Effects of Geometric Design Features and Traditional Traffic Control Devices on Wrong-Way Driving Incident at Partial Cloverleaf Interchange Terminal: A Machine-Learning Approach

by

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Abstract

The partial cloverleaf (parclo) interchange is the second most popular interchange in the United States. Past studies revealed that the parclo interchange terminal is one of the most common entry points for wrong-way driving (WWD) crashes. However, to our best knowledge, few studies have focused on what interchange terminal design features caused those WWD entries at this type of interchange. This study aims to explore the effects of geometric design features and traditional traffic control devices on WWD incidents at parclo interchange terminals.

In this study, a total of 75 parclo interchange terminals from 13 states were monitored in order to collect WWD incident data. Based on 5984 hours of traffic monitoring video, 410 cases of WWD incidents were captured at 28 locations. Each case of WWD incident was reviewed and analyzed to record the time of day, weather conditions, WWD distance, and reaction time to evaluate the effectiveness of traditional traffic control devices for deterring WWD. Furthermore, a total of 20 detailed design features, including geometric design, usage of traffic control devices, and AADT at each location with/without WWD incidents, were collected to analyze the cause of WWD. This study utilized three machine learning techniques, including multiple correspondence (MCA) analysis, eXtreme gradient boosting (XGboost), and least absolute shrinkage and selection operator with logistic (Lasso-logistic) regression to explore the effects of different design features on WWD incidents.

The MCA analysis provided a general idea of what design combinations will cause/prevent WWD incidents at parclo interchange terminals. Based on the results, six types of parclo interchange terminals that will cause/prevent WWD incidents can be drawn. To further quantify the effects of each design feature on WWD incidents, the XGboost was applied to fit the dataset. The results of XGboost quantified the impact of each design feature on WWD incidents; it can also be utilized to predict the risk of WWD incidents by giving a specific parclo interchange terminal. In real practice, the local practitioners may need to evaluate dozens of parclo interchange terminals in order to find high-risk locations; collecting twenty design features and running a tree-based XGboost model for each location could be difficult to achieve. Therefore, lasso-logistic regression was applied in order to use fewer design features to conduct prediction and evaluation in real practice. The fitted lasso-logistic regression included eight design features instead of twenty, which made the network screening process easier and more efficient.

The XGboost and lasso-logistic models were verified by using the subset of collected data. The average accuracy of the fitted XGboost model was 80%, and the average accuracy of the fitted Lasso-logistic regression model was 78%. Finally, the results produced by this study were used to propose design guidelines for deterring WWD. The fitted lasso-logistic model was used to develop a checklist for field inspection, for local practitioners to conduct network screening, and identify locations with the potential of recurring WWD incidents.

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
CFX	Central Florida Expressway Authority
DNE	Do Not Enter
DRS	Directional Rumble Strips
ELT	Early Left Turn
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
HSM	Highway Safety Manual
ICT	Illinois Center for Transportation
IDOT	Illinois Department of Transportation
IIRPM	Internally Illuminated Raised Pavement Markers
LED	Light-emitting Diode
LT	Left Turn
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
NTTA	North Texas Tollway Authority
RPM	Raised Pavement Marker
RT	Right Turn
SPDI	Single-point Diamond Interchange
SPUI	Single-point Urban Interchange
TCD	Traffic Control Device

TMC	Traffic Management Center
USDOT	United States Department of Transportation
WSDOT	Washington State Department of Transportation
WW	Wrong Way
WWD	Wrong-way Driving

Chapter 1 Introduction

1.1 Research Background

Wrong-way driving (WWD) is a challenging safety issue. WWD crashes are characterized by its high severity, infrequency, and randomness. During 2004–2019, there was an average of 295 WWD fatal crashes on freeways causing 400 fatalities per year based on the Fatality Analysis Reporting System (FARS) database (NHTSA, 2021). The fatality rate (death per crash) of fatal WWD crashes accounts for 1.35, while other types of fatal crashes had a fatality rate of 1.11, indicating that WWD crashes typically result in more fatalities compared with other types of crashes (Song et al., 2021). Although efforts have been made by federal, state, and local transportation agencies to reduce WWD crashes, their number remains a slightly increasing trend in the United States (**Figure 1.1**). In order to address this issue, the reasons causing WWD must be further investigated.

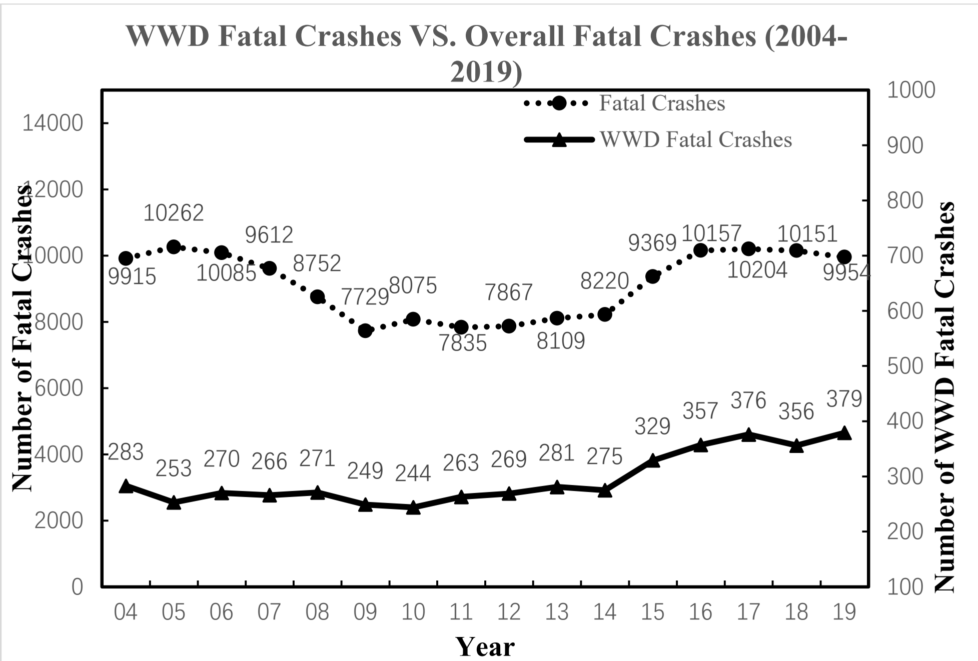

Figure 1.1 Trends of overall fatal crashes and WWD fatal crashes on the U.S. highway

Common contributing factors have been well identified that increase the chance of WWD crashes, such as driving under the influence (DUI), young drivers, older drivers, nighttime, etc. based on the WWD crash records (Zhou et al., 2012; Braam, 2015; Scaramuzza and Cavegn, 2007; Cooner et al., 2008; Kemel, 2015). However, due to the rareness of WWD crashes, few studies have been conducted to identify the initial entry point of WWD crashes. In fact, based on the current crash database in the U.S., it would be challenged to extract the initial entry point of WWD crashes due to the limited records of WWD crashes. In order to better prevent WWD crashes, WWD incidents must be further investigated.

WWD incident is defined as the act that a driver driving the wrong way (WW) without ending up with a crash. It occurs much more frequently than WWD crashes since it can be either self-corrected or stopped by police officers/WW-related countermeasures. Based on the report from National Transportation Safety Board (NTSB), WWD crash on the freeway usually start from the freeway off-ramp (NTSB, 2012). Recent studies have proven that some ramp terminals with design deficiencies are experiencing recurring WWD incidents, which means WWD incidents cannot be simply considered as random events (Zhou et al., 2020; Atiquzzaman and Zhou, 2020; Chang et al., 2019). Eliminating recurring WWD incidents at the off-ramp terminals could be a good solution for preventing WWD crashes. Currently, locations with design deficiencies causing WWD typically remain unnoticed until severe WWD crashes occur. As a result, it is important to identify how different types of road design features may affect WWD incidents in order to develop a method that will identify the locations with recurring WWD incidents.

Partial cloverleaf (parclo) interchange has been found prone to WWD incidents due to the parallel spaced on- and off-ramps. This type of interchange is the second most popular interchange, and it accounts for 16% of all the interchanges in the United States (Zhou et al., 2012; Bonneson et al., 2015; Copelan, 1989). In order to identify the risky locations, there is a strong need to study the design features that might confuse drivers at this type of interchange terminal. Recent studies proposed several mathematical models to predict the risk of parclo interchange off-ramp terminals for WWD based on geometric design, placement of traffic control devices (TCDs), traffic volume, etc. (Atiquzzaman and Zhou, 2020; Pour-Rouholamin and Zhou, 2016; Baratian-Ghorghi et al., 2016). These studies mainly adopted WWD crash data or traffic simulation to establish their model, which couldn't be applied for WWD incident prediction. Therefore, in order to identify what kind of parclo interchange terminals are prone to WWD incidents, there is a need to collect and analyze WWD incident data.

1.2 Research Objectives

Only a few transportation agencies collect WWD incident data at ramp terminals; these data were mainly collected by intelligent transportation systems (ITS) deployed at specific ramps. Other than that, some agencies collected WWD incident data via 911 calls or police citations. However, most 911 calls or citations are for the incidents on the freeway mainline, and the initial WW entry points may still be unknown. In this study, the video data at 75 parclo interchange terminals were first recorded using portable traffic cameras, then the WWD incident data at each terminal were extracted by manually watching the videos. While watching the videos, the driving behaviors of each WWD incident, including time of day, reaction time, WWD distance, and time used for self-correction, will be observed and recorded by researchers to preliminarily identify the design deficiencies. For each location, the geometric design features and usage of TCDs were recorded based on Google map satellite view and street view, also verified by a field visit while installing the cameras. The AADT data for each on- and off-ramp was collected through the local DOT's website. The detailed driving behavior collected for each WWD incident will be used to evaluate the effectiveness of traditional WW-related TCDs and intersection geometric design features. Based on the monitoring results, each parclo interchange terminal can be categorized as one of the two groups, depending on the existence of recurring WWD incidents. A comparative analysis will be conducted between two groups to identify key geometric design features causing WWD incidents. Finally, the effectiveness of geometric design features and usage of wrong-way-related TCDs, as well as AADT and nearby conditions on the risk of WWD incidents at parclo interchange terminals, will be considered together and quantified by normalizing the results using machine learning techniques. The final model could be able to predict/evaluate the risk of WWD for specific parclo interchange terminals. Based on the findings, guidelines for preventing WWD incidents at parclo interchange terminals will also be developed. In summary, the objectives of this study are to:

- Collect WWD incident data and road design features at 75 parclo interchange terminals;
- Analyze the driving behaviors of WWD incidents and identify preliminary design deficiencies;
- Evaluate the effectiveness of low-cost WW-related TCD countermeasures;
- Identify key geometric design features causing WWD incidents at parclo interchange terminals;
- Modeling the risk of WWD incident at parclo interchange terminal based on geometric design features, usage of TCDs, AADT, and nearby conditions;
- Develop guidelines on the application of TCDs and geometric design features for WWD incident prevention.

Chapter 2 Literature Review

The literature review for this study is divided into five sections. The first section summarized the state of art studies using WWD incident data. The second section investigated the effectiveness of WW-related countermeasures, as well as the methodologies used for evaluation. The third section reviewed the studies focusing on how geometric design features would affect WWD, including types of design features that may cause/deter WWD. The fourth section summarized the current practice of preventing WWD in different states, including different WWD policies and guidelines. The final section concluded the previous research and described the current research gap.

2.1 Past studies on WWD incidents

Due to the rareness of WWD crashes, some states started to collect and analyze WWD incident data. Past studies indicated that the WWD incident data could help understand the impact of geometric design features and TCDs on WWD. **Table 2.1** lists the recent WWD incident studies conducted by five states. Based on 13 past studies, three types of WWD incident data were collected and analyzed. The first type of WWD incident data includes citation data, 911 calls, and incident data collected by traffic detection systems. They have been used to identify locations/segments with higher potential for WWD incidents for implementing WWD countermeasures on the mainline or nearby ramp terminals. The second type of WWD incident data was collected at specific off-ramp terminals. This type of data can be used to identify geometric design deficiencies and the need for WW-related TCDs at specific ramp terminals. The third type of WWD incident study relied on the survey and traffic simulation outputs that have been used to estimate the potential risk for WWD for a roadway segment or an intersection.

According to **Table 2.1**, it can be found that the state of Florida conducted the state of art WWD incident studies. These studies indicated a correlation between WWD incidents and crashes, which implies that the locations with WWD incidents are more likely to have WWD crashes. In 2016, Rogers et al. attempted to predict WWD crashes by using 911 calls and citations as well as route characteristics; thus, two WWD crash prediction models were proposed for determining WWD hot spots (Rogers et al., 2016). The proposed models were verified by comparing predicted values obtained from the models with the actual crash data. Later, Sandt et al. improved the previous models to predict WWD crash risks for roadway segments by using predicted WWD crashes obtained from the proposed model and collected WWD crash data; further, the duration of WWD events was also predicted by employing WWD crash data (Sandt et al., 2016). More specifically, Kays et al. developed a model for estimating the number of WWD entries at limited access exit ramps located in Florida (Kays et al., 2019). To do so, WWD citations and 911 call data were obtained as well as traffic and roadway characteristics. The results obtained from the proposed model suggested that trumpet interchanges, as well as directional interchanges, increase the chance of WWD entries compared with cloverleaf interchanges in Florida. Sandt et al. developed a WWD crash risk model and WWD countermeasure optimization algorithm to identify the optimal locations for deploying intelligent transportation systems (Sandt et al., 2021).

Table 2.1 List of WWD incident studies

Year	Study Area	Data	Key Findings
2021	Florida	WWD crashes, 911 calls and citations; interchange characteristics	1. Segments with more WWD 911 calls, citations, higher crossing road volumes, rest areas had more WWD crashes. 2. Segments contained trumpet interchanges and slip ramps had fewer WWD crashes (Sandt et al., 2021).
2019	Alabama	WWD incident data at parclo interchange terminal	3. Appropriate and well-maintained pavement marking at parclo interchange can reduce more than 60% of WW entries. 4. More than 90% of WWD incidents self-corrected before the first and second set of WW signs combined with WW arrow (Chang et al., 2019).

2019	California	WWD incident videos monitored by the vision-based sensor system	1. Time of day for the WWD incidents detected trends to match the results from previous researches. The events tended to be in the early morning hours. 2. Exit-ramp configuration and signage seem to have a significant influence on WWD incidents. 3. WWD incidents are essentially prevalent in both daytime and nighttime. (Yen et al., 2019).
2019	Central Florida	WWD crashes, 911 calls and citations	The interchange type, intersection angle of exit-ramp terminals, presence of tolling at the entrance ramp, presence of a channelizing island between the exit ramp lanes, number of lanes on the exit ramp, area type, and traffic volumes will affect WWD incidents (Kayes et al., 2018).
2018	Florida	Survey	1. 81% of officers respond to at least one non-crash WWD event per year. 2. 73% of officers respond that WWD events occur mainly in urban or suburban areas. 3. Over 60% of the WWD events are either "not found and never pulled over or never crashed." 4. 90% of officers have worked on cases where the WW driver traveled at least 1 mile before being stopped; and 47% of officers have worked on cases where the WW driver traveled at least 4 miles before being stopped, which indicates that WW drivers can travel far before either self-correcting, being pulled or causing a crash. 5. 71% of officers found that WW drivers were DUI. 6. 96% of officers said that WW drivers typically travel alone (Wertanen et al., 2018).
2018	Alabama/Illinois	WWD incidents data collected at ramp terminals with crash history in Alabama and Illinois	Mathematical models were developed to predict the risk of WW entries at the exit ramp terminals of full diamond interchanges (Atiquzzaman and Zhou, 2018).
2017	Central Florida	WWD event data (citations and 911 calls with GPS locations); roadway data (interchange locations, interchange types, and traffic volumes)	Using WWD citations and 911 call data to estimate the risk of WWD. Additionally, the WWD event data to estimate the durations of WWD events are also applicable for modeling WWD risk (Sandt et al., 2017).
2016	South Florida	Citations and 911 calls	WWD no crash events such as WWD citations and 911 calls positively affect the yearly crash prediction. The results showed several freeway segments with high WWD risk had crash history (Rogers Jr. et al., 2016).
2015	Florida	Survey	1. 14% of the WWD events resulted in a crash. 2. Only 10% of the WWD events witnessed by participants were reported to law enforcement or roadway agencies. 3. WWD is more frequent than indicated by crashes or 911 calls (Sandt et al., 2015).
2015	Florida's Toll Road System	Crash reports, citation data, 911 call data, survey	1. Measure and understand WWD trends and statistics for the central Florida toll road network. 2. Recommended a three-tiered-level approach for countermeasures to preventing WWD (Rogers Jr. et al., 2015).
2014	Signalized Partial Cloverleaf Interchanges	Field video data and traffic simulation outputs	Potential WWD events increase when left-turn volume toward an entrance ramp increases and stopped vehicles at an exit ramp decrease (Baratian-Ghorghi et al., 2014).
2014	Central FL Toll Road Network	Crash reports, citation data, 911 call data, and survey	1. Systematic ranking of central Florida toll roads with respect to WWD. 2. WWD is a problem in central Florida that requires attention (Rogers Jr. et al., 2014).

2013	Arizona	Recording by WWD detection systems	WW vehicles can be detected using equipment currently available on the market, while each system had missed or false calls (Simpson, 2013).

2.2 Evaluation of WW-related countermeasures

Although many agencies applied different kinds of WWD countermeasures, the evaluation of WWD countermeasures can be difficult due to the randomness of WWD crashes and the lack of before-and-after data. The survey studies conducted by Pour-Rouholamin and Zhou gave an overview of the effectiveness and level of acceptance for over ten engineering countermeasures, including WW-related signage, pavement markings, geometric modification, and ITS technologies (Pour-Rouholamin et al., 2014). According to the ENTERPRISE Transportation Pooled Fund TPF5 Study (Athey Creek Consultants, 2016), the purposes of these countermeasures can be grouped into two categories:

1. “Preventative” countermeasure, which can prevent vehicles entering the WW.
2. “Reactive” countermeasures, which can warn WW drivers that they are going the WW.

