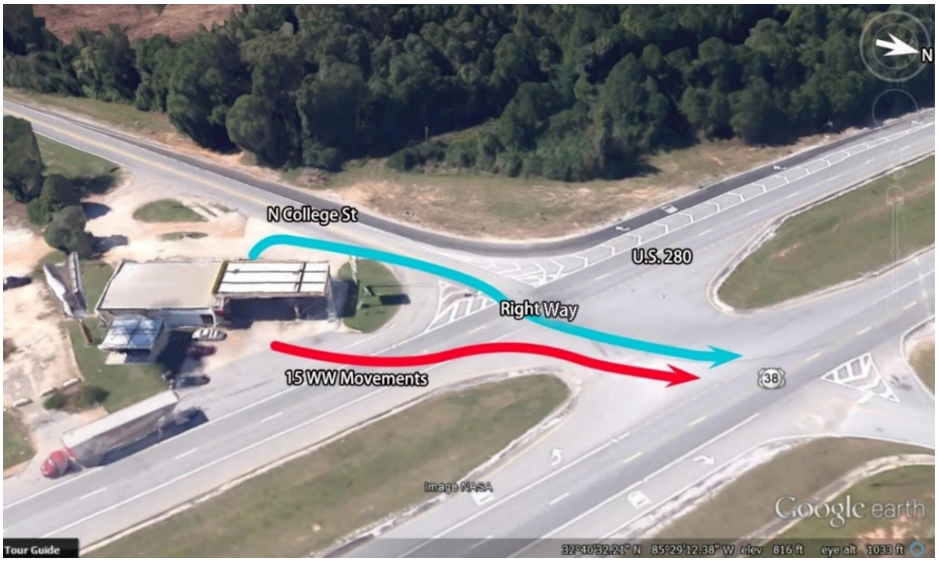


Figure 32. Location of Median Opening at Location 1 (Source: Google Earth)

Figure 33. Location of Downstream U-turn Median Opening at Location 1 (Source: Google Earth)

Wrong-Way Data Analysis

By watching the 48-hours video data of this location, a total of 15 WW left turn movements were observed. Nine of them happened in daytime, and six of them occurred during nighttime or early morning. Based on an average of 7.5 WW movements per day, approximately 2,738 WW movements can be predicted to be made at this location for one year. Figure 34 shows the screenshots of an example of WW movement track by time series from the video recording. The red circle was used to point out the WWD vehicle. The same red circles can be found in the similar screenshots of the following case studies.

It was found that all the WW drivers tried to make a WW left turn as a shortcut to the NB of the U.S. 280 because of the lack of a nearby downstream U-turn median opening. They intentionally made the WW left turns and drove WW for a shortcut to an upstream median opening. A field review of site design features and existing TCDs was conducted. Some possible factors for the deliberate WW movements were identified, including: (1) lack of channelized island and TCDs to make the driveway as right-in and right-out only; (2) the distance for downstream U-turns at this location is too far; and (3) traffic volume on side street (N College St.) is very high at peak hours and often block the gas station's other exit to the side street.

Figure 34. Screenshots of a WW Movement Track by Time Series at Location

Recommended Countermeasures

Figure 35 shows the potential improvements at this location to deter the intentional WW left turn movements at driveways with a close upstream median opening, including:

- Install Stop sign, Right Turn Only sign (R3-5R), and Keep Right sign (R4-7) or No Left Turn (R3-2) sign at the highway entrance of the gas station, and add a One-Way sign (R6-1) on highway median facing to customers leaving the gas station.
- Add WW pavement arrows on the divided highways.
- Add a right-in/right-out channelization.
- Add a closer exclusive U-turn median opening for U-turns, and add a sign to show XX ft to the next U-Turn median openings.

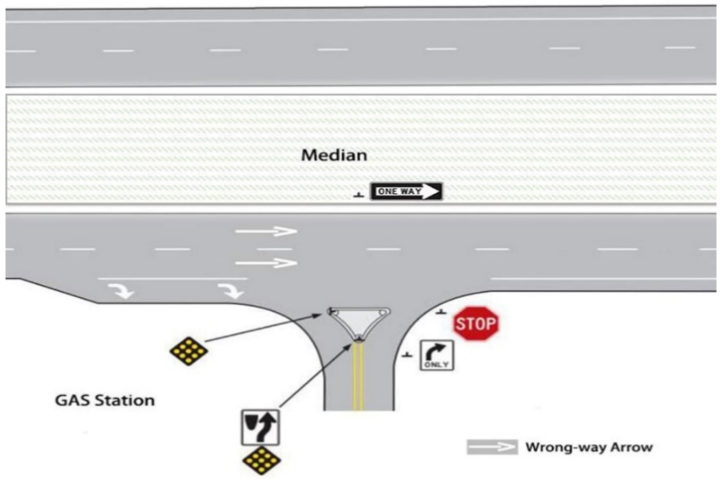


Figure 35. Improvements for Deterring WWD at Driveways with No Median Openings

6.1.2 Case Two: Poor Front Access Control

Study Location Description

The second WW entry point of this study is a parking lot in front of a lounge located at 2842 S Eufaula Ave, Eufaula, AL, which was recorded as an entry point of a WWD crash that occurred in the year of 2011. Figure 36 shows a Google aerial photo of study location 2. Field data were collected by video cameras from 5:00 p.m. February 17, 2017 (Friday) to 5:00 p.m. February 19, 2017 (Sunday).

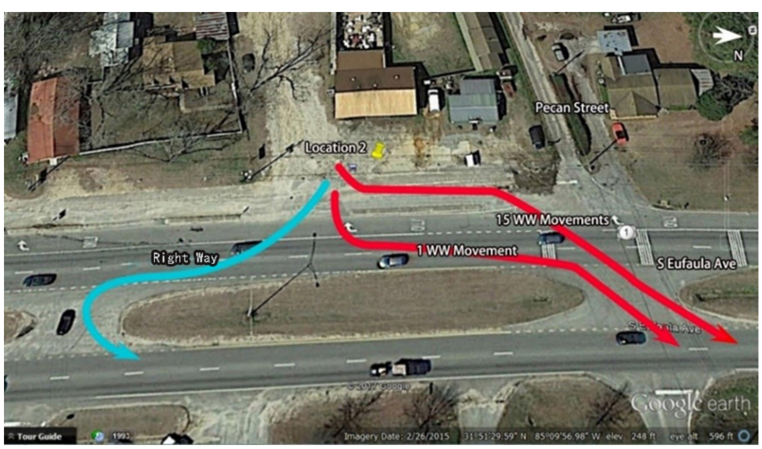


Figure 36. An Aerial Photo of the Study Location 2 (Source: Google Earth)

The business property is located on the SB side of S Eufaula Ave, which is a four-lane divided highway with a 30-ft wide median. There is an unsignalized intersection at S Eufaula Ave and Pecan St upstream of the access point to the business and there are no access control or traffic signs for the driveways connecting the property and highway. The weaving distance between the property parking lot exit and the next downstream median opening is only 100 ft. The terrain is level and drivers have enough sight distance. The speed limit in this segment of S Eufaula Ave is 65 mph. Notably, there is a 10 ft-wide uncontrolled one-way frontage road separated by a raised curb in front of the lounge and a nearby grocery store. The authors observed a large number of drivers who drove along the frontage road as a shortcut to enter the S Eufaula Ave and Pecan Street intersection.

Wrong-Way Data Analysis

In the 48-hour video data from this location, a total of sixteen WW left-turn movements were observed. An average of eight WW movements made here per day. Of the sixteen observed WWD incidents, fifteen drove along the frontage road as a shortcut to turn left to S Eufaula Ave, and more than half of them (eight) performed this WW movement at night (with the headlights on). One WW driver made a left turn to travel north in the SB lanes of S Eufaula Ave before crossing the upstream median opening at around 12:30 a.m. after leaving the parking lot. Figure 37 shows the screenshots from a video recording of an example of a WW movement track. The red circle shows the WWD vehicle.

Figure 37. Screenshots of a WW Movement Track by Time Series at Location 2

It was found that most drivers made the WW movements intentionally as a shortcut to enter the NB S Eufaula Ave, even though the distance to the downstream median opening is only 100 ft. The original function of the frontage road was to connect customers between the lounge and the store. However, because of low customer volumes of both the lounge and the store, its function has diminished from that of the original design objective. As such, the poor front access control at this location provided the opportunities for misguided drivers to drive in the wrong direction.

Recommended Countermeasures

Based on our analysis of the video data, the following suggestions are made for reducing WW movements at the location with poor front access control:

- Provide sufficient throat length when frontage crosses the intersections. According to the ALDOT Access Management Manual, frontage roadways that run parallel to ALDOT roadways are recommended to provide a 200 ft throat length (or greater) whenever possible (ALDOT 2014).
- Install a Right Turn Only sign (R3-5R) and a Keep Right sign (R4-7) (see Figure 33) at the driveway with no median opening.
- Add an additional right-in/right-out channelization (see Figure 35).

6.1.3 Case Three: Lack of a Backage Road Connection

Study Location Description

The location of the third case study is an access point to a Jet Pep gas station located at 3066 U.S. 280, Alexander City, AL. Figure 38 shows a Google aerial photo of the study location. The location was recorded as an entry point of a WWD crash that occurred in 2010. The field data were collected by video cameras from 5:00 p.m. on February 10, 2017 (Friday) to 5:00 p.m. on February 12, 2017 (Sunday).

Figure 38. Image of Study Location 3 (Source: Google Earth)

The SB U.S. 280 has two separate left-turn lanes, two through lanes, and one right-turn lane at this unsignalized intersection. The speed limit on U.S. 280 is 45 mph. There is a signalized intersection 320 ft downstream of the study driveway, and another median opening located 290 ft upstream from the driveway. The width of the median is around 30 ft, and there is no conspicuous change of grade in this location. Generally, the sight distance at this location is adequate. There is a liquor store close to the gas station, connected by a continuous right-turn lane, and there is a residential area near these two business buildings.

Wrong-Way Data Analysis

On watching the 48 hours of video data of this location, a total of fifteen intentional WW movements were observed. Six WWD incidents happened at night (with headlights on) and nine happened in the daytime. Among the fifteen WW drivers, thirteen of them drove WW along the frontage road to make the shortcut to the residential area, and the remaining two made a left turn to enter the median opening. Meanwhile, there is one vehicle trying to make a left turn to go to NB in the SB lane, but due to the continuous coming traffic, he/she gave up and made a U-turn back. Based on an average of 7.5 WW movements per day, approximately 2,738 WW movements could be made at this location for one year. Figure 39 shows the screenshots of an example of WW movement track by time series from the video recording.

There are two reasons for making the intentional WW movements at this location. One is that during peak hours the queue of the downstream intersection is too long that indirect left turn drivers cannot merge into the left-side lane to make a U-turn downstream; another is a lack of connection road between this business area and the nearby residential areas.

Figure 39. Screenshots of a WW Movement Track by Time Series at Location 3

Recommended Countermeasures

The following are some suggestions to reduce WW movements at the intersections connecting two different land use areas based on the data analysis.