Table 2.2 summarizes the evaluation results of the recently implemented traditional and advanced WWD countermeasures in these two categories.

Table 2.2 Evaluation results of WWD countermeasures

Preventative WWD Countermeasures		Reactive WWD Countermeasures	
Newly developed signing standard: Lower-mounted signs and specific requirements for sign installation (CA2008)	90% reduction in WWD incident frequency (Leduc, 2008)	**Red Retroreflective Raised Pavement Markings (RRPMs)** (HI2008)	RRPM helped drivers realize when they were going in the wrong direction, replacing supplemental RRPMs with supplemental arrows always improved the rates of self-correct responses (Miles et al., 2014)
Newly developed signing and pavement markings standard: Enhanced pavement and specific sign installation (FL2018)	Very positive effectiveness on arterials (Lin et al., 2018)	**WW sign combined with WW arrow** (AL2019)	More than 90% come back rate for WWD incidents (Chang et al., 2019)

Improved pavement marking and signs: Repainting, striping additions, and WW signs on signal mast arms (TX2013)	The number of WWD incidents have decreased significantly after sign and pavement marking improvements (Ouyang, 2013)	**Directional rumble strips (DRS)** (AL2018)	Improve self-correction rates and reduce WWD incidents while offering good visual attentiveness and applicability (Yang et al., 2018)
Improved pavement markings: Repaint of the double yellow line, left turn skip strips, and stop bar (AL2019)	63% reduction in the number of WWD incidents (Chang et al., 2019)	**Delineators along exit-ramps** (FL2018)	The least effective countermeasure (Lin et al., 2018)
Countermeasure combo: Trailblazers, low mounted WW signs, stop bar, yellow ceramic buttons (GA1988)	97% reduction in WWD incident frequency (Campbell and Middlebrooks, 1988)	**Red Rectangular Rapid Flash beacons (RRFBs)** (FL2017)	60% – 85% self-correction rates, more effective on alleviating WWD due to their higher intensity and speed (Ozkul and Lin, 2017)
LED border: for DNE and WW sign (TX2013)	30% reduction in WWD incident frequency (Finley et al., 2014) LED WRONG WAY sign had a 47.9 % reduction in WWD 911 calls, 50.2% reduction in WWD citations, and 48.1% reduction in combined WWD 911 calls and citations. 16% of the 72 detected wrong-way vehicles self-corrected at the LED sites. (Kayes et al., 2019)	**Rectangular flashing beacon (RFB) WW sign** (FL2018 & FL2019)	77% reduction in WWD incident frequency (Lin et al., 2018) 48.5% reduction in 911 calls, 52.9% reduction WWD citations, and 44.1% reduction in combined WWD 911 calls and citations. (Al-Deek et al., 2019) 84.5 % reduction in WWD 911 calls, 59.7% reduction in WWD citations, and 69.4% reduction in combined WWD 911 calls and citations. 81% of the 353 detected wrong-
Intersection balance: Stop line on the crossroad located at no more than 60% of the way through the intersection (IL2017)	Provided better sight distance to deter WWD entries (Wang et al., 2017)	**Wigwag flashing beacons** (FL2018)	Effective for mitigating WWD (Lin et al., 2018)
Directional arrows (TX2005)	90% reduction in WWD incident frequency (Chrysler and Schrock, 2005)	**Detection-triggered blank-out signs that flash "WW"** (FL2018)	Effective for mitigating WWD (Lin et al., 2018)
Raised/vertical longitudinal channelizing devices (MI2013)	No more WWD left turn incidents within the study period (Morena and Ault, 2013)	**Detection-triggered LED lights around WW signs** (FL2018)	Effective for mitigating WWD (Lin et al., 2018)
Geometric modification: Raised median extension (TX2013)	No more WWD incidents within the study period (Ouyang, 2013)	**Light-emitting diode (LED) WW sign** (FL2018)	14% reduction in WWD incident frequency (Lin et al., 2018)
		Red flush-mount internally illuminated raised pavement markers (FL2018)	Consider as a supplemental countermeasure (Lin et al., 2018)

The evaluation methods conducted by different agencies mainly focused on before-and-after studies of WWD crashes or incidents, driving simulation, survey, field test, and investigation of agency records. For the preventative WWD countermeasures, five states have made the improvement or enhancement for traditional "DO NOT ENTER" (DNE) or WW signs and pavement markings for deterring WWD incidents, which showed a significant reduction in WWD incidents up to 97% (Leduc, 2008; Lin et al., 2018; Ouyang, 2013; Chang et al., 2019; Campbell and Middlebrooks, 1988). In addition, the LED border for DNE and WW signs, directional arrows on exit ramps were proved to be effective for deterring WWD incidents (Lin et al., 2018). Last, the raised/vertical longitudinal channelizing devices and geometric modifications for exit-ramp terminals can prevent WWD incidents (Ouyang, 2013).

As for reactive WWD countermeasures, transportation agencies tended to apply more advanced countermeasures, such as RFBs, which was found to reduce WWD incidents, 911 calls, WWD citations, as well as the combined 911 calls and citations efficiently (Kayes et al., 2019; Al-Deek et al., 2019 & Lin et al., 2018). Other reactive WWD countermeasures like red RRFBs, wigwag flashing beacons, LED WW sign, detection-triggered blank-out signs that flash "WRONG WAY" and detection-triggered LED lights around WW signs have been proved to be significantly effective for improving self-correction rates. The IIRPM is not as effective as other kinds of advanced countermeasures (Lin et al., 2018), which can be considered as a supplemental countermeasure. The traditional reactive countermeasures such as a WW sign combined with a WW arrow and directional rumble strips (DRS) can also effectively reduce WWD incidents (Chang et al., 2019). Compared with the WWD countermeasures mentioned above, the delineators along exit ramps were considered as the least-effective countermeasures (Lin et al., 2018).

2.3 Effects of geometric design features for WWD

Parclo interchange terminal has been well identified as prone to cause driver's confusion due to the parallel spaced on- and off-ramps by several past studies (Copelan, 1989; Conner et al., 2004; Zhou et al., 2015). In this section, more geometric design deficiencies for WWD related to parclo interchange terminals are summarized based on the past literature.

According to the study conducted by Atiquzzaman and Zhou, geometric design features such as larger corner radius, traversable medians on the crossroad, unsignalized ramp terminals, and acute intersection angles are more likely to create WWD incidents at the ramp terminal of full diamond interchanges (Atiquzzaman and Zhou, 2018). Turning radius, type of the median on the crossroad, median width between on- and off-ramps, intersection balance, distance to the nearest access point, and types of channelizing island also have a significant effect on WWD entries (Zhou and Pour-Rouholamin, 2014). The presence of access points close to off-ramp terminals may increase driver's confusion. Pour-Rouholamin and Zhou revealed that exit-ramp terminals with access points within 600 feet have a higher chance of WWD crashes (Pour-Rouholamin and Zhou, 2016). Similar results were found by the North Texas Tollway Authority (NTTA), i.e., the minor road near an off-ramp was appealing for WW entries from the crossroad (Ouyang. 2013). Baratian-Ghorghi found that potential WWD incidents were more likely to happen at parclo interchange terminals when fewer vehicles were stopped on an off-ramp and more left-turn vehicles on the crossroad (Baratian, 2015). Chassande-Monttin and Ganneau claimed that the complexed intersection such as the existence of two or more channelizing islands would confuse drivers (Chassande-Mottin and Ganneau, 2008); further, Cooner et al. reported that off-ramps located on the left-side of drivers, one-way streets connected with freeways and short sight distances caused more WWD (Conner et al., 2004).

Previous studies also concluded that some geometric features could be effective for deterring wrong-way entries at the parclo interchange terminals. A recent study conducted by Wang and Zhou found that an intersection balance of less than 60% can provide better sight distance, which can reduce the risk for WWD (Wang and Zhou, 2018). The Illinois Department of Transportation (IDOT) recommended that the median width between the entrance and exit ramp should be more than 50 feet 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 exit-ramp throat, which has been suggested via numerous researches (Zhou et al., 2012; Cooner and Ranft, 2008). The American Association of State Highway and Transportation Officials (AASHTO) Green Book suggests 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; (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 wrong-way entry (AASHTO, 2011).

2.4 Existing policy and guidance for WWD

Table 2.3 summarizes the policies of nine different state DOTs. Most state DOTs used the national *Manual on Uniform Traffic Control Devices* (MUTCD) for WW-related TCDs. Some state DOTs use their own MUTCDs. Few states have specific policies for additional requirements for mitigating WWD. The literature review results suggest that existing WWD policies can be grouped into two categories: (i) policy related to the WWD crash studies; and (ii) policy related to roadway design and TCDs. For instance, Arkansas established a policy that requests ARDOT to prepare an annual WWD study report (Representative Pyle, 2009). FDOT had a policy that requested WW-related signs and pavement markings should follow the specific design guidelines developed by the FDOT (FDOT, 2019a). The *ADOT Traffic Engineering Guidelines and Processes* contains the policy and a section on the usage of WW-related signs in Arizona (ADOT, 2015). Iowa DOT uses the MUTCD except for the exceptions shown in the Administrative Rule Chapter 761, Section 130.1 (1) (Iowa DOT, 2015). California, Michigan, Ohio, and Texas DOTs use their own MUTCD, which combined national MUTCD and state-specified guidelines (Caltrans, 2019; MDOT, 2010; MDOT, 2011; Ohio DOT, 2012; TxDOT, 2014). Additionally, California and Michigan also use their state *Geometric Design Guides* (Caltrans, 2018a; MDOT, 2010) for supplementing guidelines from AASHTO Green Book.

Table 2.3 Existing state WWD policy

State	WWD Policy
Arizona	For conventional roadways and expressways, sign sizes and mounting should be in accordance with the regulatory signs chapter of the MUTCD. For new and reconstructed freeway traffic interchanges, or at freeway traffic interchanges where a sign rehabilitation or replacement project is replacing existing signs, the *ADOT Traffic Engineering Guidelines and Processes* should be used (ADOT, 2015).
Arkansas	Act 641 of the 87th Arkansas General Assembly requires the ARDOT to analyze all WWD crashes on the Interstates and other freeways with full control of access and to prepare an annual report (Representative Pyle, 2009).
California	The Caltrans followed the California MUTCD (CA MUTCD) for (TCDs). The CA MUTCD is in conformance with MUTCD and contains policies on TCDs issued by Caltrans (Caltrans, 2019). The highway design in California should follow the *California Highway Design Manual* to deter WWD (Caltrans, 2018a).
Florida	FDOT followed MUTCD, *FDOT Design Manual* Section 230.4 and *Roadway Design Bulletin 15-08/Traffic Operations Bulletin 03-15* for DO NOT ENTER and WRONG WAY signs and pavement markings (wrong-way arrow, route interstate shield, etc.) (FDOT, 2019a).
Iowa	The Iowa DOT currently uses the 2009 MUTCD except for exceptions noted in the *Administrative Rule* Chapter 761, Section 130.1 (1) (Iowa DOT, 2015).
Michigan	The MDOT currently followed 2011 Michigan MUTCD (Michigan DOT 2011) and *Geometric Design Guides* (Michigan DOT, 2010)
Ohio	The Ohio DOT followed the Ohio MUTCD (OMUTCD) for WW-related TCDs. Most of the text in the OMUTCD is identical to the national MUTCD, while some have been modified to meet state laws or to more closely reflect conditions and policies in Ohio (Ohio DOT, 2012).
Pennsylvania	The PennDOT adopted the most recent MUTCD as standard for TCDs in this commonwealth, and Publication 212 for new regulations, warrants, principles, and guidelines established by Penn State (PennDOT 2006).
Texas	The TxDOT adopted the Texas MUTCD for TCDs that contains the national MUTCD and the standards developed by the state DOT (TxDOT, 2014).

Table 2.4 lists the existing WWD guidelines developed by each state. Except for the MUTCD, which is commonly adopted for each state, 11 states have developed additional

guidelines for deterring WWD. Based on the literature review, two types of guidelines are provided by the state DOTs. In 2014, Illinois DOT published a guideline for reducing WWD on freeways intended to serve state and local agencies as an informational resource to supplement existing standards and manuals. In 2017, a WWD toolbox was published by NCDOT, which can also be used as a general guidebook for state agencies. Most of the other states, such as Arizona, Florida and Michigan, have developed simple and specific guidelines to supplement their own existing MUTCD or geometric design guidelines.

Table 2.4 Existing state WWD guidelines

Year	State	Primary Content
2014	Illinois	1. Provided guidelines for signs (DNE sign, WW sign, ONE WAY sign, KEEP RIGHT sign, and turn prohibition sign), pavement markings (in-lane arrows, longitudinal lines, stop lines, and enhanced delineation), and traffic signals 2. Provided design guidelines of the geometric element (exit/entrance ramps, frontage road, raised median, channelizing island, corner radius, and sight distance) 3. Provide design guidelines by using advanced technologies 4. Provide guidelines on enforcement and education (Zhou and Pouholamin, 2014)
2015	Florida	The standard for signing and pavement marking at exit ramp intersections are described as follows: 1. Include MUTCD "optional" signs: (second DNE sign, second WW sign, ONE WAY sign) 2. Include NO RIGHT TURN and NO LEFT TURN signs 3. Use 3.5 x 2.5 ft. WRONG WAY signs with 4 ft. mounted height. Apply the retroreflective strip on sign supports 4. Include two to four dotted guideline striping for left turns 5. Include retroreflective yellow paint on-ramp median nose where applicable 6. Include a straight arrow and route Interstate shield pavement marking in left-turn lanes 7. Include a straight arrow and ONLY pavement message (FDOT, 2015; FDOT, 2019b)
2015	Arizona	1. Use DNE sign and WW sign assemble on the same post 2. Use large-sized signs: DNE 48 x 48 in., WW 48 x 36 in. 3. The minimum mounting height is 3 ft. 4. Strips of red retroreflective sheeting may optionally be placed on the signpost (ADOT, 2015)
2015	Connecticut	The following guidelines were used to improve the static signing and pavement markings at the interchange ramps: 1. Mount larger-sized sign at exit ramps (48-in. DNE signs, 42 x 24 in. WW signs) 2. Low-mounted WW and DNE signs (5 ft., consideration of snow) 3. Applied red reflective delineator strips on the signpost 4. 24-in. wide stop bar applied 5. As for the locations with an adjacent on/off ramps: (a) Applied the pavement marking extension lines at signalized locations (b) Double yellow centerline between the ramps (Athey Creek Consultants, 2016)
2015	Wisconsin	The basic requirements should follow MUTCD, additionally: 1. The following strategies may be used at freeway ramp locations that have exhibited problems with WW drivers entering the freeway: (a) Larger-sized the DNE and WW signs (b) Stop bar and type-4 pavement arrows (c) Dotted pavement markings line extensions through the intersection 2. The following strategies are optional and shall only be used at side-by-side ramp locations that exhibited problems with WW drivers entering the freeway: (a) Additional WW sign mounted below the DNE sign at 3-ft. mounting height

		(b) Reflective strips on WW and DNE signpost (c) A freeway entrance sign (d) Dynamic (flashing) WW signs (WisDOT, 2015)
2016	Ohio	Ohio DOT created a drawing of partial cloverleaf interchanges and diamond interchanges with single-lane exits to improve signs and pavement markings at ramps. These drawings became statewide standards in 2016: 1. Two WW signs assembled on the same post with low-mounted height (3 ft.) 2. Red reflective tape shall be added to the STOP sign, DNE sign, and WW sign 3. Include pavement marking extension line to guide drivers onto the right way 4. Include dual-directional route marker signs at the end of ramps 5. Include a yellow-painted island between the entrance and exit ramp 6. Additional signs followed MUTCD minimum requirements The DNE sign may be angled 45 degrees toward the left turning vehicle (Ohio DOT, 2016)
2017	Michigan	1. For freeway ramps, the mounting height of DNE and WW signs shall be 4 ft. 2. Red reflective sheeting shall apply to the signposts. WW and DNE signs should be turned around 20 degrees from the crossroad to face the protentional WW drivers (Michigan DOT, 2011)
2017	North Carolina	1. List tools used on signs to deter WWD (low mounting height, reflective strips, dynamic signs, larger-sized signs, turn prohibition signs, etc.) 2. List tools used on markings to deter WWD (WW pavement marking arrows, lane extensions, stop line, delineate median, etc.) 3. List tools used on geometric design to deter WWD (channelizing island, median, corner radius, median barrier, roundabout, lighting) (UNC Highway Safety Research Center, 2017)
2018	Oregon	1. Additional guidance regarding low mounted installations for WW entrance signing on the interstate freeways 2. The standard for low-mounted installations (Oregon DOT, 2018)
2018	California	1. All standard interchange sign packages (e.g., R5-1 [WW], R6-1 [double lane control], etc.) are required and must be located where they are clearly visible to reduce the risk of WW movements at exit ramps. 2. Minimize intersection size to reduce the driver confusion and WW movements (Caltrans, 2018b).
2018	California	1. Access openings on expressways: to discourage WW movements, access openings should be located directly opposite or at least 300 feet from a median opening (Index 205.1). 2. Isolated off-ramps or partial interchanges shall not be used because of the potential for WW movements (Index 502.2). 3. The minimum distance between successive exit ramps on collector-distributor roads interest areas should be 600 ft; one-way vehicular circulation should be provided through the safety roadside rest area to reduce WW reentry to the freeway. 4. The entrance and exit ramps should be clearly visible from the crossroad. A concrete barrier or guardrail placed between the ramps can block driver view from the crossroad. If feasible, the concrete barrier or guardrail channelization feature should be set back from the crossroad edge of the shoulder 20 to 50 ft., with a raised traffic island placed from the ramp termini to the beginning point of the separation feature (Caltrans, 2018a).
2019	California	1. The DNE (R5-1) sign and WW (R5-1a) sign shall be used at the exit end of a one-way road or ramp to inform motorists that an entrance thereto is prohibited. 2. At intersections where the left-turn lane treatment results in channelized offset left-turn lanes (e.g., a parallel or tapered left-turn lane between two medians), the size of the DNE (R5-1) sign or WW (R5-1a) sign, if used, should be of the next higher roadway classification, to reduce the potential for WW maneuvers by road users turning left from a stop-controlled, intersecting minor roadway. 3. Where there are no parked cars, pedestrian activity, or other obstructions such as snow or vegetation, and if an engineering study indicates that a lower mounting height would address WW movements on freeway or expressway exit ramps, a DNE sign(s) and/or a WW sign(s) that is located along the exit ramp facing a road user who is traveling in the wrong direction may be installed at a minimum mounting height of 3 ft., measured vertically from the bottom of the sign to the elevation of the near edge of the pavement.