- Use a backage road (also known as reverse frontage road) connecting the business area and residential areas to improve the connectivity between two close land use areas. According to the report of Access Management in The Vicinity of Intersections (FHWA-SA-10-002, October 2000), frontage/backage roads that parallel the major roadway may be employed as a means to provide access to each of the adjacent properties. This solution can help to eliminate several access points to the major roadway as access to each development is achieved via the frontage/backage road rather than to the major roadway (FHWA 2000).

- Install a Right Turn Only sign (R3-5R) and Keep Right sign (R4-7) (see Figure 35).
- Add an additional right-in/right-out channelization (see Figure 35).

6.1.4 Case Four: Limited Sight Distance

Study Location Description

The fourth study location is a driveway for a Shell gas station, which is close to an upstream unsignalized intersection of the U.S.280 and Bloise Zeigler Boulevard in Sylacauga, AL. Figure 39 shows a Google aerial photo of the study location. The driveway to the gas station connects the SB of U.S.280, which has one separate left turn lane, two through lanes, and one separate right turn lane. The raised curb median is narrow (around 6 ft). The speed limit on U.S.280 is high (65 mph). There is another median opening for making a right-turn followed by a U-turn movement located more than 2,000 feet downstream. Notably, the grade increases 7% from the gas station parking lot onto U.S. 280, which may contribute to a short sight distance problem.

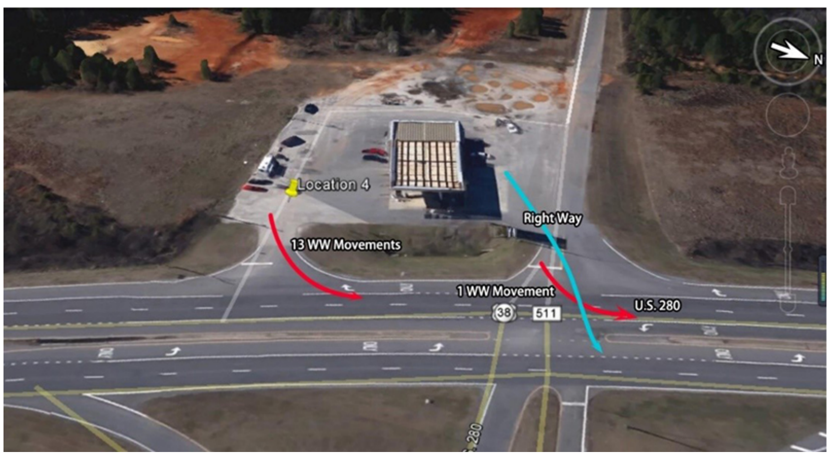


Figure 40. Image of Study Location 4 (Source: Google Earth)

As a result of a large upgrade, drivers exiting the gas stations may not be able to see median closure for this drivewy. It was observed that many drivers backed to the gas station when they found no median openings to make a left turn to US 280. These drivers either made a WW left turns or turned back to use the exit to the side street. The field data were collected by video cameras from 6:00 p.m. on April 7, 2017 (Friday) to 6:00 p.m. on April 9, 2017 (Sunday).

Wrong Way Data Analysis

On watching the 48-hours video data of this location, thirteen drivers were seen to drive to the exit (on U.S. 280 side), and then backed up to use the exit to the side street. Seven of these movements happened in the dark light condition. The steep grade limited drivers' sight distance so that they did not know that it was a right turn only exit until they climbed the hill. There was one truck coming from the minor road of the intersection during the night that made a WW left turn onto U.S. 280, and immediately realized that it was the WW and then backed up to turn around to the right direction.

It was found that limited sight distance because of the grade change contributed to all fourteen WWD movements. Figure 40 shows the screenshots of an example of the backup movement track by time series from the video recording.

Figure 41. Screenshots of a WW Movement Track by Time Series at Location 4

Recommended Countermeasures

The following are some suggestions to reduce WW movements at the highway access where the sight distance is poor, and the grade change is significant.

- Install a Stop sign and Stop line to improve the road visibility.
- Close the driveways or median openings that provide insufficient sight distance for turning vehicle drivers.
- Add roadside lighting to improve the highway visibility.
- Install a Stop sign, Right Turn Only sign (R3-5R), No Left Turn sign (R3-2), and One-Way sign (R6-1) (see Figure 35).
- Add an additional right-in/right-out channelization (see Figure 35).

6.2 Summary

Based on the field studies, researchers found that drivers tend to drive in the wrong direction due to the driveways with a close median opening, poor front access control, lack of the backage road connection, and limited sight distance due to a large grade difference. The study also found that there is a high frequency of intentional WWD at some access points connecting gas stations, businesses, and residential areas on the divided highway.

Through the analysis of 48-hour video data and the access control features of each case, the following are summarized engineering AM countermeasures. They can be applied to deter WWD on divided highways or corresponding conditions.

- Provide downstream U-turn median openings at a reasonable distance for indirect left turns from driveways.
- Add a sign to show XX feet to the next U-Turn median openings.
- Use channelized islands for right-in/ right-out driveways.
- Use TCDs such as WW pavement arrows, Right Turn Only sign (R3-5R), Keep Right sign (R4-7), No Left Turn sign (R3-2), and One-Way sign (R6-1) at driveways with no median openings.
- Improve the access control to one-way frontage road.
- Provide a backage road to connect commercial areas and residential areas.
- Close the driveways with poor sight distance.

7. CONCLUSIONS

This report presents the results of low-cost countermeasures and AM strategies for deterring WWD on freeway off-ramps and multilane divided highways in Alabama. To better understand driver's needs and preferences for WWD-related countermeasures, an assessment was conducted via in-person surveys for truck drivers. The following sections summarize the findings accordingly.