		4. A stop beacon shall be used only to supplement a STOP sign, DNE sign, or WW sign (Caltrans, 2019).
2019	Florida	1. Install a pair of LED highlighted WW signs; two sets of the pairs of highlighted signs may be used on long ramps or the ramps with limited sight distance (FDOT, 2019c).
2019	Washington	Three categories of countermeasures to discourage WWD: 1. Signing and Delineation DNE and WW sign, ONE WAY signs, turn restriction signs, red-backed raised pavements markers (RPMs), directional pavement arrows, yellow edge line on left and white edge line on right side of exit ramps, pavement marking extension lines. 2. Intelligent Transportation Systems (ITS) 3. Geometric Design 2. Separate on-and off-ramp terminals, reduced off-ramp terminal throat width, increased on-ramp throat width, intersection balance, visibility, angular corners on the left of off-ramps terminals (WSDOT, 2019).

According to **Table 2.4**, common guidelines for additional WW-related countermeasures are summarized below:

Signs

- *Size:* Oversized signs (DNE sign, WW sign, or both) are required to be implemented on the roadside to ensure better visibility. The 48 x 48-in. DNE signs were commonly included in guidelines for those 11 state DOTs. However, there is no uniform size for the WW sign.
- *Mounting height:* Low-mounted signs (DNE sign, WW sign, or both) were recommended by 10 out of 11 state DOTs. The height of the sign may be different from state to state, which varies from 3 to 5 ft. For example, the 5 ft. DNE sign and WW sign were contained in Connecticut DOT’s (CTDOT) guidelines due to the snow accumulation in winter (Athey Creek Consultants, 2016).
- *Retroreflective tape:* Six (6) out of 11 state DOTs recommended applying the retroreflective tape on the signpost. Four states set this guideline as standard, while two states regarded it as optional. However, there is no uniform requirement on retroreflective material among 11 states.
- *Assembled sign:* Three state DOTs included the assembled sign in their guideline; however, different states will assemble different signs on the same post. For example, the ADOT put

DNE sign and WW sign on the same post (ADOT, 2015), whereas the Ohio DOT assembled two WW signs on the same post (Ohio DOT, 2016).

Except for those common features appearing in the state guidelines, other features such as sign angles, dynamic signs, or additional signs were also mentioned by several states.

Pavement Markings

- *Pavement marking extension line:* Six out of 11 state DOTs were encouraged to apply pavement marking extension lines between ramps and crossroads to guide drivers in the right direction. However, there are no uniform requirements on the line type, the number of lines, or applied conditions among the six states. For example, the FDOT required two (2) or four (4) dotted guidelines striping at the intersections between exit ramp and crossroad (FDOT, 2015; FDOT, 2019b). However, in Connecticut, the extension line only applied at the signalized intersections with adjacent on and exit ramps (Athey Creek Consultants, 2016).
- *Lane use arrows:* Several states applied the lane use arrows on the ramps. However, different states had different requirements for lane use arrows.
- *Route shield signs:* Except for those common features that appeared in the state guidelines, other features such as route shield signs and stop bars were also recommended by several states. However, there is no guideline on the application of route shield signs.

Literature review results suggest that 11 states had their own guidelines on deterring WWD.

2.5 Gaps in previous research

The results provided by previous research and guidelines identified various contributing factors, countermeasures, and geometric design elements that may affect WWD. However, most of these results are based on WWD crash data, 911 calls, or police reports. Considering that the confirmed initial WW entry points are usually not available for these types of data, most of the studies made assumptions or estimations while conducting the research. While conducting the evaluations for WW-related countermeasures, past studies mainly relied on survey, or using few amounts of WWD incidents recorded by cameras or ITS at specific locations. To fill this gap, in this study, the WWD incidents data collected at certain parclo interchange terminals was utilized to identify road design features related to WWD incidents, evaluating the effectiveness of low-cost countermeasures and providing practical guidance.

Chapter 3 Methodology

In this chapter, the methodologies adopted in this study were discussed. The first section described the collection of WWD incident data at study locations; the second section introduced the geometric design features and usage of TCDs collected at each location; and the third and fourth section introduced three types of machine learning techniques applied in this study.

3.1 WWD incident data collection based on the field monitoring

The purpose of collecting WWD incident data by monitoring the parclo interchange terminals is to get certain and reliable WW entry information for further analysis. As shown in **Figure 3.1**, the portable road monitoring camera (ConutCam2) was mounted on the pole of the traffic sign on the roadside near the study location, where the camera could monitor the entire ramp terminal. The red point represents the position of the portable traffic camera, and the shaded-red region represents the monitoring zone.

Figure 3.1 Monitoring the entire interchange terminal using a portable camera

The cameras can record videos with a quality of 480p for up to 72 hours per charge. The monitoring was performed on either weekdays (Monday–Friday) or weekends (Friday–Sunday) without any severe weather (i.e., heavy rain). For each location, a 50- to 72-hour video was recorded based on the camera's ability. Then, researchers manually reviewed the videos to observe and record WWD incidents. In this study, a total of 5,984 hours of videos at 75 parclo interchanges in 13 different states were recorded for capturing WWD incidents, as shown in **Table 3.1**.

Table 3.1 Summary of WWD video data collection

State	Number of Locations	Duration (hr.)
Alabama	11	1,868
Arkansas	9	576
Tennessee	9	550
California	8	484
Connecticut	7	404
Virginia	5	300
Georgia	4	338
North Carolina	4	250
New Jersey	8	576
Florida	3	192
Mississippi	3	172
Texas	2	144
South Carolina	2	130
Total	**75**	**5,984**

A total of 410 WWD incidents were found based on video review. Regarding the monitoring results for each location, these parclo interchange terminals were divided into two categories: 1) 28 locations with at least one WWD incident found within 48 hours were considered as locations with a high risk of WWD; these locations were assumed to have recurring WWD incidents; 2) The remaining 47 locations with no WWD incident found within the monitoring period were considered as low-risk locations for WWD; these locations were assumed to have rare/random WWD incident.

As most WWD incidents can be self-corrected or stopped by WW-related countermeasures before entering the freeway, each case of WWD incident was reviewed in detail to measure the WWD distance and reaction time. These factors can serve as evidence when evaluating the effectiveness of low-cost countermeasures. In this study, the WWD distance was measured from the end of the off-ramp to the position where the WW vehicle finally stopped. As shown in **Figure 3.2**, the blue vehicle entered the off-ramp by making a WW left-turn and stopped at the middle of the off-ramp; the stopping position will be identified accordingly by researchers using Google Map satellite views. Then the distance between the stopping position to the end of the off-ramp will be measured as WWD distance for this case. Similarly, the reaction time was measured between the moment that driver started traveling on the WW (passed the double yellow lines) until the driver hit the brake (the brake lights were on) by using the stopwatch.

Figure 3.2 Example of measuring WWD distance and reaction time

3.2 Geometric design and usage of TCDs for study locations

The geometric design features and TCDs at the study locations were collected/measured using Google Maps aerial and street view function, and the collected features were also verified while installing the camera in the field in case any improvements had been made. Based on past studies and guidelines, the road design features which may contribute to the generation of WWD at parclo interchange terminals were first collected. In addition, other geometric features and TCDs describing the condition of the terminal were also collected for modeling, as these features may also affect the probability of a WWD.

A total of twenty design features were collected for each location based on five aspects: (1) crossroad design; (2) off-ramp design; (3) intersection design; (4) traffic sign information; and (5) pavement marking information. Based on that information, the real condition for a specific parclo interchange terminal can be well-described, and a sketch map can be drawn. **Figure 3.3** illustrates all the design features that have been collected accordingly, except for features 11, 14, 15, 16, 17, 18, and 20 (which could not be represented by the figure). A descriptive summary of the collected data is presented in **Table 3.2**; a brief description for each feature is provided as follows:

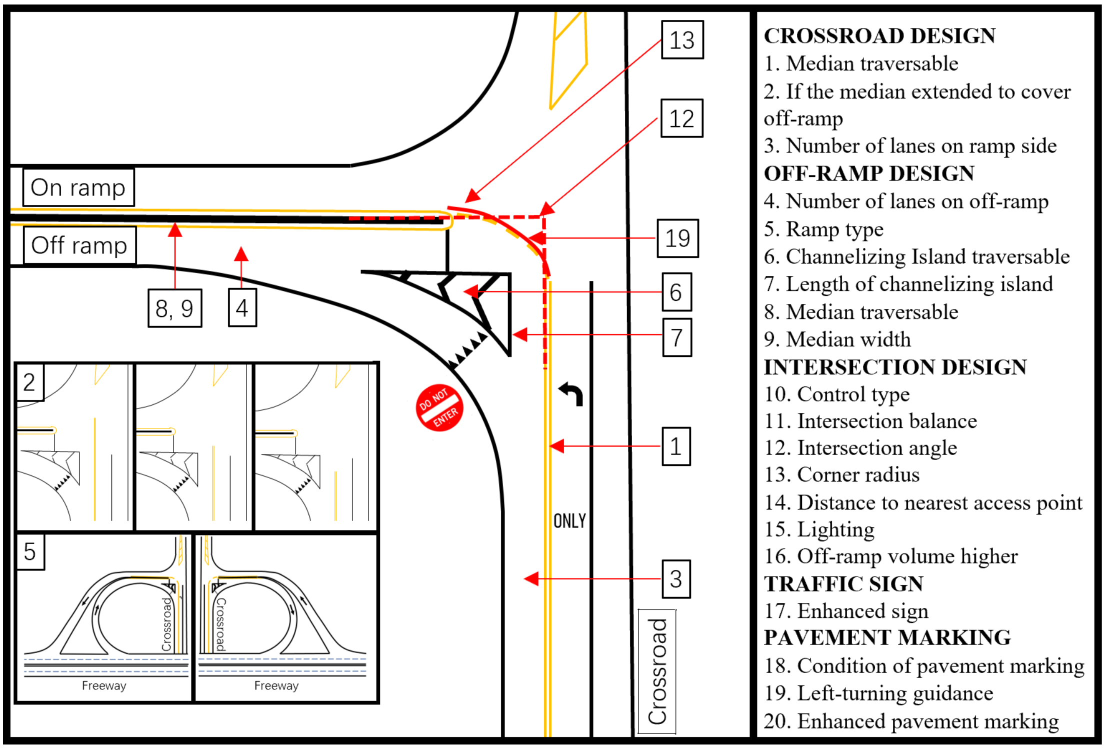

Figure 3.3 Design features collected for study locations

Crossroad Design

1. Median traversable: If a vehicle can pass through the median on the crossroad (e.g., double yellow lines or concrete barrier). The non-traversable median can effectively block the WW entry caused by early left turns (AASHTO, 2011).
2. If the median is extended to cover the off-ramp: As shown in **Figure 3.3(2)**, if the median on the crossroad has fully/half/not covered the off-ramp opening.
3. The number of lanes on the ramp side: For a two-direction crossroad, how many driveways exist on the ramp side?

Off-ramp Design

4. The number of lanes on the off-ramp: How many lanes exist on the off-ramp?

5. Ramp type: As shown in **Figure 3.3(5)**, the on- and off-ramp for a parclo interchange terminal can be located at the left or right side of the crossroad; as a result, the off-ramp is going to be looped or curved. The looped off-ramp may generate confusion for left-turning drivers from the crossroad because it is oriented in the same direction where the driver is planning to go. Suppose that one driver coming from the south is planning to enter the westbound lanes of the freeway. If the off-ramp is located at the west side of the crossroad, a driver needs to make a left turn. Note that the westbound on-ramp of the most popular diamond interchange terminal is always located at the left side of the crossroad when a driver is coming from the south. In this situation, a driver will notice the off-ramp of the parclo interchange terminal first. If a driver does not realize it is an off-ramp, he/she will probably take the off-ramp as an on-ramp of the diamond interchange.
6. Is channelizing island traversable: Is the channelizing island painted or raised? A raised channelizing island could help narrow the opening of the off-ramp to prevent WW entries (Zhou and Pour-Rouholamin, 2014; WSDOT, 2013).
7. Length of channelizing island: Measuring how long the edge of the channelizing island is parallel with the crossroad; this length influences the angle between the exclusive right-turn lane and the crossroad. The longer the edge is, the smaller the angle between the off-ramp right-turn lane and the crossroad.
8. Median traversable: Can a vehicle can pass through the median on the ramp (e.g., double yellow lines or concrete barrier)? The guideline for WWD prevention developed by the Illinois Department of Transportation (IDOT) suggested that a raised median on the ramp with a minimum width of 50 ft. could help reduce WWD entries (IDOT, 2010).
9. Median width: Measuring how wide the median is on the ramp.

Intersection Design

10. Control type: Is the intersection controlled or not? (Signalized, all-way stop controlled would be considered as controlled, other than that would be uncontrolled).
11. Intersection balance: Measuring the ratio between the distance from the stop bar of the left-turn lane on the crossroad to the centerline of the median between the ramps and the entire length of the intersection. Past studies have recommended that intersection balance should not exceed 60% to prevent WWD entries (Wang and Zhou, 2018).
12. Intersection angle: Measuring the angle between the centerline of the ramp and the centerline of the crossroad.
13. Corner radius: Measuring the design turning radius from the left-turn lane on the crossroad to the on-ramp. The IDOT manual suggests a maximum of 80 ft. (IDOT, 2010).
14. Distance to the nearest access point: the distance from the nearest access point to the terminal; previous studies suggested that the existence of a nearby access point is likely to cause WW entries. Past studies have shown that the existence of an access point within 600 ft. of the ramp terminal may increase the risk of WW entries (Zhou, et al., 2008).
15. Lighting: If streetlights are nearby.
16. Off-ramp volume higher: Does the off-ramp have higher traffic volume than the on-ramp? Past studies have shown that the higher occupancy of the off-ramp could decrease the number of potential WWD incidents (Atiquzzaman and Zhou, 2020; Baratian-Ghorghi et al., 2015).

Traffic sign

17. Enhanced sign: if low-mounted, enlarged WW-related sign, retroreflective tape on the sign pole, or extra guidance sign exists. Having none will be recorded as level 0, one or two of them as level 1, and three or four of them as level 2.

Pavement marking

18. Condition of pavement marking: Are pavement markings well maintained (good condition) or faded (bad condition)?
19. Left-turning guidance: Do left-turn skip strips to guide the left-turning vehicle from the crossroad to the on-ramp exist?
20. Enhanced pavement marking: Are there enhancements of pavement markings at the terminal deterring WWD (e.g., directional rumble strips, raised pavement markers, or bolder pavement markings)?

Table 3.2 Summary of Variables and Categories

<table>
<tr><th rowspan="2"></th><th rowspan="2">Features
(Coding name)</th><th rowspan="2">Categories
(Coding name)</th><th colspan="2">All Locations (75)</th><th colspan="2">Nonrecurring Locations (47)</th><th colspan="2">Recurring Locations (28)</th></tr>
<tr><th>Count</th><th>Percent</th><th>Count</th><th>Percent</th><th>Count</th><th>Percent</th></tr>
<tr><td rowspan="8">Crossroad Design</td><td rowspan="2">Median Traversable (CRMediantran)</td><td>Non-traversable (0)</td><td>14</td><td>19%</td><td>10</td><td>21%</td><td>4</td><td>14%</td></tr>
<tr><td>Traversable (1)</td><td>61</td><td>81%</td><td>37</td><td>79%</td><td>24</td><td>86%</td></tr>
<tr><td rowspan="3">If the median extended to cover off ramp (CRmedianext)</td><td>Half Covered (0)</td><td>26</td><td>35%</td><td>17</td><td>36%</td><td>9</td><td>32%</td></tr>
<tr><td>Fully covered (1)</td><td>22</td><td>29%</td><td>21</td><td>45%</td><td>1</td><td>4%</td></tr>
<tr><td>Not covered (2)</td><td>27</td><td>36%</td><td>9</td><td>19%</td><td>18</td><td>64%</td></tr>
<tr><td rowspan="3">Number of lanes on ramp side (CRlaneonrampside)</td><td>1 (1)</td><td>48</td><td>64%</td><td>27</td><td>57%</td><td>21</td><td>75%</td></tr>
<tr><td>2 (2)</td><td>20</td><td>27%</td><td>16</td><td>34%</td><td>4</td><td>14%</td></tr>
<tr><td>3 or more (3)</td><td>7</td><td>9%</td><td>4</td><td>9%</td><td>3</td><td>11%</td></tr>
<tr><td rowspan="10">Off-ramp Design</td><td rowspan="3">Number of lanes on the off-ramp (ERnumlane)</td><td>1 (1)</td><td>60</td><td>80%</td><td>37</td><td>79%</td><td>23</td><td>82%</td></tr>
<tr><td>2 (2)</td><td>6</td><td>8%</td><td>4</td><td>9%</td><td>2</td><td>7%</td></tr>
<tr><td>3 or more (3)</td><td>9</td><td>12%</td><td>6</td><td>13%</td><td>3</td><td>11%</td></tr>
<tr><td rowspan="2">Ramp looped? (ERLooped)</td><td>No (0)</td><td>30</td><td>40%</td><td>21</td><td>45%</td><td>9</td><td>32%</td></tr>
<tr><td>Yes (1)</td><td>45</td><td>60%</td><td>26</td><td>55%</td><td>19</td><td>68%</td></tr>
<tr><td rowspan="3">Channelizing island traversable (ERChantran)</td><td>No (0)</td><td>32</td><td>43%</td><td>19</td><td>40%</td><td>13</td><td>46%</td></tr>
<tr><td>Yes (1)</td><td>13</td><td>17%</td><td>9</td><td>19%</td><td>4</td><td>14%</td></tr>
<tr><td>None (2)</td><td>30</td><td>40%</td><td>19</td><td>40%</td><td>11</td><td>39%</td></tr>
<tr><td rowspan="2">Length of channelizing island</td><td>None (0)</td><td>30</td><td>40%</td><td>19</td><td>40%</td><td>11</td><td>39%</td></tr>
<tr><td>Less than 50 ft. (1)</td><td>17</td><td>23%</td><td>7</td><td>15%</td><td>10</td><td>36%</td></tr>
</table>

	(ERChanLen)	51–100 ft. (2)	19	25%	13	28%	6	21%
		More than 100 ft. (3)	9	12%	8	17%	1	4%
	Median traversable (ERMEDTran)	No (0)	64	85%	39	83%	25	89%
		Yes (1)	11	15%	8	17%	3	11%
	Median width (ERmedwid)	0-30 (0)	56	75%	39	83%	17	61%
		31–60 (1)	13	17%	7	15%	6	21%
		Larger than 60 (2)	6	8%	1	2%	5	18%
Intersection Design	Control type (INType)	Uncontrolled (0)	50	67%	30	64%	20	71%
		Controlled (1)	25	33%	17	36%	8	29%
	Intersection balance (INIB)	Less than 40% (0)	22	29%	16	34%	6	21%
		40–60% (1)	47	63%	28	60%	19	68%
		Larger than 60% (2)	6	8%	3	6%	3	11%
	Intersection angle (INANGLE)	Right (0)	62	83%	38	81%	24	86%
		Obtuse (1)	7	9%	6	13%	1	4%
		Acute (2	6	8%	3	6%	3	11%
	Corner radius (INRAD)	Less than 50 ft. (0)	39	52%	23	49%	16	57%
		51–100 ft (1)	31	41%	19	40%	12	43%
		Lager than 100 ft. (2)	5	7%	5	11%	0	0%
	Distance to nearest access point (NEARDIS)	0–50 ft. (0)	24	32%	11	23%	13	46%
		51–500 ft. (1)	39	52%	26	55%	13	46%
		More than 500 ft. (2)	12	16%	10	21%	2	7%
	Lighting (NEARLIG)	No (0)	33	44%	17	36%	16	57%
		Yes (1)	42	56%	30	64%	12	43%
	Off-ramp volume higher than on-ramp (Ratio)	No (0)	56	75%	31	66%	25	89%
		Yes (1)	19	25%	16	34%	3	11%
Sign	Enhanced sign (SignEnhanced)	Level 0 (0)	23	31%	9	19%	14	50%
		Level 1 (1)	29	39%	17	36%	12	43%
		Level 2 (2)	23	31%	21	45%	2	7%
Pavement Marking	Pavement Condition (PAVCOND)	Not good (0)	5	7%	1	2%	4	14%
		Good (1)	70	93%	46	98%	24	86%
	Left-turn guidance (PAVLEFT)	No (0)	56	75%	37	79%	19	68%
		Yes (1)	19	25%	10	21%	9	32%
	Enhanced (PAVENHANCE)	No (0)	67	89%	40	85%	27	96%
		Yes (1)	8	11%	7	15%	1	4%

3.3 Identify the characteristics of parclo interchange terminals with a high risk of WWD

In order to address WWD issues, producing meaningful inferences from WWD crash/incident data could help developing efficient highway design guidance. However, regarding the rareness and randomness of WWD, it is difficult for researchers to measure the impact of a single design element with a lack of WWD crash/incident data by using classic statistical methods.

Since the data adopted in this study contains 20 design features for each study site, the complexity and heterogeneity would require a larger number of samples in order to develop reliable conclusions by adopting classic statistical methods. In order to deal with the high dimension features for each study site, machine learning techniques could be a more flexible and powerful tool to help generating meaningful inferences. During recent years, machine learning techniques have been widely incorporated for classification purposes (Li, et al., 2017; Taccari et al., 2018; Dogru et al., 2018, Hassan et al., 2013), which allows researchers to conduct risk evaluation based on specific design features. This method provided more opportunities for researchers and designers to investigate the highway design practice regarding the high dimension and/or lack of data.

In this study, the multiple correspondence analysis (MCA) method was first applied to explore the characteristics of the locations with recurring WWD incidents. The MCA is a dimension-reduction method that aims to plot all variable categories onto low dimension space. Each individual or variable category is regarded as a point; more similarity between two individuals or variable categories, less distance between two points. Although the MCA method was not frequently applied in the transportation field previously, increasing importance has been attached to the MCA method in recent studies, especially to identify the contributing factors for a certain type of crash. Das et al. performed MCA on five years of WWD crash data in Louisiana to examine the key association between the contributing factors (Das et al., 2018). A study conducted by Baireddy et al. analyzed pedestrian crashes within rural areas in Illinois using the MCA method (Baireddy et al., 2018). Jalayer et al. analyzed WWD crashes in Alabama and Illinois by deploying the MCA method and identified contributing factors for such crashes (Jalayer et al., 2018). In another study conducted by Das et al., the MCA method was applied to eight-years of fatal run-off-road crashes in Louisiana to determine the interaction between risk factors (Das and Sun, 2016).

Xu et al. performed MCA to identify the degree of association between key crash-prone factors for pedestrian crashes in Las Vegas (Xu et al., 2015). Das and Sun collected eight years of pedestrian crashes in Louisiana and performed an MCA analysis to identify the contributing factors to such crashes (Das and Sun, 2015). Similarly, to explore the key factors for the maritime crash, Chauvin et al. performed the MCA and found that most of the crashes happened due to decision errors (Chauvin et al., 2007). To identify the characteristics of the pedestrian-involved crashes in Hawaii, Kim and Yamashita deployed MCA in their study (Kim and Yamashita, 2007). Mabunda et al. also used the MCA method to determine the correlation between pedestrian fatalities and temporal factors (Mabunda et al., 2008).

In this part, the basic principle of the MCA method was summarized based on the reviewed literature (Das et al., 2018; Baireddy et al., 2018; Jalayer et al., 2018). More detailed concepts and computations of MCA could be found in some statistical books and studies (Roux and Rouanet, 2010; Husson et al., 2017).

The MCA calculation is conducted on the matrix, which is derived from the original data set. Typically, the most classical and standard matrix that is widely applied in the MCA studies is the indicator matrix. The indicator matrix, denoted as Z, corresponds to a binary coding of the factors. Instead of using a variable that contains several categories within one column, the indicator matrix will expand this one variable into several columns containing binary values, and each column represents one category within this variable. As an example shown in **Figure 3.4**, the "Types of Channelizing Island" is a variable with three categories documented within a column in the original dataset. To transform it into the indicator matrix, information on "Types of Channelizing Island" is conveyed in three columns, one representing each category. Only one column that satisfies a certain crash condition is coded as “1”. Additionally, other columns will be coded as “0”.

Original Dataset

Individuals	Types of Channelizing Island
Crash 1	Non-traversable
Crash 2	None
Crash 3	None
Crash 4	Traversable
Crash 5	Non-traversable

Indicator Matrix

Individuals	Types of Channelizing Island		
	None	Non-Traversable	Traversable
Crash 1	0	1	0
Crash 2	1	0	0
Crash 3	1	0	0
Crash 4	0	0	1
Crash 5	0	1	0

Figure 3.4 Creation of the indicator matrix from the original dataset

The same procedures shown above are repeated for each variable within the original dataset. After that, the indicator matrix could be created. Suppose I is a set of individuals, and Q is a set of variables that can generate an I×Q original dataset. For each variable q, it contains K_q of categories. Let K denotes an overall collection of categories, then the total number of categories in the indicator matric would be $K = \sum_{q=1}^{1} K_q$.

After the creation of the indicator matrix, the MCA can be performed. Typically, the results of MCA yield two clouds of points: the points of individuals and the cloud of categories. The cloud of individuals is computed based on the distance between individuals. Suppose the number of individuals in the dataset is n, and n_k represents the number of individuals who have chosen category k. As a result, the relative frequency of individuals who have chosen this category is $f_k = n_k/n$. Considering that there are two different individuals, i and i’, who choose the category k and k’, respectively, within the variable q, then the squared distance between two individuals due to the variable q can be calculated by **Equation 3-1**:

$$d_q^2\,(i, i') = \frac{1}{f_k} + \frac{1}{f_{k'}} \qquad (3-1)$$

Since there are Q variables contained in the dataset, then the overall squared distance between two individuals is derived by **Equation 3-2**:

$$d^2(i,i') = \frac{1}{Q}\sum_{q\in Q} d_q^2(i,i') \qquad (3-2)$$

The cloud of individuals consisting of n points is determined by the set of all distance individuals. Let G denote the mean point of the cloud and Mi is the point denoting individual record I, the squared distance from point Mi to point G is calculated by **Equation 3-3**:

$$(GM^i)^2 = (\frac{1}{Q}\sum_{k\in K_i}\frac{1}{f_k}) - 1 \qquad (3-3)$$

Where K_i is the category pattern for Q variables of individual i. Similarly, the cloud of categories is a weighted cloud of the category points. Suppose that the sum of the weights of category points for each variable is n, for each category point denoted as Mk, will have weight n_k. That means the number of individuals selected by category k. For two category points represented by M^k and $M^{k'}$, respectively, $n_{kk'}$ is denoted as the number of individuals who have chosen both category k and k'. Then **Equation 3-4** indicated the squared distance between two category points:

$$(M^k M^{k'})^2 = \frac{n_k + n_{k'} - 2n_{kk'}}{n_k n_{k'}/n} \qquad (3-4)$$

3.4 Modeling the risk of WWD incidents at parclo interchange terminal

Here, different types of parclo interchange terminals were studied as a classification problem and tried to explore what kind of design features may lead to recurring WWD incidents. The classes in this study were two types of parclo interchange terminals, having recurring WWD incidents and nonrecurring WWD incidents. Different from conventional statistical methodologies, two state-of-art machine learning techniques under supervised learning, i.e., extreme gradient boosting (XGBoost) and logistic regression with least absolute shrinkage and selection operator (Lasso-logistic regression) were applied. XGBoost is one of the most popular tree-based ensemble methods that give accurate results (Volkovs, et al., 2017; Sandulescu, et al., 2010). It can handle small data sets and control the overfitting by tuning a series of parameters. Logistic regression with Lasso can perform both variable selection and regularization, which improves the classification accuracy and interpretability of the model. Compared with logistic regression, the Lasso-logistic regression can produce more accurate and explanatory results regarding our question. The main reason for picking Lasso-logistic regression is for comparison with XGBoost. Furthermore, the XGBoost model consisted of a large number of sequential boosting trees, and it is difficult to visualize the effect of each variable for XGBoost method. While Lasso-logistic regression can generate analytical expressions of the final model, which can be more applicable for engineers to conduct field evaluation. In this study, *RStudio version 3.05* was applied to conduct Lasso-logistic regression and XGBoost studies with R packages "*glmnet*" and "*xgboost*," respectively (Friedman et al., 2010; Chen, et al., 2021). The concept for each method is subsequently introduced as follows.

3.4.1 eXtreme Gradient Boosting

XGBoost can handle regression and classification problems; it produces a prediction model as an ensemble of weak prediction models, typically decision trees. It then builds the model in a stage-wise fashion as other boosting methods do, and it generalizes them by allowing optimization of an arbitrary differentiable loss function. XGBoost is one of the implementations of the gradient boosting concept, but what makes XGBoost unique is that it applies regularized boosting, which controls over-fitting problems and gives better performance. More detailed interpretation and derivation can be found in (Chen and Guestrin, 2016; Yang et al., 2021; Parsa et al., 2020).

For a data set with n samples, each variable x_i contains m features where $x_i \in \mathbb{R}^m$. Each sample will have a corresponding dependent variable y_i representing the classification. Then, the tree ensemble model predicts the output using K additives function, as shown in **Equation 3-5**:

$$\hat{y}_i = \phi(x_i) = \sum_{k=1}^{K} f_k(x_i), \qquad f_k \in \mathcal{F}, \qquad (3-5)$$

where $\mathcal{F}$ is the space of regression trees, and $\mathcal{F} = \{f(x) = w_{q(x)}\}(q: \mathbb{R}^m \to T, w \in \mathbb{R}^T)$. Here, q is the structure of each tree and T is the number of leaves in the tree. Each f_k corresponds to an independent tree structure q and leaf weights w. To learn the set of functions used in the model, the following regularized objective **Equation 3-6** should be minimized:

$$\mathcal{L}(\phi) = \sum_i l(\hat{y}_i, y_i) + \sum_k \Omega(f_k), \qquad (3-6)$$

where the difference between the prediction ($\hat{y}_i$) value and the target value (y_i) can be measured by the differentiable convex loss function l. The second term Ω is used to penalize the complexity of the model, and

$$\Omega(f) = \gamma T + \frac{1}{2}\lambda \|w\|^2. \qquad (3-7)$$

The tree ensemble model in **Equation 3-7** is trained in an additive manner. After applying the second-order approximation and removing the constant terms, the simplified equation at step t can be obtained as:

$$\tilde{\mathcal{L}}^{(t)} = \sum_{i=1}^{n} [g_i f_t(x_i) + \frac{1}{2} h_i f_t^2(x_i)] + \Omega(f_t). \qquad (3-8)$$

By solving **Equation 3-8**, the optimal weight w_j^* of leaf j and the corresponding optimal value can be obtained as

$$w_j^* = -\frac{\sum_{i \epsilon I_j} g_i}{\sum_{i \epsilon I_j} h_i + \lambda}, \qquad (3-9)$$

$$\tilde{\mathcal{L}}^{(t)}(q) = -\frac{1}{2}\sum_{j=1}^{T} \frac{\left(\sum_{i \epsilon I_j} g_i\right)^2}{\sum_{i \epsilon I_j} h_i + \lambda} + \gamma T. \qquad (3-10)$$

In reality, it is difficult to calculate all the possible tree structures q via **Equation 3-10.** Instead, another algorithm, which begins with a single leaf and adds branches to the trees interactively, is applied. Suppose I_L is the instance sets of the left nodes after the split and I_R is the instance sets of the right nodes after the split. When $I = I_L \cup I_R$, the final equation can be represented as

$$\mathcal{L}_{split} = \frac{1}{2}\left[\frac{\left(\sum_{i \epsilon I_L} g_i\right)^2}{\sum_{i \epsilon I_L} h_i + \lambda} + \frac{\left(\sum_{i \epsilon I_R} g_i\right)^2}{\sum_{i \epsilon I_R} h_i + \lambda} - \frac{\left(\sum_{i \epsilon I} g_i\right)^2}{\sum_{i \epsilon I} h_i + \lambda}\right] - \gamma. \quad (3-11)$$

The results of XGBoost consisted of a large number of decision trees, which made the results nearly impossible to properly present. In this study, the Shapley Explanation package in R was used to represent the final results of XGBoost by calculating the SHAP value (Lee and Lundberg, 2016; Yang and Just, 2021). The SHAP value is a powerful index helping users to visualize the complex results generated by tree-based models such as XGBoost. By calculating SHAP value, the effects of each design feature over different trees were considered and the total contributions to the final prediction can be identified. For detailed interpretation and derivation, please refer to the previous study conducted by Lundberg et al. (Lundberg et al., 2019).

3.4.2 Lasso-logistic Regression

The Lasso-logistic regression is a penalized regression model that adds a penalty term to the logistic model in order to find the subset of features that optimize the model performance. Different from ridge regression, Lasso regression forces the coefficients of less contributed variables to be zero and only keeps the most important variables in the final model, which is easier to interpret and gives higher prediction accuracy. In our case, whether a parclo interchange terminal will have recurring WWD incidents is a binary dependent variable, which can be represented by 0 and 1. Due to the fact that multiple indicators are likely to be correlated with each other, the redundant variables need to be eliminated. The characteristics of the Lasso model can perfectly handle this issue, so the Lasso-logistic model was constructed. Suppose the WWD location data (x_i, y_i), where x_i are specific design features and y_i are class labels for recurring WWD location and 0 for nonrecurring WWD location). The logistic regression computes the probability of y = 1 by the linear function of x:

$$log\frac{P(y=1|\,x\,)}{P(y=0|\,x)} = \beta_0 + x^T\beta. \qquad (3-12)$$

where β_0 represents the intercept and β represents the corresponding coefficients for each design feature. By extending logistic regression into Lasso-logistic regression, the parameter estimation for Lasso-logistic regression can be represented as

$$\sum_{i=1}^{n}\left(y_i - \beta_0 - \sum_{j=1}^{p}\beta_j x_{ij}\right)^2 + \lambda\sum_{j=1}^{p}|\beta_j| = RSS + \lambda\sum_{j=1}^{p}|\beta_j|, \quad (3-13)$$

where λ directly controls the penalty term and has an impact on the feature selection. By increasing the value of λ, the less contributed coefficients β_j will shrink to zero. In this study, the fivefold cross-validation was used to estimate the λ to achieve the least error. Specifically, the data were first separated into *n* parts, (*n-1*) parts were used to fit the model, and the rest one part was used for the validation.

Chapter 4 Data Analysis and Results

In this chapter, the effectiveness of WW signs and WW arrows on deterring WWD incidents were first investigated based on analyzing the WWD behaviors; the second section explored the geometric design differences that may cause different types of WWD behaviors; the third section applied MCA method to explore the characteristics of parclo interchange terminals that may cause/deter WWD incidents; the fourth section applied XGBoost and Lasso-logistic regression to quantify the effects of each design feature on WWD incidents and conduct prediction of recurring WWD incidents at specific sites.