Signs, Pavement Markings, and Geometric Features

One objective of this research was to evaluate the effectiveness of signs, pavement markings and geometric features through case studies on SB off-ramps at Exits 208 and 284 on I-65 in Alabama. The study revealed that DNE, WW signs, WW arrows, pavement markings, and channelizing island, if used properly, can effectively reduce WWD incidents and WWD distance on off-ramps, therefore reducing the risk and severity of WWD crashes.

The results of the case study at I-65 Exit 284 suggested that the new pavement markings (double yellow line, left-turn skip strips, yield line for right turn lane, and stop bar) resulted in a 62% reduction in the total number of WWD incidents. At night, the number of WWD incidents were reduced by 73%. However, the nighttime WWD incidents were found to increase considerably due to heavy rain, which indicated that the pavement markings could be less effective with wet road surface conditions. Further analysis showed that the drivers' compliance with the new solid double yellow line on crossroads during the night is significantly higher than daytime. More than 70% of the drivers crossed the new solid double yellow line on crossroads to turn left onto the on-ramp during the daytime. Comparing with 81% of drivers complied with the new solid double yellow line during the nighttime, it implies that the double yellow line during the nighttime could be more effective. But the driver's incompliance at this location could result in fading double yellow line faster than usual. This study concluded that pavement markings have a significant impact on WWD incidents and recommended that agencies consider frequent maintenance to keep the double yellow line and left-turn skip strips highly visible.

The results of the case study at I-65 Exit 208 showed that the frequency of WWD incidents increased by 64% after the implementation of a channelizing island. After the signs were implemented on the channelizing island and pavement markings were improved, the frequency of WWD incidents was decreased compared with the before period.

The analysis of WWD distance at the two study sites suggested that a large percentage (70-80%) of drivers stopped and made self-corrections before the first pair of WW signs. However, the second pair of WW signs should still be considered since there were approximately 20-30% WWD vehicles drove past the first pair of WW signs. Similar analysis for I-65 Exit 208 revealed that approximately 86% of the WW drivers turned around right before the WW pavement arrow, which implies that the pavement arrow is very effective in helping the WW drivers to turn around after they have already entered the WW. Only 2% of WW drivers drove for more than 200 ft and passed all the WW signs and WW arrows on the off-ramp.

The study also found that WWD incidents increase on rainy days on wet pavement, which implies further needs for research on ways to increase the visibility of pavement markings during low visibility conditions. According to the findings, this study offers the following recommendations regarding preventive and reactive measures for WWD:

Preventive measures (avoiding drivers driving on WW):

- It is very important to maintain highly visible pavement markings to reduce the possibility of WWD incidents, especially at locations with no street lighting.
- The pavement markings could become less effective with wet road surface conditions, the RRPMs should be considered as a supplement at high-risk locations.
- The drivers may fail to comply with the double yellow line and left-turn skid strips pavement marking at some locations with small turning radius due to the large turning speed. These locations could result in fading the pavement marking faster than usual.
- The channelizing island implemented without proper pavement markings and signs might cause more confusion and lead to more WWD incidents. The implementation of the stop bars and additional signs on the channelizing island are required to reduce driver confusion.
- Most of WWD incidents are caused by drivers from crossroad making left turn onto off-ramp right-turn lane. Raised curb median or Qwick Kurb (Figure 42) are recommended at these two locations to prohibit WW left-turns onto off-ramp right turn lane.

Reactive measures (stopping drivers driving on WW):

- The WW arrows and signs should be installed closer to ramp terminals to reduce the WWD distance. This study results support the ALDOT new design guideline that requests WW arrows should be installed less than 100 ft from ramp terminals.
- The supplemental WW signs or pavement markings (second pair of WW sign, WW pavement arrows) on the off-ramp are very important.
- Advanced countermeasures should be considered for about 2% of WW drivers who could pass all the traditional WW countermeasures.

Directional Rumble Strips

Three DRS patterns were developed and implemented for deterring WWD on freeway off-ramps in this study. Speed and video data were collected using cameras and magnetic sensors. Field driving tests were conducted to collect sound and vibration data at various speed categories for both RW and WW drivers. Time-series were applied to analyze sound, while spectrum analysis was used in analyzing vibrations. For these two off-ramps, Pattern D3, which was shaped like an arrow to indicate the right direction, was installed at the off-ramp terminal near the stop bar/yield lines. Pattern C was implemented at the segment between the terminal and the ramp curve. WW drivers were alerted by the increasing sound and vibrations from three strip groups so that they could pay attention to the standard WW-related signs and pavement markings. Pattern E.1 was installed on the tangent part before the ramp curve, which can alert a WW driver before entering the freeway mainline and reduce aggressive driving speeds for vehicles exiting the freeway before entering the curve segment.

Before and after studies were conducted to evaluate the effectiveness of these patterns based on WWD incidents, RW traffic speeds, and drivers' behavior changes. Both numbers of WWD incidents and WWD distances can be significantly reduced by the DRS patterns. Pattern D3 is considered the most effective, as it can prevent vehicles from entering the off-ramps from crossroads. After implementing Pattern D3, WWD frequencies and distances were reduced to near zero. After deploying Pattern C, WWD frequencies and average WWD traveling distances were reduced by almost half. Only one WW vehicle was stopped on the ramp curve by Pattern E.1 because these kind of critical events are rare (e.g., WW vehicle drove all the way to the freeway). Further evaluation is needed to test its effectiveness in countering WWD incidents. No WWD vehicles traveled farther than the latest implemented DRS pattern in this study.