4.1 Effectiveness of WW sign and WW arrows regarding WWD incident

4.1.1 Descriptive statistics

Among 28 monitored parclo interchange terminals with WWD incidents been captured, nine of them from six states with more than five recorded WWD incidents were first used to evaluate the effectiveness of traditional wrong-way countermeasures. **Table 4.1** lists the number of WWD incidents recorded, types of wrong-way countermeasures, and their position (the distance to the end of the off-ramp) at each location. Where "A" represents "wrong-way Arrow," "S" represents a single "wrong-way sign," and "SS" represents a two-side "wrong-way sign."

Table 4.1 Number of WWD incidents and wrong-way-related TCDs and their placements

State	Location	#WWD Incidents	Implemented wrong-way-related Countermeasures							
			Dis. (ft)	Type	Dis. (ft)	Type	Dis. (ft)	Type	Dis. (ft)	Type
AL	I-65 Exit 284 SB	70	100	A+S	200	S	400	A+SS	-	-
AL	I-65 Exit 208 SB	59	50	A	250	SS	-	-	-	-
GA	I-85 Exit 147 SB	134	400	SS	-	-	-	-	-	-
GA	I-75 Exit 61 SB	18	150	A+S	240	A+S	400	A+S	450	SS
AR	I-40 Exit 55 EB	15	150	A	200	S	440	S	-	-

TN	I-65 Exit 37 NB	11	50	A	120	A	170	SS	-	-
SC	I-85 Exit 106 EB	9	200	SS	-	-	-	-	-	-
NC	I-77 Exit 79 SB	26	50	A	90	A	180	SS	-	-
NC	Hwy 421 Exit 234C WB	14	150	SS	-	-	-	-	-	-

A total of 356 WWD incidents were analyzed at these locations to record the WWD distance and the reaction time used by wrong-way drivers to realize they are driving the WW. The return rates before each TCD were estimated to evaluate their effectiveness in deterring WWD. **Table 4.2** lists the return rate, average WWD distance, and reaction time at each location. It was found that the average reaction time of the WW drivers is 5.1 seconds; the average WWD distance is about 38 ft.; 91% of WW drivers self-corrected themselves with the help of traditional WW signs and arrows; 9% never turned around. The results show that WW-related TCDs can stop most WW drivers before entering the freeway. There are three locations where more than 10% of WW drivers never turned around, while two of them only have one pair of WW signs, which indicates the locations with fewer TCDs tended to have a larger percentage of WW drivers never coming back.

Table 4.2 Effectiveness of traditional WW signs and WW arrows

State	Location	Avg. Reaction Time	Avg. WWD Dis.	Effectiveness of WW-related Countermeasures								
				1st	Return Rate	2nd	Return Rate	3rd	Return Rate	4th	Return Rate	Never Return
AL	I-65 Exit 284 SB	5.3	47	100	74%	200	17%	400	3%	-	-	6%
AL	I-65 Exit 208 SB	5.1	41	50	86%	250	12%	-	-	-	-	2%
GA	I-85 Exit 147 SB	7.6	211	400	100%	-	-	-	-	-	-	0%
GA	I-75 Exit 61 SB	4.3	92	150	89%	240	0%	400	11%	450	0%	0%
AR	I-40 Exit 55 EB	5.2	93	150	73%	200	7%	440	0%	-	-	20%
TN	I-65 Exit 37 NB	3.5	69	50	55%	120	27%	170	9%	-	-	9%
SC	I-85 Exit 106 EB	9.4	163	200	67%	-	-	-	-	-	-	33%
NC	I-77 Exit 79 SB	1.6	24	50	92%	90	8%	180	0%	-	-	0%
NC	Hwy 421 Exit 234C WB	3.7	38	150	86%	-	-	-	-	-	-	14%
Average		5.1	38	144	80%	183	12%	318	5%	450	0%	9%

The return rates for each countermeasure at different locations are plotted in **Figure 4.1**. It suggests that the first set of WW sign(s) or WW arrow(s) on the off-ramp could have the potential to stop most WWD incidents (55%-100%); furthermore, the supplemental WW sign and arrows stopped 7%-36% of WWD incidents.

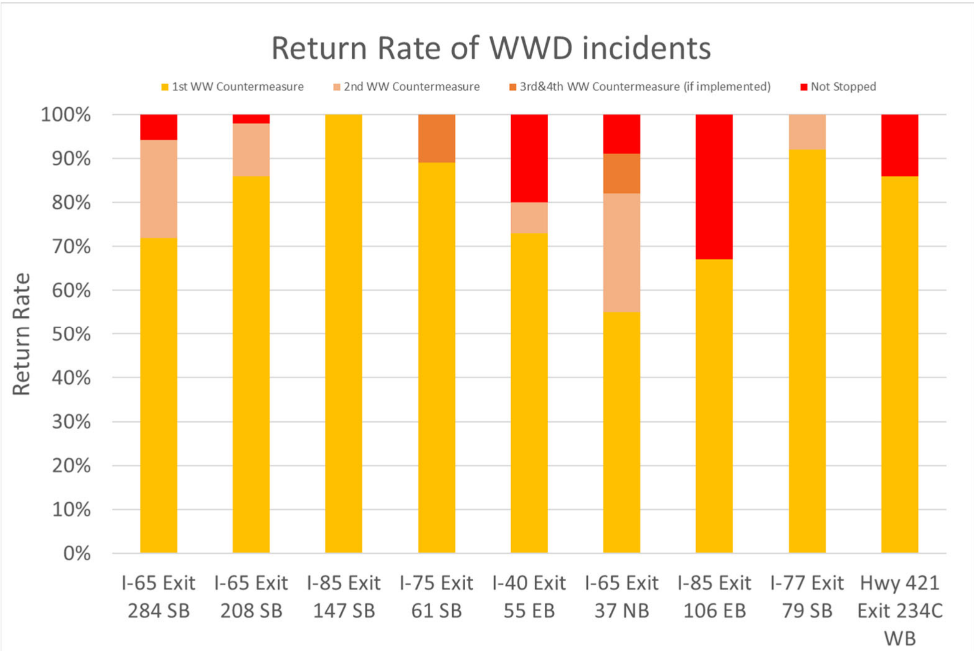

Figure 4.1 Return rate of WWD incidents at each location

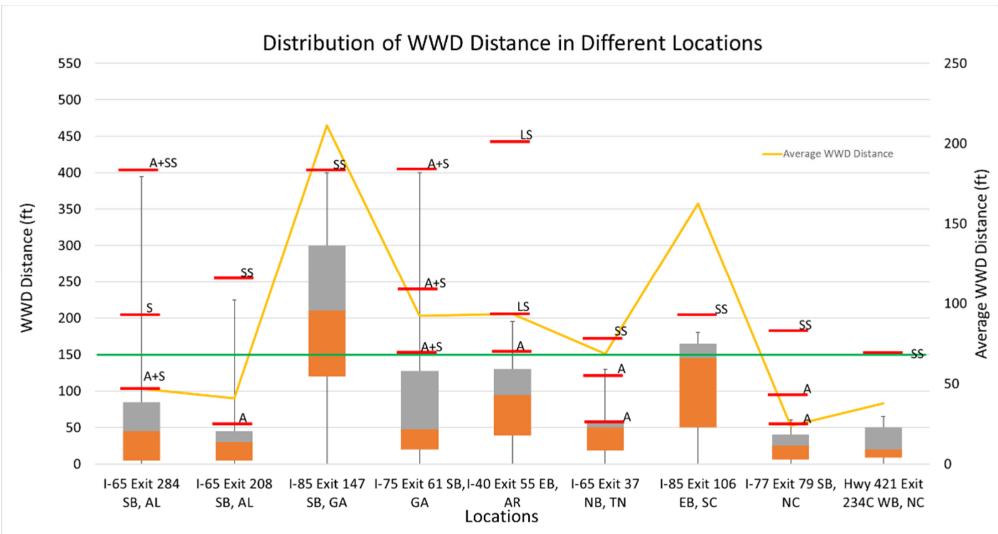

Figure 4.2 Distribution of WWD distance and placement of TCDs

The distribution of WWD distance at each location was plotted in **Figure 4.2**, where the red segments represent what kind of wrong-way-related countermeasures and where are they located (distance to the end of the off-ramp), and the yellow line represents the average WWD distance at each location, and each box plot described the distribution of WWD distance at each location. Based on the graph, there are two locations having much higher average WWD distance (I-85, Exit 147 SB, GA, and I-85 Exit 106 EB, SC) where they only have one set of WW-related countermeasures implemented, located farther than 200 ft. from the end of the off-ramp. Based on such results, the study assumed that the average WWD distance increases as the placement of wrong-way-related TCD is farther from the stop bar on the off-ramp; and decreases as more supplemental wrong-way signs are implemented on the off-ramps. Statistical tests were then designed to validate the assumption in the next section.

4.1.2 Statistical tests for the effect of WW-related TCDs

A total of 410 WWD incidents at all 28 parclo interchange terminals were used to conduct the statistical tests to evaluate the effectiveness of traditional TCDs. Some of the interchange terminals in the previous part were not included due to the low amount of WWD incidents collected at those locations, which could not draw reliable results by analyzing them separately. According to the assumptions made in the previous chapter, in this section, all the WWD incidents at 28 locations would be used and grouped based on two categories: (1) whether the first set of wrong-way signs/arrows was placed within 100 ft. from the end of the off-ramp. (2) whether there is more than one set of wrong-way signs/arrows placed on the whole off-ramp.

As shown in **Table 4.3,** the left column lists the 12 locations that have the first set of WW signs/arrows located less than 100 ft from the end of the off-ramp, and the right column lists the

16 locations that have the first set of WW sign/arrow located farther than 100 ft. The average WWD distance at each location is represented below the location name, followed by the total number of WWD incidents. The nature of the application of WW signs and WW arrows (types and their placements) at each location are listed under the "Countermeasure" and "Distance" columns.

For example, at I-65 Exit 284 SB in Alabama, the average WWD distance is calculated as 82 ft based on 77 WWD incidents. At this location, there are two sets of countermeasures: the first one includes a single WW arrow and a single WW sign located approximately 100 ft from the end of the off-ramp. The second set includes a single WW sign located 200 ft. from the end of the off-ramp.

Table 4.3 The first placement of WW sign(s) and/or arrow(s)

Group 1: First set of TCD within 100 ft.			Group 2: First set of TCD beyond 100 ft.		
Avg. WWD Distance (# of WWD incidents)	**Countermeasure**	**Distance (ft.)**	**Avg. WWD Distance (# of WWD incidents)**	**Countermeasure**	**Distance (ft.)**
AL I-65 Exit 284 SB	WW arrow +WW sign	100	TN I-40 Exit 172 WB	Two-side WW sign	120
82 ft. (77)	WW sign	200	254 ft. (5)		
AL I-65 Exit 208 SB	WW arrow	50	TX I-635 Exit 15 SB	Single WW sign	160
41 ft. (59)	Dual WW sign	150	20 ft. (3)		
TN I-65 Exit 37 NB	WW arrow	30	TN I-24 Exit 49 SB	WW sign + WW arrow	110
68 ft. (11)	Enhanced two-side WW	170	118 ft. (5)		
NC I-77 Exit 79 SB	WW arrow	90	VA I-81 Exit 141 SB	WW sign	220
24 ft. (26)	Two-side WW sign	180	134 ft. (5)		
AR I-40 Exit 260 WB	WW sign	80	TX I-635 Exit 15 SB	WW sign	160
67 ft. (5)			20 ft. (3)		
AL I-65 Exit 208 NB	WW arrow	50	MS I-59 Exit 97 SB	Two-side WW	350
30 ft. (1)	WW sign	250	80 ft. (5)		
	WW sign	380	NC Hwy 421 Exit 234C WB	Two-side WW sign	150
AR I-40 Exit 94 WB	WW sign + WW arrow	80	112 ft. (14)		
10 ft. (1)	WW sign	410	TN I-40 Exit 182 SB	WW sign + WW arrow	160
AR I-40 Exit 47 WB	WW arrow	90	87.5 ft (1)		
90 ft. (1)	WW sign	200	TX I-35 Exit 370 NB	WW sign	650
TN I-40 Exit 182 NB	WW arrow	70	70 ft (1)		
60 ft. (5)	WW sign	260	MS I-22 Exit 85 EB	NA	NA
NC I-77 Exit 79 NB	WW arrow	50	30 ft. (1)		
40 ft. (1)	WW sign	110	TN I-65 Exit 22 NB	WW arrow	150
NC Hwy 421 Exit 242 WB	WW arrow	60	60 ft. (1)	WW sign	250

Group 1: First set of TCD within 100 ft.			Group 2: First set of TCD beyond 100 ft.		
Avg. WWD Distance (# of WWD incidents)	**Countermeasure**	**Distance (ft.)**	**Avg. WWD Distance (# of WWD incidents)**	**Countermeasure**	**Distance (ft.)**
25 ft. (1)	WW sign	165	NJ I-295-16B-E 10 ft. (1)	WW sign	470
VA I-77 Exit 41 NB	WW arrow	25	GA I-85 Exit 147 SB 178 ft. (134)	WW sign	400
10 ft. (1)	WW sign	185	GA I-75 Exit 61 SB 92 ft. (18)	WW sign WW arrow Dual WW sign	240 420 450
			AR I-40 Exit 55 EB 93 ft. (15)	WW Arrow Low-mounted Enhanced Single WW Sign Low-mounted Enhanced Single WW Sign	140 200 440
			SC I-85 Exit 106 EB 163 ft. (9)	Two-side WW sign	200

A two-sample t-test was conducted to check if there was a significant difference between the WWD distances between the two groups. As shown in **Table 4.4**, the results suggested that the average WWD distance (61.66 ft.) at the locations in group 1 was significantly lower than the locations in group 2, with a 99% confidence level (p-value<0.01).

Table 4.4 T-test for two implementation plans (Based on 100 ft distance)

t-test: Two-Sample Assuming Unequal Variances		
	Group 1	Group 2
Mean	61.66	175.17
Variance	11,008.78	3,3042.00
Observations	191	223
Hypothesized Mean Difference	0	
df	364	
t Stat	-7.91	
P(T<=t) one-tail	1.53E-14	
t Critical one-tail	1.65	
P(T<=t) two-tail	3.07E-14	
t Critical two-tail	1.97	

In order to determine if the second (or more) set of WW sign(s) and/or arrow(s) has an impact on WWD distance, all the study locations are then divided into two groups: (1) at least two sets of WW signs/arrows; (2) only one set of WW sign/arrow. As shown in **Table 4.5**, the left column lists the locations in group 1, and the right column lists the locations in group 2.

Table 4.5 Amount of WW sign(s) and/or arrow(s) implemented at each location

Group 1: At least two sets of WW sign/arrow			Group 2: Only one set of WWD sign/arrow		
Avg. WWD Distance (# of WWD incidents)	**Countermeasure**	**Distance (ft)**	**Avg. WWD Distance (# of WWD incidents)**	**Countermeasure**	**Distance (ft)**
AL I-65 Exit 284 SB	WW arrow +WW sign	100	AR I-40 Exit 260 WB	WW sign	80
82 ft. (77)	WW sign	200	67 ft. (5)		
AL I-65 Exit 208 SB	WW arrow	50	TN I-40 Exit 172 WB	Two-side WW	120
41 ft. (59)	Dual WW sign	150	254 ft. (5)		
TN I-65 Exit 37 NB	WW arrow	30	TX I-635 Exit 15 SB	WW sign	160
68 ft. (11)	Enhanced two side WW	170	20 ft. (3)		
NC I-77 Exit 79 SB	WW Arrow	90	TN I-24 Exit 49 SB	WW sign + WW arrow	110
24 ft. (26)	Two-side WW sign	180	118 ft. (5)		
GA I-75 Exit 61 SB	WW sign	240	VA I-81 Exit 141 SB	WW sign	220
92 ft. (18)	WW arrow	420	134 ft. (5)		
	Dual WW sign	450	TX I-635 Exit 15 SB	WW sign	160
AR I-40 Exit 55 EB	WW Arrow	140	20 ft. (3)		
93 ft. (15)	WW sign	200	MS I-59 Exit 97 SB	Two side WW	350
	WW sign	440	80 ft. (5)		
AL I-65 Exit 208 NB	WW arrow	50	NC Hwy 421 Exit 234C WB	Two-side WW sign	150
30 ft. (1)	WW sign	250	112 ft. (14)		
	WW sign	380	TN I-40 Exit 182 SB	WW sign +WW arrow	160
AR I-40 Exit 94 WB	WW sign + WW arrow	80	87.5 ft. (5)		
10 ft. (1)	WW sign	410	GA I-85 Exit 147 SB	WW sign	400
AR I-40 Exit 47 WB	WW arrow	90	178 ft. (134)		
90 ft. (1)	WW sign	200	SC I-85 Exit 106 EB	Two-side WW sign	200
TN I-40 Exit 182 NB	WW arrow	70	162.5 ft. (9)		
60 ft. (1)	WW sign	260	TX I-35 Exit 370 NB	WW sign	650
TN I-65 Exit 22 NB	WW arrow	150	70 ft. (1)		
60 ft. (1)	WW sign	250	MS I-20 Exit 1A WB	Two-side WW sign	450
NC I-77 Exit 79 NB	WW arrow	50	30 ft. (1)		
40 ft. (1)	WW sign	110	NJ I-295-16B-E	WW sign	470
NC Hwy 421 Exit 242 WB	WW arrow	60	10 ft. (1)		
25 ft. (1)	WW sign	165			
VA I-77 Exit 41 NB	WW arrow	25			
10 ft. (1)	WW sign	185			

A two-sample t-test was conducted to examine if there is a significant difference in WWD distances between the two defined groups. As shown in **Table 4.6**, the results indicate that the average WWD distance at the locations in group 2 (168.26 ft.) is significantly longer than the locations in group 1 with two or more sets of WW-related countermeasures implemented on the off-ramp (80.18 ft.) at 99% confidence level (p-value<0.01).

Table 4.6 T-test for two groups with one or more pairs of WW sign(s)/arrow(s)

t-Test: Two-Sample Assuming Equal Variances		
	Only one set	two sets or more
Mean	168.26	80.18
Variance	25,106.42	23,133.64
Observations	201	214
Pooled Variance	24088.98	
Hypothesized Mean Difference	0	
df	413	
t Stat	5.78	
P(T<=t) one-tail	7.46E-09	
t Critical one-tail	1.65	
P(T<=t) two-tail	1.49E-08	
t Critical two-tail	1.97	

4.2 Geometric Design Deficiencies Causing WWD Incidents

Altogether, 28 parclo interchange terminals are being identified as high-risk locations for WWD due to the monitored WWD incidents. Depending on the existence of channelizing islands at different locations, the WWD incidents were found to have different kinds of trajectories entering the off-ramp. As shown in **Figure 4.3 (a)**, the WWD incidents could enter the off-ramp either through the left-turn (LT) or right-turn (RT) at the intersection area. However, when channelizing island exists at the end of the off-ramp, the WWD incidents could also enter through the channelized right-turn lane by making an early left-turn (ELT) as shown in **Figure 4.3 (b)**.

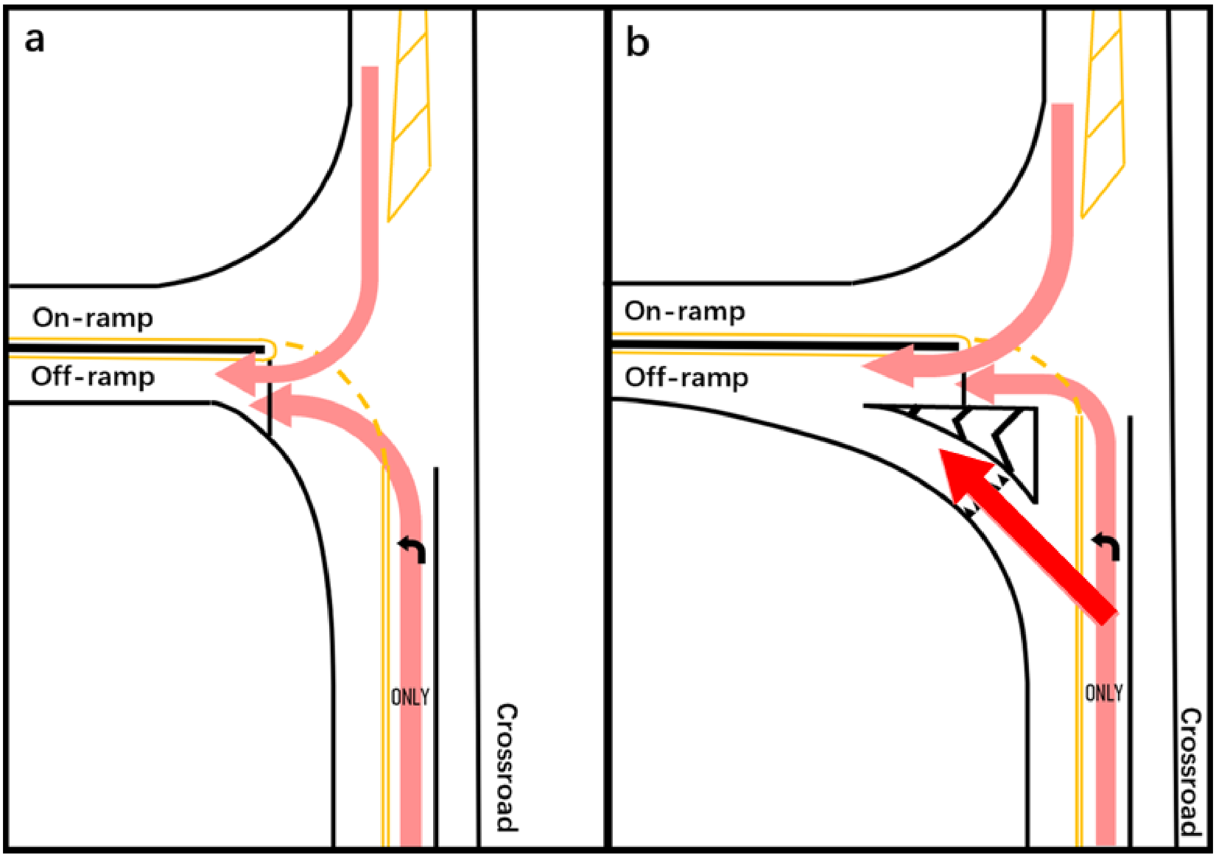

Figure 4.3 Different trajectories of WWD incidents

To better present the distribution of WWD incidents, the high-risk locations were grouped based on the existence of channelizing islands on the off-ramp. Where 17 out of 28 terminals have the channelizing island at the end of the off-ramp, 11 out of 28 terminals do not. For each group of terminals, the WWD entering types were counted separately. In this study, the monitoring periods for each study location were different. Some locations may have more incidents due to the longer monitoring time. In order to make a fair comparison, the number of WWD incidents for each location was limited to a 48-hour monitoring period. As shown in **Table 4.7**, there is a total of 175 WWD incidents were recorded at 17 parclo interchange terminals with channelizing island on the off-ramp. 77% of the WWD incidents were entered through the exclusive right-turn lane by making ELT. As for the 11 terminals without channelizing island on the off-ramp, only 21 WWD incidents were recorded, and 86% of the WWD incidents were entered through LT at the intersection area. For both types of terminals, the RT wrong-way entries occupy a relatively low percentage compared with the LT wrong-way entries. The large portion of WWD incidents entering through ELT and LT encouraged researchers to further investigate the potential reasons.

Table 4.7 Different Wrong-way entering trajectories at parclo interchange terminals

	17 off-ramps with channelizing Island		**11 off-ramps without channelizing Island**	
Entering type	Count	Percentage	Count	Percentage
Early left-turn	134	77%	NA	NA
Left-turn	33	19%	18	86%
Right-turn	8	5%	3	14%
Total	175		21	

4.2.1 WWD incidents entering through ELT

Not all of the 17 parclo interchange terminals with channelizing islands on the off-ramp have issues with ELT. To further analyze the difference between these locations, these 17 locations were grouped based on the occurrence of WWD incidents entering through ELT. As shown in **Table 4.8**, the first group represents the locations with a high frequency of ELTs, which contains ten locations with a frequency of 3-26 WWD incidents entering through ELT. In comparison, the second group contains seven locations with a frequency of 0-1 WWD incidents entering through ELT, representing the locations with a relatively low frequency of ELTs.

In order to conduct the comparison, some design features at these locations that might affect the occurrence of ELT were collected. Based on the definition of WWD incidents entering through ELT, the presence of channelizing islands is the primary cause. Hence, information regarding the channelizing islands was collected, including the length (measuring the side parallel with the crossroad) and traversability (either painted or raised). In the meantime, whether the median on the crossroad is traversable is also recorded since the non-traversable median on the crossroad could physically block the ELT. The control type of the interchange terminal may also affect the ELT since a controlled intersection may provide more reaction time for coming drivers. Lastly, some locations may have implemented enhanced WW-related signs such as enlarged wrong-way or DO NOT ENTER (DNE) signs, low-mounted wrong-way or DNE signs, red retroreflective tapes on the sign poles, or extra guidance signs; these locations were considered as enhanced for signage while other locations only met the requirements of MUTCD. The two-sample t-test and Fisher exact test were conducted to compare if certain differences in design features are statistically different between the two groups.

Table 4.8 Comparison of high/low-frequency locations for ELT

	10 High-frequency locations		7 Low-frequency locations		Two-sample T-test	
Number of ELTs	Mean	(Min, Max)	Mean	(Min, Max)	t	p value
	13.2	(3, 26)	0.3	(0, 1)	4.23	<0.01*
Length of Channelizing Island	Mean	Std.	Mean	Std.	t	p value
	32.3	17.2	63.9	44.5	-1.91	0.04*
Median on the crossroad					Fisher exact Test	
	Count	Percentage	Count	Percentage	odds ratio	p value
Traversable	4	40%	1	14%	3.7	0.34
Non-traversable	6	60%	6	86%		
Interchange terminal control type						
uncontrolled	9	90%	4	57%	5.96	0.25
controlled	1	10%	3	43%		
Sign enhancement						
Minimum Requirement of MUTCD	7	70%	3	43%	2.9	0.35
Enhanced Signs	3	30%	4	57%		

As shown in **Table 4.8**, the average length of channelizing islands from the group with a higher frequency of ELTs is shorter than the group with a lower frequency of ELT. The two-sample t-test also indicated there is a significant difference (t=-1.91, p=0.04) between the two groups. Based on the Fisher exact test, the rest of the design features in both groups were shown to have similar practices (p=0.34 regarding the median on the crossroad, p=0.25 regarding control type, p=0.35 regarding sign enhancement). As a result, the length of channelizing islands is playing an important role in the occurrence of WWD incidents entering through ELT.

Based on reviewing the WWD behavior entered through ELT, it was found that a smooth WWD route from the crossroad to the channelized right-turn lane of the off-ramp is always available at high-frequency locations. Where the length of the channelizing island on the off-ramp is highly correlated with the generation of potential WWD route, as shown in **Figure 4.4(A)**, when the length of channelizing island on the off-ramp is short, the exclusive right-turn lane on the off-ramp will have a larger angle with the crossroad. As a result, the opening of the channelized right-turn lane will be close to the intersection area and face toward LT drivers coming from the crossroad. Under such conditions, the potential WWD route (represented by the red band) can be generated and overlap with the normal driving route (represented by the green band). This kind of design provided opportunities for LT drivers coming from the crossroad to enter the wrong way through ELT. In contrast, when the length of channelizing island on the off-ramp is long, the channelized RT lane on the off-ramp is near parallel with the crossroad. As a result, the opening of the channelized RT lane will be far to the intersection area and not face the LT drivers coming from the crossroad. As shown in **Figure 4.4(B)**, the LT drivers coming from the crossroad are less likely to enter through the potential WWD route smoothly since it is not overlapped with the normal driving route.

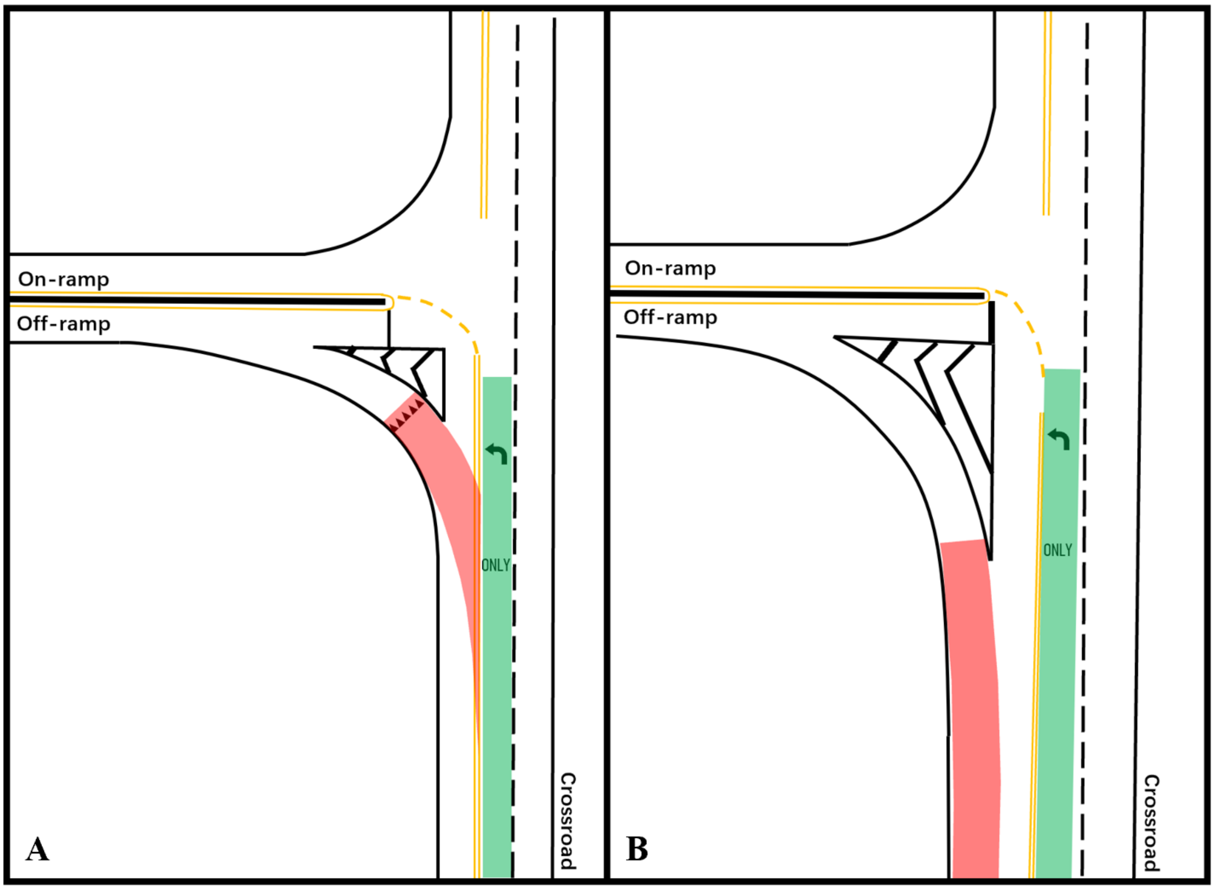

Figure 4.4 Potential WWD route at parclo interchange terminal

Relationship between potential WWD route and off-ramp channelizing island design

As described in the previous chapter, a common feature at locations with high-frequency WWD incidents entered through ELT is that a potential WWD route is formed from the off-ramp right turn lane intersecting with the crossroad. As for the locations without WWD incidents entering through ELT, they usually have an off-ramp right-turn lane tangent to the crossroad or have a controlled intersection. This section summarizes the relationship between potential WWD route and off-ramp channelizing island design to further summarize this finding and provide practical guidance.

Figure 4.5 shows two schematic diagrams of the parclo interchange terminal, where the horizontal roads represent the on- and off-ramps, and the vertical roads represent the crossroad. The green triangles represent the channelizing island at the end of the off-ramps. It can be observed that the curve in **Figure 4.5(A)** generated by the channelizing island (represented by the red curve) is tangent to the median of the crossroad (represented by the double yellow lines), which represents the critical condition for the generation of potential WWD route. If the red curve shifts to the right side, a smooth potential WWD route could be generated from the crossroad to the off-ramp right-turn lane. In contrast, if the red curve shifts to the left, a smooth potential WWD route could be less likely to be generated.

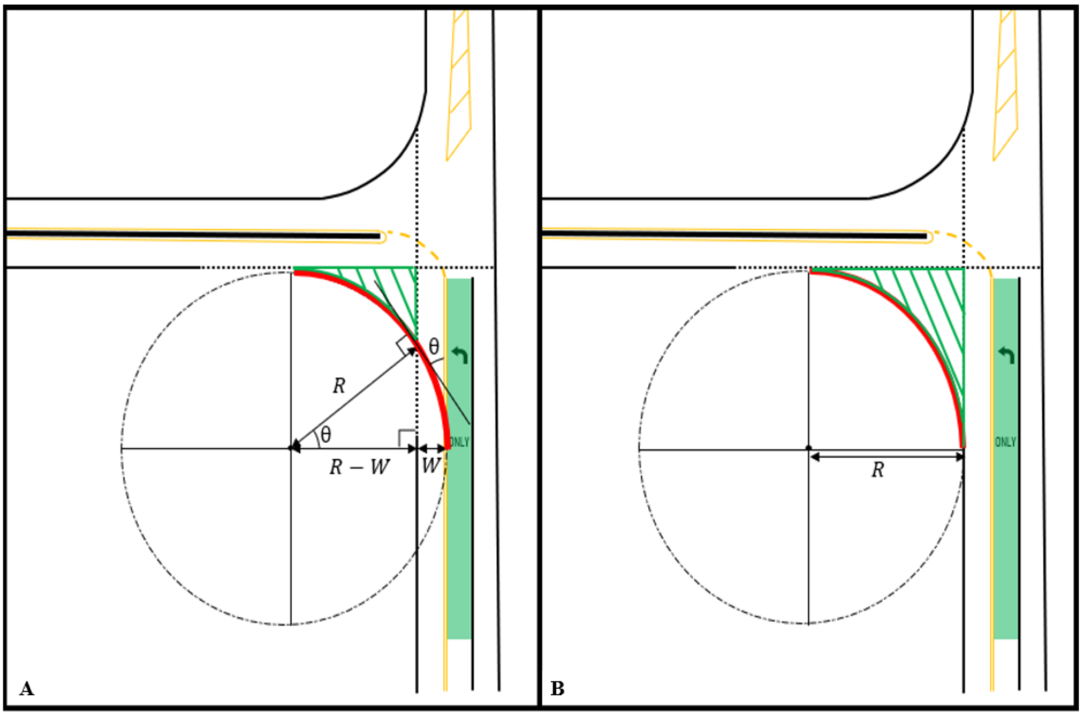

Figure 4.5 Relationship between the right-turning radius and angle between the exit-ramp right-turn lane and the crossroad

In order to avoid the generation of potential WWD route, both the turning radius of the off-ramp right-turn lane (represented by R in **Figure 4-5**) and the connection angle (represented by θ in **Figure 4.5**) between the right-turn lane and the crossroad should be considered. As represented by **Equation 4-1**, where R represents the radius of the right-turn lane curve generated by channelizing island, it can also represent the left-turning radius of the potential WWD routes from the crossroad to the off-ramp right-turn lane. W represents the intrusion distance on the crossroad generated by the red curve. θ represents the angle between the off-ramp right-turn lane and the crossroad.

$$\begin{cases} \theta = cos^{-1}\left(\frac{R-W}{R}\right) & when\, W > 0 \\ \theta = 0 & when\, W = 0 \end{cases} \tag{4-1}$$

In order to avoid the generation of a potential WWD route, the length of *W* should be controlled within the lane width multiplied by the number of lanes on the crossroad (near the ramp side). While the ideal design of an off-ramp right-turn lane, avoiding the generation of potential WWD routes, is shown in **Figure 4.5(B)**, at the end of the curve generated by channelizing island, the angle between the off-ramp right-turn lane and the crossroad becomes zero by moving the whole circle into the crossroad edge. This off-ramp right turn lane design can eliminate the potential WWD routes and reduce the risk of WWD. **Equation 4-1** can also be applied for any angles between an off-ramp right-turn lane and the crossroad. **Figure 4.6** illustrates examples of off-ramp right turn lane design at acute and obtuse intersections.