The before and after speed analysis suggested that Pattern E.1 can reduce average speed by 2.3 to 6.5 mph. For the location at Exit 208, when the operational average speed was about 10 mph over the speed limit, Pattern E.1 could also reduce speed SD by 2.5 mph. The results from both locations showed that the Pattern C can reduce average speeds and speed SDs by 2.7 and 0.5 mph, respectively. Pattern D3 helped lower the speed SDs by 0.5 and 1.0 mph at the stopped and yield-controlled terminals, respectively. The trends of changes in speed SDs indicated that two to three days were needed for drivers to become familiar with these new TCDs. Speed comparisons between daytime and nighttime illustrated that Pattern C could reduce the speed SD 5% more during the nighttime than the daytime.

While all the DRS patterns generated enough interior sound to alert drivers, WW drivers could perceive louder sound from all three patterns (12 dBA by Pattern D3, 5 dBA by Patterns C and E.1). Vibration data analysis results showed that all of the patterns can generate higher frequencies of vibrations for WW drivers. Pattern D3 produced 0.045 *g* more vibrations for WW drivers, while Pattern C generated at least 0.011 g more and Pattern E.1 0.027 *g* more.

In addition to the above findings, Pattern D3 showed that it can provide additional guidance for RW left-turn drivers. Confused left-turns at the channelized island were reduced by nearly 50% after installing Pattern D3. Moreover, the center gaps at Patterns C and E.1 provided convenience to motorcyclists. ALDOT recently implemented DRS on off-ramps and Qwick Kurb on crossroads to prohibit potential WW drivers from entering the off-ramps at I-85 Exits 58 and 60 (Figure 42). The speed data were collected and analyzed at these two locations. The results of before and after speed comparisions are contained in Appendix A.

Figure 42. Qwick Kurb Installed on the Croassroad near an Off-Ramp Terminal

Assessment of Needs and Preferences for WWD Countermeasures

A large number of semi-trucks that traveled WW onto off-ramps were observed in the field. To identify the needs and preferences for WWD countermeasures at freeway off-ramp terminals for truck drivers, the WWD incident data by truck drivers were first analyzed to summarize the characteristics of those incidents. Second, a survey-based study was conducted to collect data from 115 truck drivers at two truck stations near freeways. Based on the video analysis results, it is found that truck WW drivers usually use 42.3 seconds to correct their ways. More than 80% of truck WWD incidents were stopped before the first pair of WW pavement arrows and WW signs. The survey results indicated that unfamiliar road conditions, low-visible on-ramps, and low-visible or poorly-understood signs were believed to be the top-three factors that contributed to WWD by truck drivers. As for WWD countermeasures, the results show that truck drivers would pay more attention to signs than to pavement markings. Following are recommendations based on survey results:

<u>Truck Driver Training</u>

- The WWD-related knowledge should be added in the training material to help truck drivers fully understand the potential hazards of WWD and the ways to avoid driving the WW.

<u>Geometric Design Issues</u>

- Provide better sight distance for on-ramps.
- Implement non-traversable median on crossroad and between on and off ramp.

<u>Countermeasures of TCDs</u>

- Implement larger and high reflective WW-related signs.
- Keep WW-related pavement markings in good condition.
- Do not place "WRONG WAY" signs between on- and off-ramps.
- For those low-visible on-ramps, a Directional Assembly (route name with an arrow plaque) that can guide the truck driver to the right direction is recommended.

Access Management Countermeasures

To investigate why people drive in the wrong direction on the multilane divided highways in Alabama, four case studies of WWD incidents on Alabama divided highways were explored, which include WWD incidents resulting from (1) driveways with a close median opening, (2) poor front access control, (3) lack of a backage road connection, and (4) limited sight distance.

According to the case study results, all four studied locations had more than 10 WWD incidents over a 48-hour period. Most of these incidents are intentional WWD. It also was found that the frequency of WWD incidents is higher in business areas and close mixed land use areas than in other areas. The findings from this study are consistent with previous studies (Vaswani 1977; Scifres 1974) on divided highways that also found that gas stations, business areas/residential areas have relatively higher numbers of WWD incidents. They also found that many WW drivers are considered to be intentional violators (Scifres 1974).

The following are recommended engineering countermeasures:

- Provide downstream U-turn median openings at a reasonable distance for prohibited left turns from driveways.
- Use channelized islands for right-in/right-out driveways.
- Use TCDs such as WW pavement arrows, Right Turn Only sign (R3-5R), Keep Right sign (R4-7), No Left Turn sign (R3-2), and One-Way sign (R6-1) at driveways with no median openings.
- Improve the access control to one-way frontage road.
- Provide a backage road to connect commercial areas and residential areas.

- Close the driveways with poor sight distance.

To conclude, the evaluated countermeasures and strategies have been approved for effectively deterring WWD in Alabama. Transportation agencies can utilize these findings to implement these low-cost countermeasures to combat WWD at freeway off-ramps and multilane divided highways. Future studies are needed to collect more WWD incident data at more sites to assess their effectiveness in Alabama and other states. Some newly developed countermeasures, such as LaneAlert 2X pavement marking and LED WW signs, should be evaluated for deployment in Alabama.

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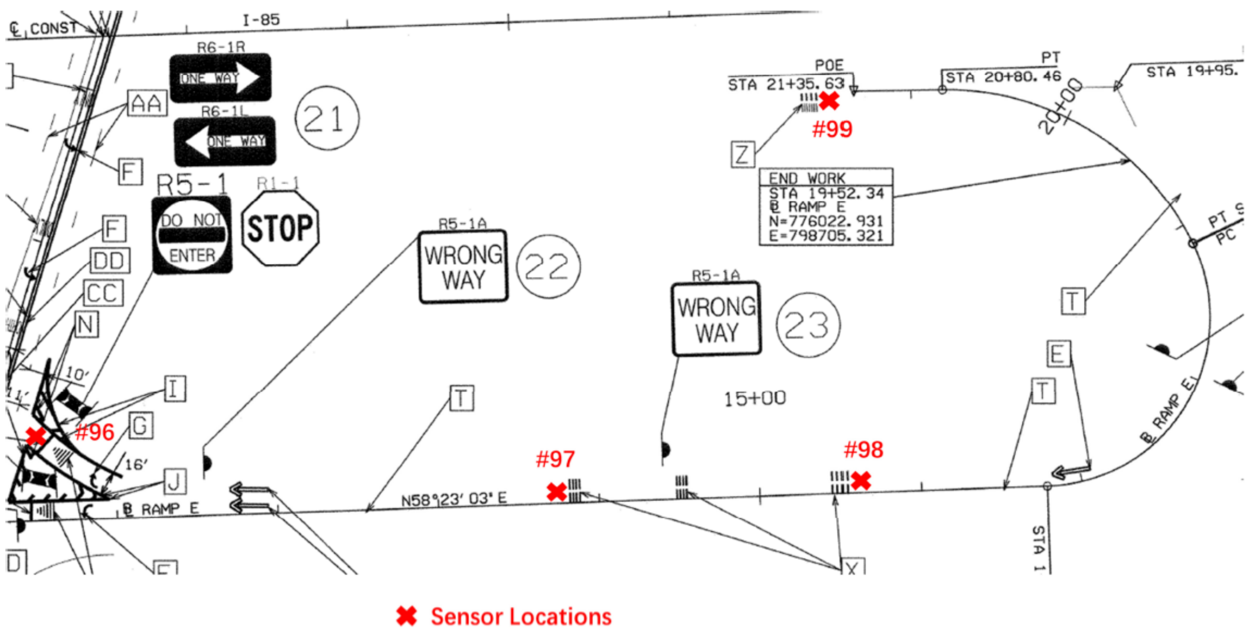
APPENDIX A: Speed Analysis on Off-Ramps at Exits 58 and 60 on I-85

In June and July 2020, ALDOT implemented DRS on off-ramps at Exits 60 (Figure A-1) and 58 (Figure A-2) on I-85. Magnetic sensors were installed at the locations indicated in the figures one week before DRS installation to collect speed data. They were uninstalled one week after the DRS was installed. Speed data was analyzed to examine the potential speed reduction for right-way drivers caused by DRS. It should be noted that Sensor #100 was damaged and later found on the roadside. Therefore, no speed data from this sensor was collected. Overall, the results showed that DRS can reduce average speed, speed standard deviation, and 85th percentile speed, which are consistent with the findings from Exits 208 and 284 on I-65.

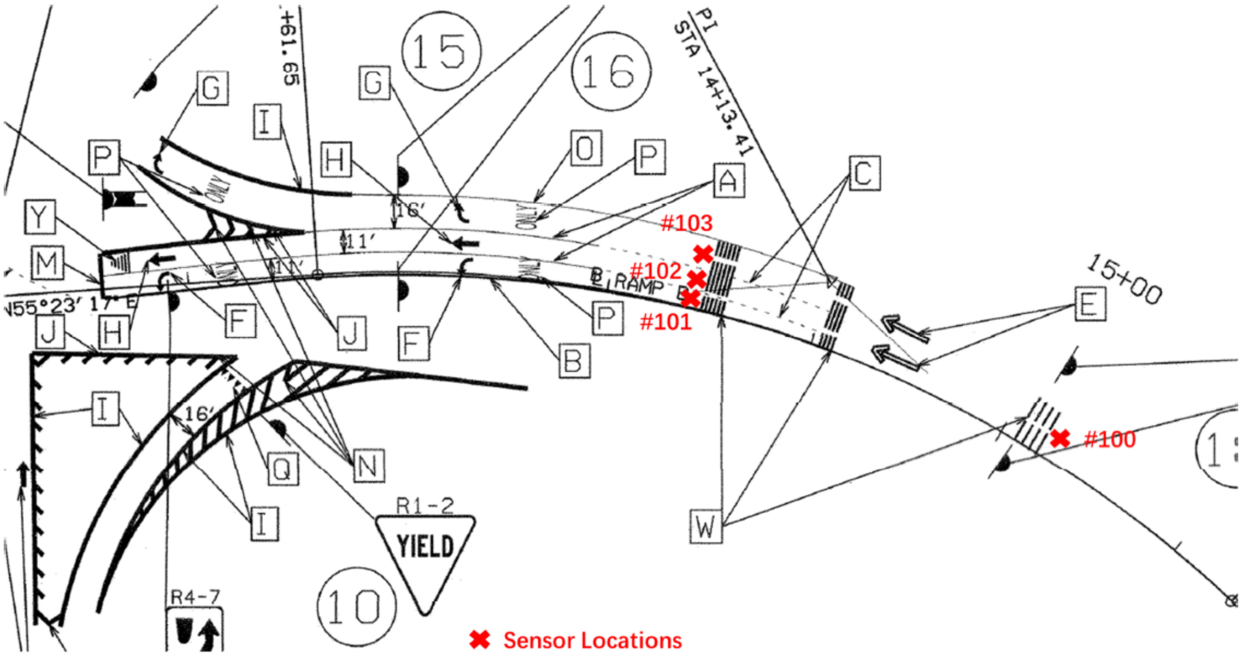
Exit 60, I-85



Note: Technical Drawings by ALDOT [HSIP-I085(356)]

Figure A-1. Locations of DRS and Sensors on the Southbound Off-Ramp at Exit 60, I-85

Exit 58, I-85



Note: Technical Drawings by ALDOT [HSIP-I085(356)]

Figure A-2. Locations of DRS and Sensors on the Northbound Off-Ramp at Exit 58, I-85

Figure A-3 and Table A-1 show the average speed reduction on two off-ramps. At Exit 60, the advisory ramp speed is 25 mph. The average speed entering the ramp curve from the freeway mainline (Sensor #99) was nearly 40 mph before Pattern E.1 installation. The average speed was significantly reduced to 35 mph (-9.7%) after Pattern E.1. Sensors #97 and #98 recorded a significant reduction in average speed (3 to 4 mph) in the middle of the ramp as a result of installing DRS Pattern C. At Exit 58, the average speeds on all three locations were below the advisory ramp speed (45 mph) during the before and after periods. Vehicles on through and right-turn lanes reduced their average speeds by a small portion, though the average left-turn speed remained steady. The statistical results were summarized in Table A-1 based on *t*-tests with a significance level of 0.05.