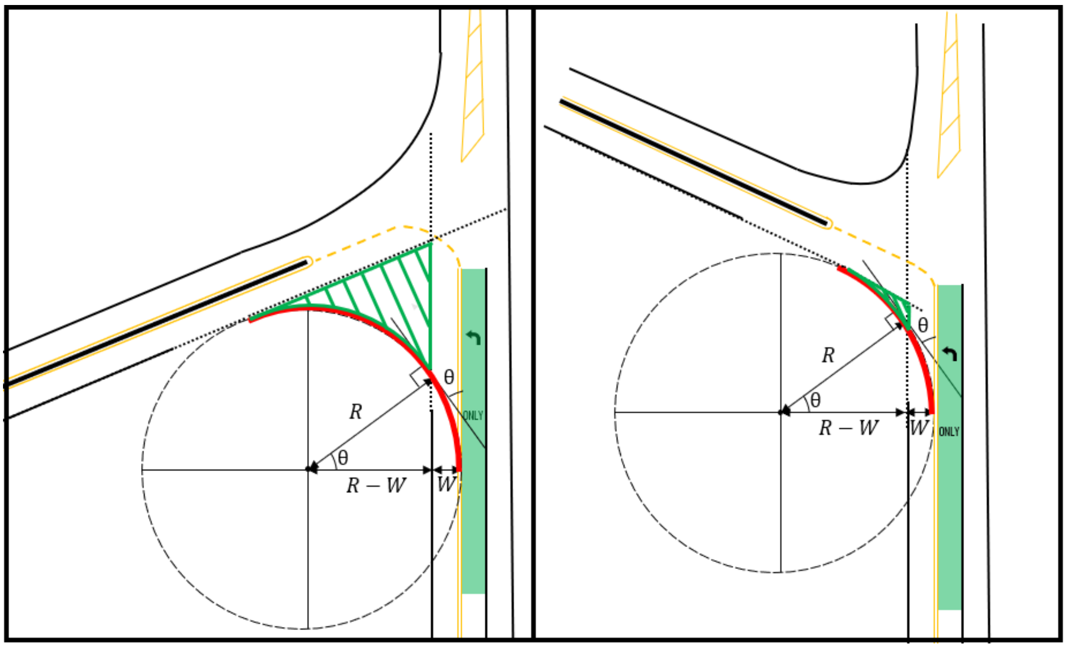

Figure 4.6 Examples of acute and obtuse connections between ramps and crossroads

To better present the design recommendation, this study listed three kinds of design practices at unsignalized parclo exit-ramp terminals. As shown in **Figure 4.7**, the black dash lines represent the same radius of the curve generated by channelizing islands; however, a different connection angle resulted in a different intrusion distance by extending the curve to the crossroad. **Figure 4.7(A)** shows a large angle between the exit-ramp right-turn lane and the crossroad, with a long intrusion distance on the crossroad. As a result, a wide and smooth potential WWD route can be easily generated. In this condition, the risk for WWD would be considered high. **Figure 4.7(B)** shows a medium angle between the exit-ramp right-turn lane with a medium intrusion distance on the crossroad, which makes the extended curve tangent with the double yellow line. In this condition, the potential WWD routes would be difficult to generate, which can be considered as the minimum requirements for deterring WWD. The design is shown in **Figure 4.7(C)** shows a relatively small angle between the exit-ramp right-turn lane and the crossroad. As a result, a right-turn acceleration lane nearly paralleled with the crossroad is generated. In this condition, the potential WWD routes would be difficult to generate, which can be considered an ideal design practice for deterring WWD.

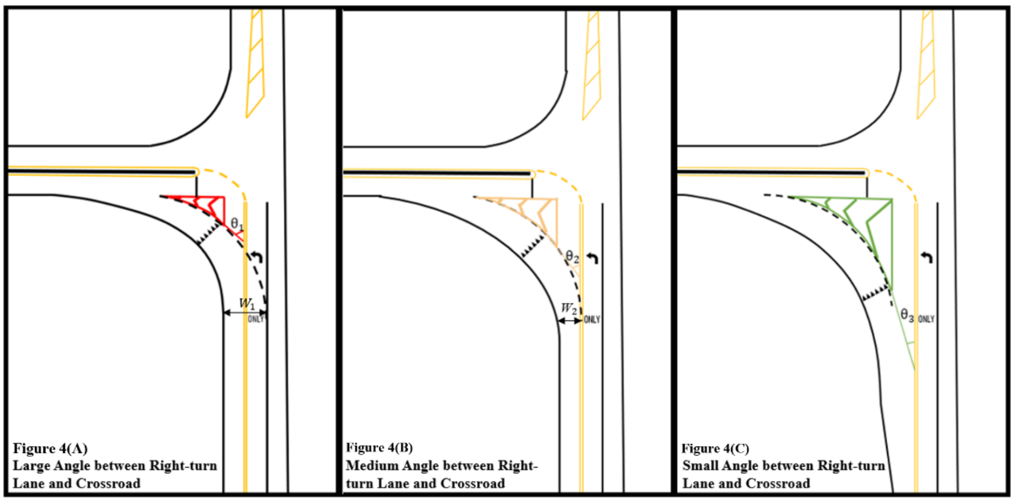

Figure 4.7 Three design practices with different intrusion distances

In summary, the off-ramp right-turn lane design at the parclo interchange terminal should avoid generating smooth potential WWD routes from the crossroad. A larger number of lanes and median width on the crossroad can provide more space to avoid the generation of potential WWD incidents. This also explains why a four-lane crossroad typically has a lower risk for WWD than a two-lane crossroad.

4.2.2 WWD incidents entering through LT

Among 28 locations with monitored WWD incidents, 12 locations were found to have 1 WWD incident occurred during the monitoring period, and 16 locations were found to have 3-28 WWD incidents during the monitoring period. It can be observed that 94% of WWD incidents are entering through LT at parclo interchange terminals. At the same time, the WWD incidents entering through RT appeared to be no more than 2 cases at each location. As a result, the locations with a high frequency of WWD incidents are primarily caused by LT drivers, which is desired for further investigation.

Comparison between high/low-frequency locations for WWD incidents

As shown in **Table 4.9**, the first group represents the locations with a high frequency of WWD incidents, which contains 16 locations with a frequency of 3-28 WWD incidents each. The second group contains 12 locations with a frequency of 1 WWD incident, which represents the locations with a relatively low frequency of WWD incidents. Besides the design features collected for ELT during the previous section, several more design features that may affect the driving behaviors of LT drivers coming from the crossroad were included: the corner radius measures the design turning radius from the LT lane on the crossroad to the on-ramp; If the median on the crossroad is extended into the intersection area, it could cover whole/part of the off-ramp opening which may discourage LT drivers turning into the off-ramp; If there are more lanes on the off-ramp, it could increase the opening width and provide more chances for wrong-way entry. Lastly, the interchange design type could affect the placement of on- and off-ramps, which may provide different perspectives for coming drivers. More detailed descriptions regarding the interchange design type are provided in the next section. The two-sample t-test and Fisher exact test were conducted to determine whether a certain design feature is statistically different between the two groups.

Table 4.9 Comparison of high/low-frequency locations for WWD incidents

	12 Low-frequency locations		16 High-frequency locations		Two-sample t-test	
Number of WWD incidents	Mean	(Min, Max)	Mean	(Min, Max)	t	p value
	1	(1, 1)	11.5	(3, 28)	-4.65	<0.01*
Corner Radius	Mean	Std.	Mean	Std.	t	p value
	50.55	15.29	48.56	17.96	0.3	0.38
Median on the crossroad					Fisher exact test	
	Count	Percentage	Count	Percentage	odds ratio	p value
Non-traversable	3	25%	1	6%	4.72	0.285
Traversable	9	75%	15	94%		
Median on the crossroad covering the ramp						
Covered (0)	5	42%	5	31%	1.55	0.70
Not covered (2)	7	58%	11	69%		
Number of lanes on the off-ramp						
1 (1)	11	92%	12	75%	3.52	0.36
2 or more (2)	1	8%	4	25%		
Interchange design type						
Parclo A	6	50%	2	13%	6.47	0.04*
Parclo B	6	50%	14	88%		
Channelized Island on the off-ramp						
Exist	6	50%	11	69%	0.47	0.44
Not exist	6	50%	5	31%		
Control Type						
Controlled	3	25%	5	31%	0.74	1.00
Uncontrolled	9	75%	11	69%		
Sign Enhancement						
Minimum requirements	6	50%	8	50%	1.00	1.00
Enhanced	6	50%	8	50%		

According to **Table 4.9,** at a significant level of α=0.05, both groups have similar design features except for the interchange design type. The Fisher exact test shows that there is a significant difference in the distribution of interchange design type between two groups (p=0.04). Since 88% of locations with a high frequency of WWD incidents were observed with parclo B design, it could be an important factor causing a large amount of WWD incidents.

Three types of parclo interchange terminal

Figure 4.8 below introduces four interchange design types: parclo A, parclo B, parclo AB, and diamond. Where the freeways were represented by horizontal roads with a median represented by the black segments, the crossroads were represented by vertical roads with double yellow lines as the median. It can be observed that the parclo A design has a symmetrical shape with parclo B. An easy way to distinguish parclo A and B is based on the on- and off-ramp design. For the parclo A design, the on-ramp is looped, and the off-ramp is curved, the other way around for the parclo B design. The parclo AB design is a hybrid of the parclo A design and the parclo B design. As a result, it has one looped on-ramp on one side and another curved on-ramp on the other side.

Another difference between the parclo A design and the parclo B design is that the on-ramp of parclo A design is always built in the opposite direction from the connected freeway. As shown in **Figure 4.8 (a)**, the on-ramp connected with the westbound labes of the freeway was built on the east side of the crossroad. While the on-ramp connected with the eastbound of the freeway was built on the west side of the crossroad. This characteristic also remains opposed to the parclo B design. For the diamond interchanges, the on-ramps are always built in the same direction with the connected freeway. As shown in **Figure 4.8(d)** the on-ramp connected with the westbound lanes of the freeway was built on the west side of the crossroad. This characteristic remains the same with the parclo B design, which could be the reason that parclo B design involves more WWD incidents.

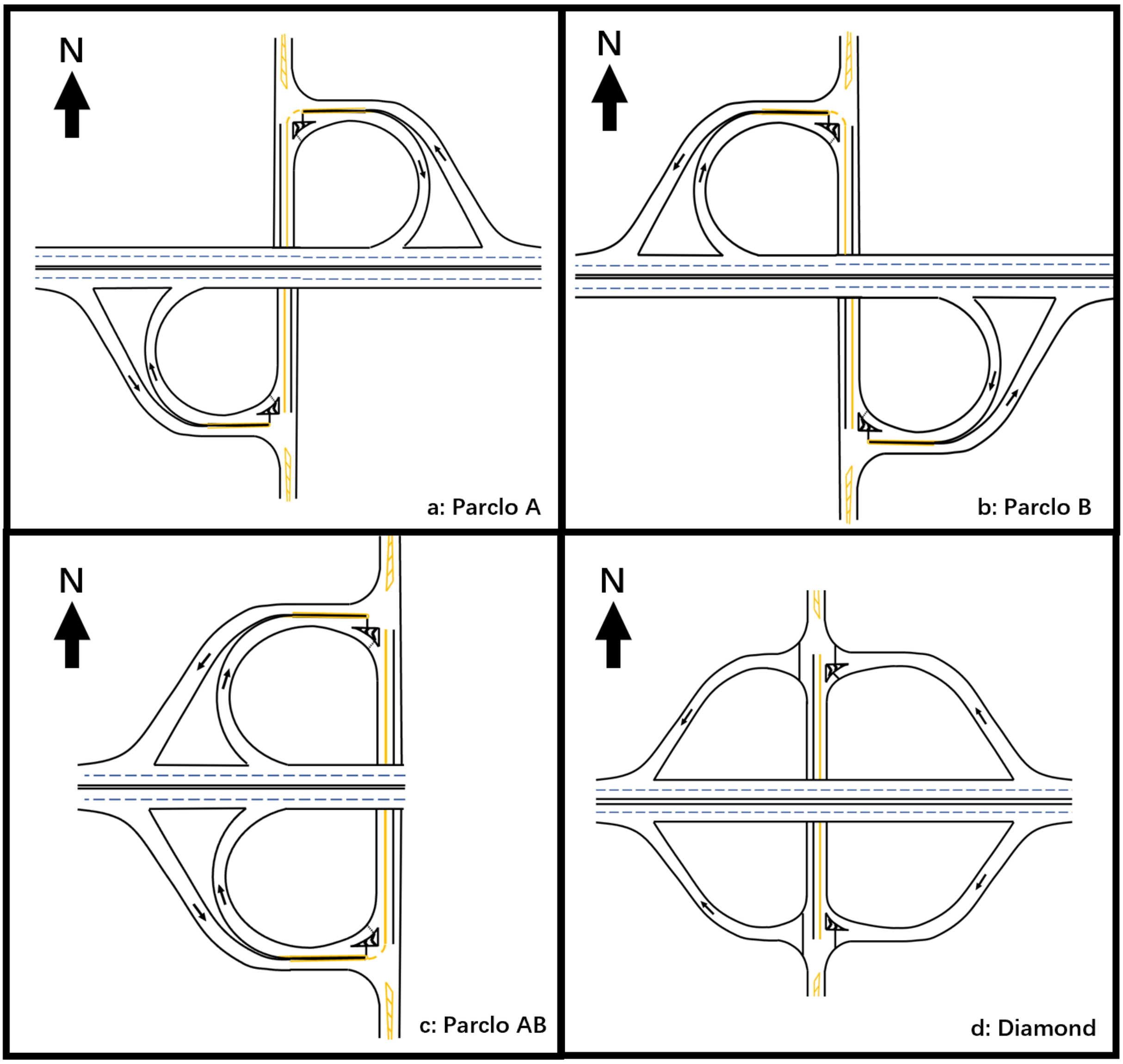

Figure 4.8 Different types of interchange design

Suppose a driver is coming from the south and planning to enter the westbound lanes of the freeway: for the diamond interchange terminal, the on-ramp is located on the driver's left side and what he has to do is make LT; for parclo A interchange terminal, the on-ramp will first appear, and it is located on the driver's right side and what he has to do is making RT; for parclo B interchange terminal, the off-ramp will appear first, and it is located on the driver's left side-same direction as the driver's proposed traveling direction, as well as a diamond interchange terminal. At this moment, if the driver doesn't realize that the on-ramp is actually behind the off-ramp he has seen, he may treat the off-ramp as the on-ramp of a diamond interchange and make wrong-way LT. And the exact same thing could happen to the drivers coming from the north and planning to enter the eastbound of the freeway. Furthermore, the parclo B design could only confuse the LT drivers since the on-ramp will always appear first for RT drivers.

Figure 4.9 illustrates a comparison between a parclo AB interchange with a traditional diamond interchange. The same left turn from the crossroad should be made to enter the NB freeway. Since most of the interchanges in the U.S are diamond interchanges, some drivers may misinterpret this type of parclo interchange as a diamond interchange, especially when the on- and off-ramps are very close and visibility of the on-ramp is low. More detailed guidelines should be developed to reduce WWD incidents at this type of parclo interchange.

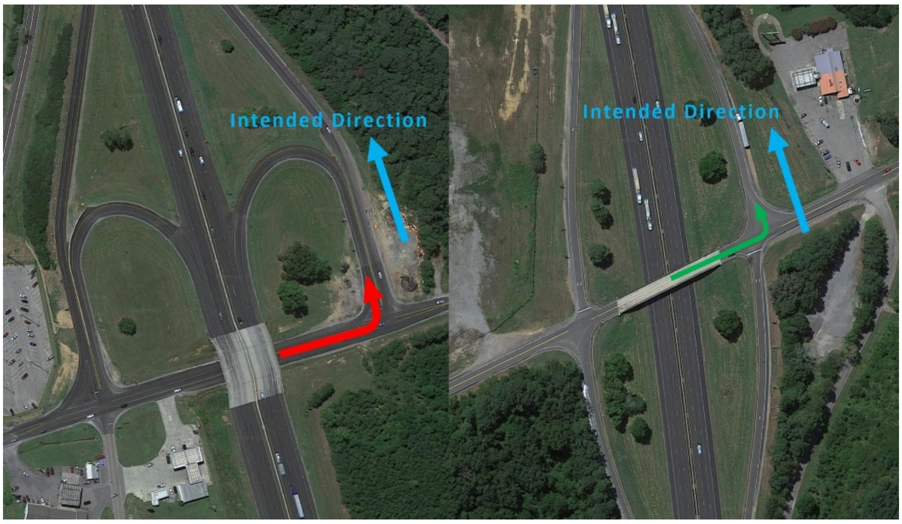

Figure 4.9 Parclo AB interchange terminal versus diamond interchange terminal (Imagery © 2021 Google)

In the AASHTO Greenbook, the Parclo A and Parclo B design has also been described as "major road exits on the near side" and "major road exits on the far side." As shown in **Figure 4.10**, this naming policy is based on whether the ramps will be constructed near or far side to the coming drivers on the highway. Based on this study, we can conclude that type F with two circular off-ramp terminals is more prone to WWD than type E.