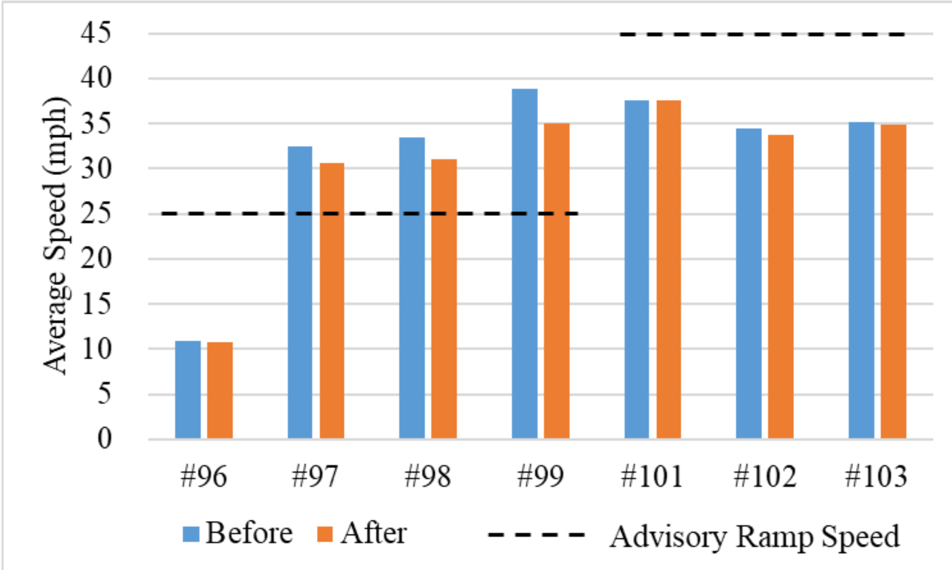


Figure A-3. Average Speed Before and After DRS Implementation

Table A-1. Changes in Average Speed Before and After DRS Implementation

Sensor	Before (mph)	After (mph)	Reduction (mph)	Reduction%	*p*-value*
#96	10.9	10.8	0.1	1.1%	0.13
#97	32.5	30.6	1.9	6.0%	< 0.01
#98	33.4	31.0	2.4	7.2%	< 0.01
#99	38.9	35.1	3.8	9.7%	< 0.01
#101	37.6	37.5	0.1	0.3%	0.47
#102	34.4	33.8	0.7	1.9%	< 0.01
#103	35.1	34.9	0.2	0.6%	< 0.01
**t*-tests with a significance level of 0.05					

Figure A-4 and Table A-2 present the changes in speed standard deviation (SSD) before and after DRS implementation and *F*-test results with a significance level of 0.05. At Exit 60, SSD before and immediately after the ramp curve has been significantly reduced by 12% (~5mph to ~4.5 mph) because of Pattern E.1 and Pattern C. After travelling over the 1-ft strip group of Pattern C, the SSD was further reduced by 8.7%. There was no significant change at the ramp terminal. At Exit 58, the only significant decrease in SSD occurred on the right-turn lane (Sensor #103) with a 7.2% reduction. The left-turn and through lanes have slightly reduced SSD but the change was not significant.

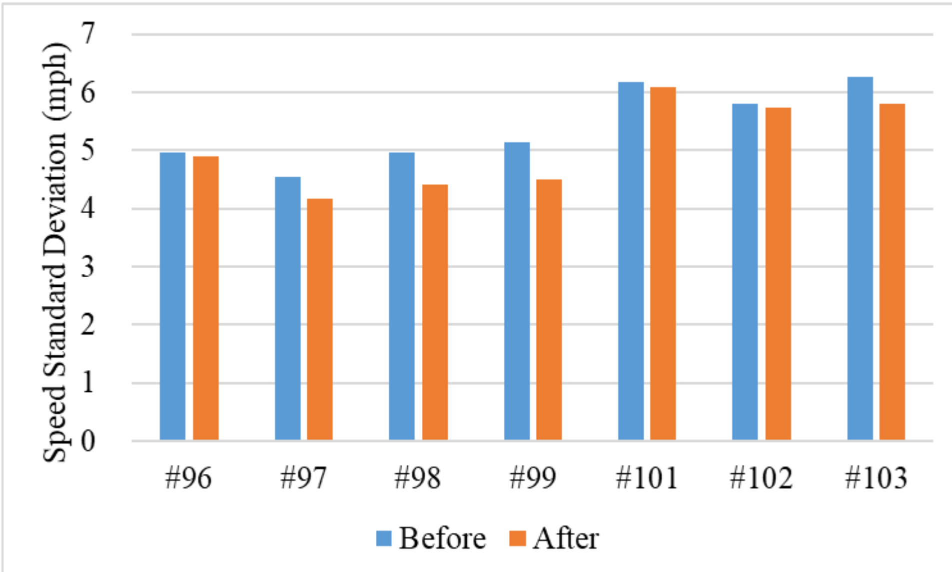


Figure A-4. Speed Standard Deviation Before and After DRS Implementation

Table A-2. Changes in Speed Standard Deviation Before and After DRS Implementation

Sensor	Before (mph)	After (mph)	Reduction (mph)	Reduction%	*p*-value*
#96	5.0	4.9	0.1	1.1%	0.25
#97	4.6	4.2	0.4	8.7%	< 0.01
#98	5.0	4.4	0.6	11.2%	< 0.01
#99	5.1	4.5	0.6	12.4%	< 0.01
#101	6.2	6.1	0.1	1.6%	0.20
#102	5.8	5.7	0.1	1.0%	0.16
#103	6.3	5.8	0.4	7.2%	< 0.01
**f*-tests with a significance level of 0.05					

Figure A-5 and Table A-3 demonstrate how 85th percentile speeds have been affected by DRS. The advisory ramp speed is 25 mph at Exit 60 and 45 mph at Exit 58. DRS Patterns E.1 and C reduced the 85th percentile speed before and after the ramp curve by 3 to 4 mph at Exit 60. At Exit 58, the 85th percentile speed of left-turn vehicles has been reduced by 1 mph and 2 mph for right-turn ones, while through vehicles have maintained the same 85th percentile speed of 40 mph.

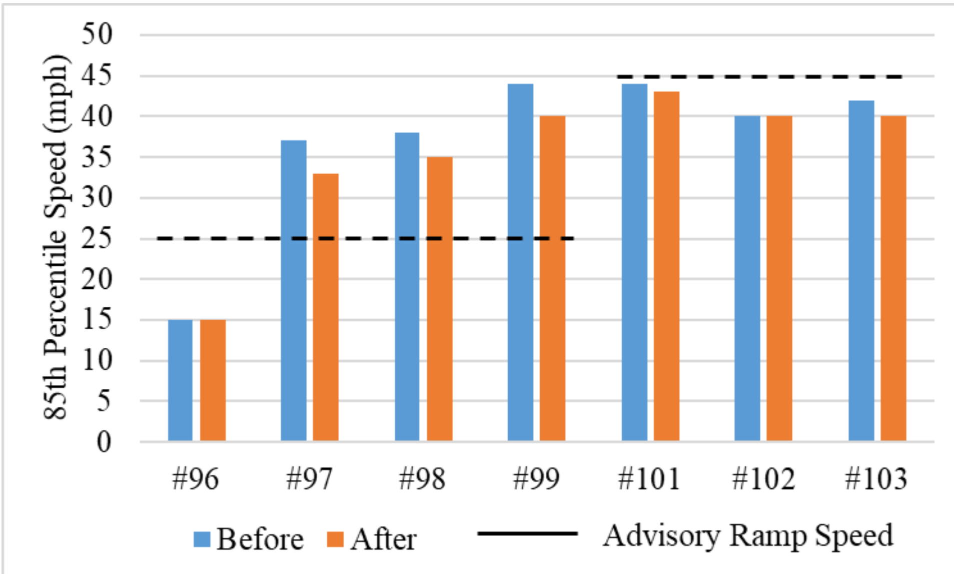


Figure A-5. 85th Percentile Speed Before and After DRS Implementation

Table A-3. Changes in 85th Percentile Speed Before and After DRS Implementation

Sensor	Before (mph)	After (mph)	Reduction (mph)
#96	15	15	0
#97	37	33	4
#98	38	35	3
#99	44	40	4
#101	44	43	1
#102	40	40	0
#103	42	40	2

APPENDIX B: Average Sound and Vibration Level

This section summarizes the average interior sound and vibration levels when a vehicle passes DRS.

Table B-1. Average Sound Level (dBA)

Pattern	D3		C-1		C-2		C-5		E.1	
Direction	RW	WW	RW	WW	RW	WW	RW	WW	RW	WW
10 mph	58.5	63.3	62.0	61.8	63.2	63.6	58.8	59.2	59.1	61.5
15 mph	63.4	67.2	63.8	63.4	64.8	65.1	60.9	60.6	61.9	63.1
20 mph	65.1	68.9	65.6	65.4	66.1	66.3	62.6	62.2	64.5	65.3
25 mph	68.3	70.2	67.5	67.1	67.2	67.9	63.1	63.5	65.4	67.4
30 mph	70.9	71.4	68.9	68.6	69.1	69.5	65.2	65.9	66.7	69.5
35 mph	72.7	72.9	70.8	70.5	71.5	72.0	68.5	69.1	67.3	71.5
40 mph	74.6	74.5	72.1	72.6	73.9	73.6	71.6	71.4	69.2	75.6

Table B-2. Average Vibration Level (*g*)

Pattern	D3		C-1		C-2		C-5		E.1	
Direction	RW	WW	RW	WW	RW	WW	RW	WW	RW	WW
10 mph	0.044	0.112	0.081	0.082	0.058	0.059	0.027	0.028	0.056	0.078
15 mph	0.043	0.105	0.093	0.091	0.062	0.063	0.030	0.032	0.063	0.086
20 mph	0.042	0.097	0.098	0.097	0.070	0.069	0.035	0.036	0.070	0.098
25 mph	0.043	0.089	0.110	0.113	0.077	0.075	0.039	0.038	0.074	0.103
30 mph	0.041	0.081	0.111	0.110	0.093	0.090	0.041	0.043	0.079	0.105
35 mph	0.040	0.075	0.113	0.121	0.116	0.117	0.053	0.054	0.080	0.106
40 mph	0.034	0.065	0.116	0.114	0.125	0.126	0.060	0.061	0.091	0.128