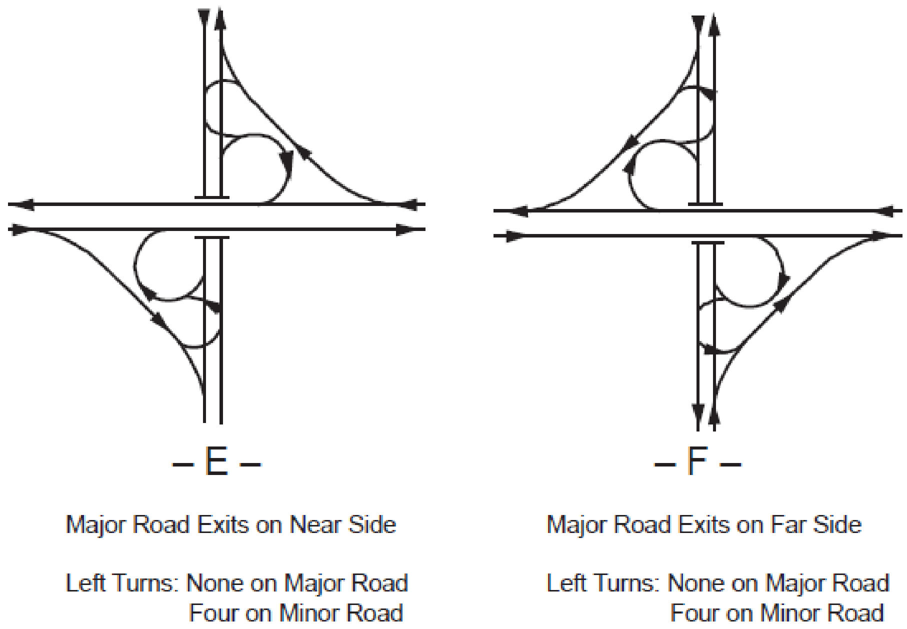

Figure 4.10 Parclo A and parclo B design in AASHTO green book (source: the green book)

4.3 Characteristics of parclo interchange terminals with a high risk of WWD

MCA is a dimension reduction method that aims to plot all variable categories onto lower-dimensional space (e.g., 2-D dimension plot). Each variable category is represented as a point on the plot. A shorter distance between two points indicates a stronger correlation between two variables. The MCA analysis was done to explore which design feature combinations tend to increase the risk of WWD incidents. As mentioned in **Chapter 3**, the study collected a set of potential design features relating to WWD incidents, which include 20 variables and 52 variable categories. The R version 3.05 statistical software was used to perform multivariate exploratory data analysis (R Core Team, 2013). Specifically, the R package "FactoMineR" (Lê et al., 2008) was applied to perform MCA analysis, and the package named "factoextra" (Kassambara and Mundt, 2020) was used for extracting, visualizing, and interpreting the results. With the MCA method, variable categories will be displayed as points with their own coordinates in the multi-dimensional space. The results show that the MCA depicts the data points in a 31-dimensional space. Each dimension carries a different amount of categorical information, which is determined by a factor known as the eigenvalue. The eigenvalue can be varied between 0 and 1, and the larger the eigenvalue, the higher the variances among variables contribute to that dimension. **Table 4.10** lists the eigenvalue, the percentage of variance, and the cumulative variance for the first ten dimensions. **Figure 4.11** describes the percentage explained by the top ten dimensions for better visualization.

Table 4.10 Eigenvalue and Percentage of Variance for the First Ten Dimensions

Dimension	Eigenvalues	Variance%	CumVariance%
1	0.200852	13.0	13.0
2	0.141285	9.1	22.1
3	0.118304	7.6	29.7
4	0.111173	7.2	36.9
5	0.101623	6.6	43.4
6	0.091247	5.9	49.3
7	0.073704	4.8	54.1
8	0.066800	4.3	58.4
9	0.064711	4.2	62.6
10	0.062263	4.0	66.6

Notes: Variance% = "Percenatge of explained variance"
CumVariance% = "Cumulative percentage of ecplained variance"

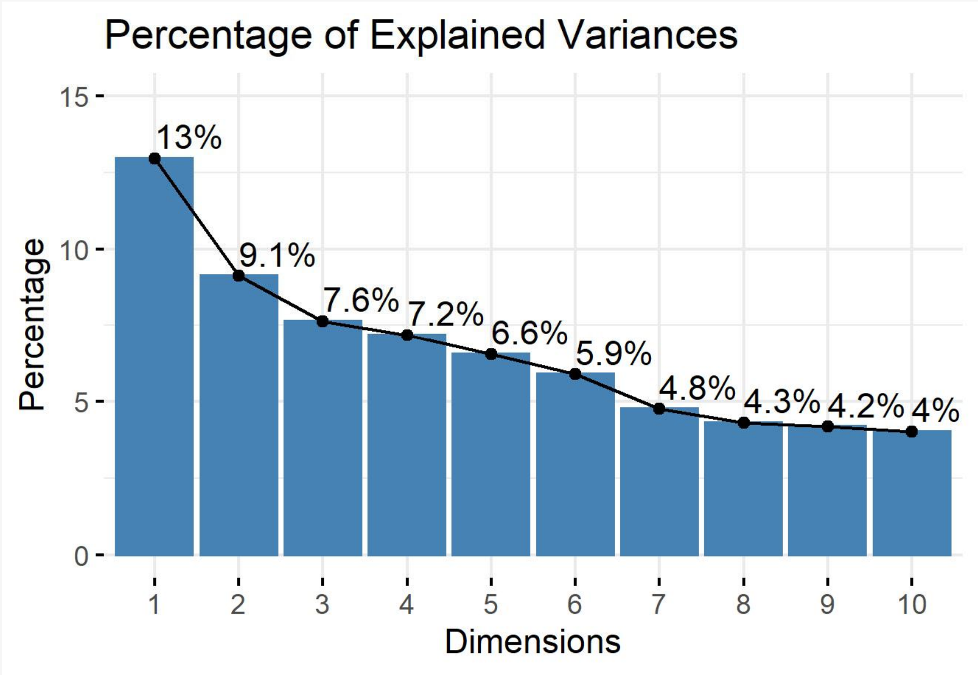

Figure 4.11 Percentage of Explained Variances for the First Ten Dimensions

As shown in the table and figure above, the first two dimensions have the eigenvalue of 0.20 and 0.14, respectively, explaining about 22% of the data variability. The eigenvalues decrease when the dimensions increase, and it can be found that the first and second dimensions contain higher degrees of variances. Considering the complexity of the result interpretation in multi-dimensional space and the fact that the first dimensions carry most of the information. The first two dimensions were selected for further analysis, which is commonly used in past studies (Song et al., 2021; Baireddy et al., 2018; Das et al., 2018; Jalayer et al., 2018). Several other crash studies also got similar eigenvalues for the first two dimensions. For instance, the study conducted by Jalayer et al. applied MCA to WWD fatal crashes and found that the first two dimensions cover 18.8% explained variance (Jalayer et al., 2018). Baireddy et al. explored pedestrian crashes in rural Illinois, and the results showed that the first two dimensions cover only 7.6% of explained variance

(Baireddy et al., 2018). The results of low explained variances might be due to the random nature of the WWD incidents, which resulted in the heterogeneity of variables.

Figure 4.12 is an illustration of variable categories and the correlation with the first two dimensions. The squared correlation between variables and the dimensions is used as coordinates, which is a coefficient and varies between 0 and 1. In other words, 0 means no relationship, and 1 indicates a strong relationship between variables and MCA dimensions. The results of the MCA reveal that the variables such as intersection balance (INIB), ramp looped (ERLooped), and traffic volume ratio between on and off-ramp (ratio) are not strongly associated with WWD incidents in these two dimensions. However, it doesn't represent that these variables are not correlated with WWD incidents in other dimensions. Additionally, variables that are associated most with the first dimension are the number of lanes on the ramp side (CRlaneonrampside), the number of lanes on the off-ramp (ERnumlane), and intersection control type (INType). Variables that contributed more to the second dimension are channelizing island traversable (ERChantran), and length of channelizing island (ERChanLen).

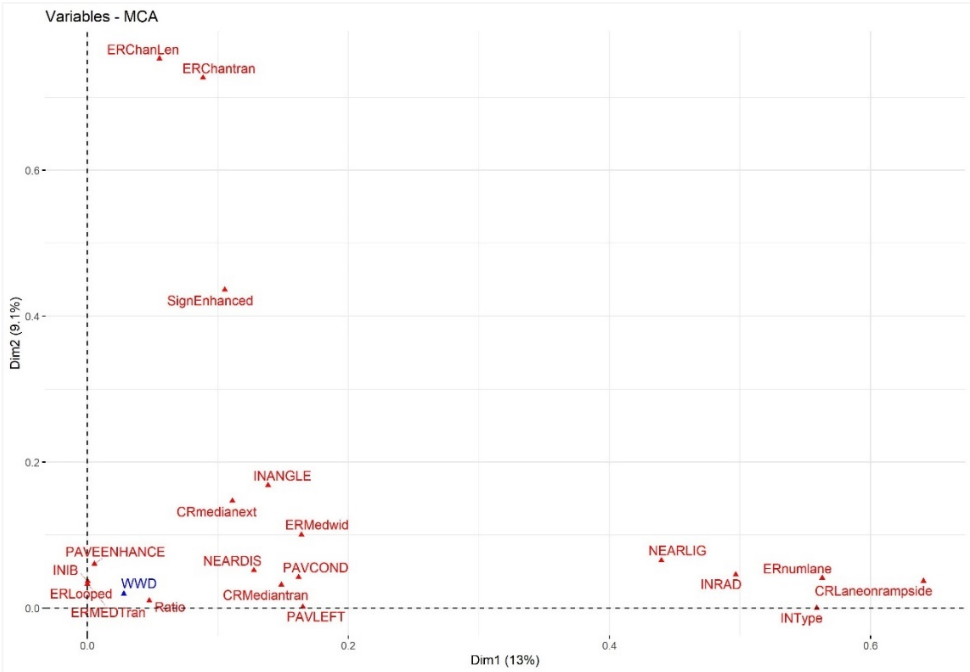

Figure 4.12 Correlation between Variables and Principal Dimensions

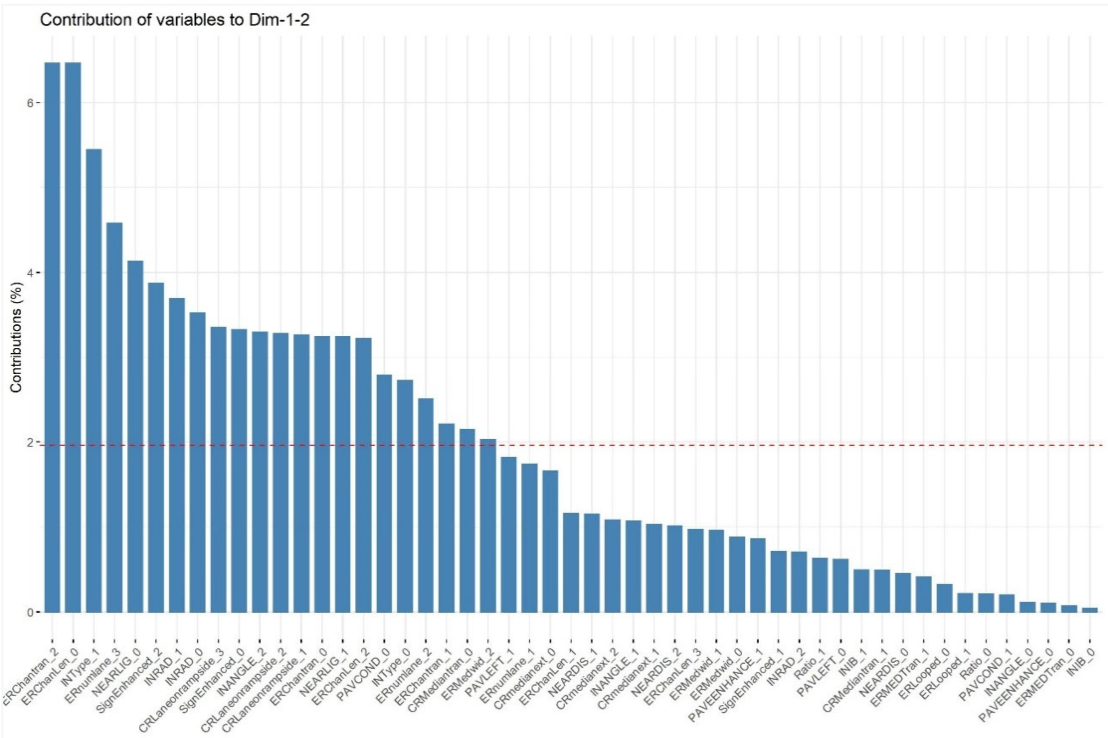

Figure 4.13 Variable Categories Contributions for the Top Two Dimensions

Figure 4.13 depicts the contribution of the variable categories (in %) for the top two dimensions in descending order. The variable category with the larger value will greatly contribute to the first two dimensions, which is important to explain the variability in the dataset (Kassambara, 2017). According to the figure, variable categories such as no channelizing island present (ERChantran_2 & ERChanLen_0), and controlled intersection type (INType_1) have higher contributions in the first two dimensions. On the contrary, variable categories such as intersection balance less than 40% (INIB_0), median non-traversable (ERMEDTran_0), and pavement markings are not enhanced (PAVENHANCE_0) are less related in the top two dimensions. In other words, the position of those points on the factor maps should be interpreted carefully.

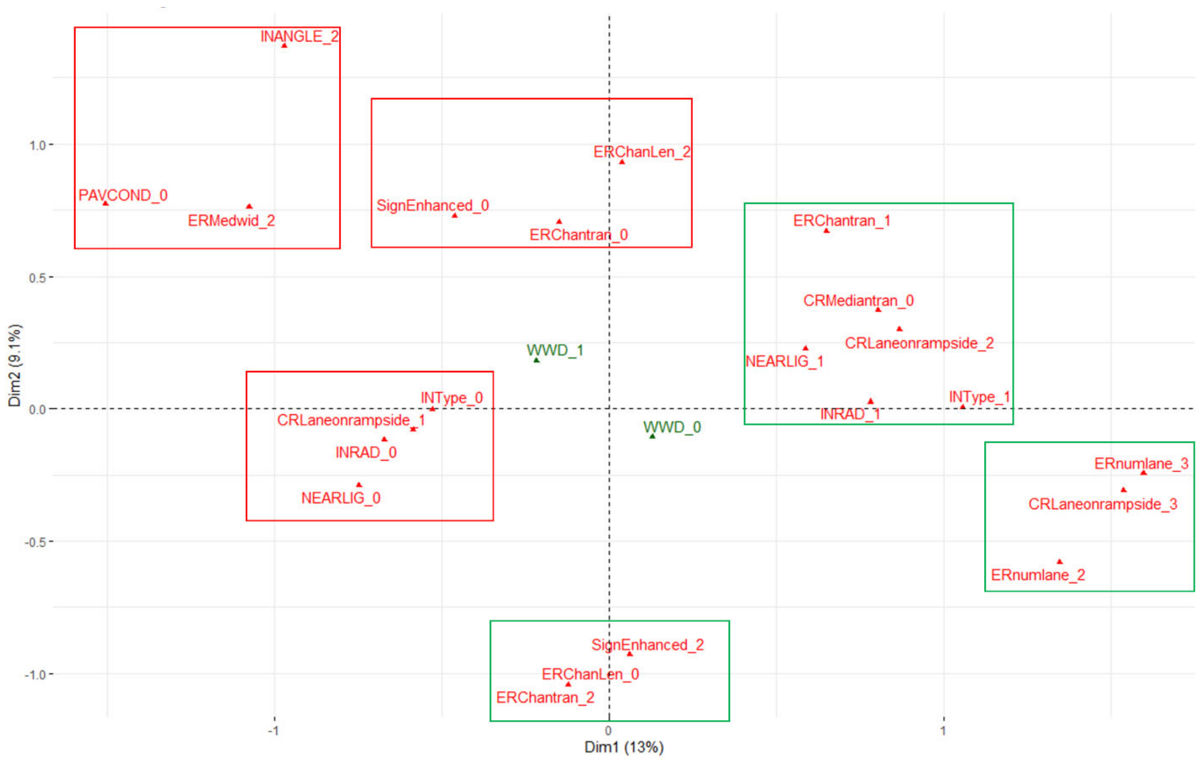

Figure 4.14 Effects of design features on WWD incidents at parclo interchange terminals

The variable categories that had a contribution above average in the first two dimensions are presented in **Figure 4.14**. Two additional points, "WWD_1" and "WWD_0," indicated whether the WWD incidents occurred at the ramp terminal or not (where 0 represents there are no recurring WWD incidents, and 1 means there are recurring WWD incidents). The variables in the plot close to each other can be grouped together, called a “cloud”. As a result, each cloud will represent some characteristics of parclo interchange terminals. Clouds close to the "WWD_1" suggested that these design features will be more likely to correlate with WWD incidents. On the contrary, clouds close to "WWD_0" suggested that these design features would be less likely to be associated with WWD incidents.

Three clouds near the “WWD_0” were identified, implying that when they exist at the same location, the likelihood of recurring WWD incidents is relatively low. Cloud 1 implies that the ramp terminals that contain three or four types of enhanced signs are less likely to have WWD incidents even when there are no channelized islands at the off-ramp. Cloud 2 confirmed that the large signalized or stop-controlled intersections are less likely to have WWD incidents. Cloud 3 suggests that non-traversable median on the crossroad and lighting on 4-lane crossroads can reduce the risk of WWD incidents. The variables in Clouds 1-3 for "WWD_0" are as follows:

Cloud 1

- The length of the channelized island is zero (ERChanLen_0)
- No channelized island at the off-ramp (ERChantran_2)
- Sign enhanced level 2 contains three or four types of enhanced signs (SignEnhanced_2)

Cloud 2

- Intersection corner radius between 51 to 100 ft (INRAD_1)
- Controlled intersection type at ramp terminal (INType_1)

- The number of lanes on the off-ramp is three or more (ERnumlane_3)
- The number of lanes on the crossroad at the ramp side is three or more (CRLaneonrampside_3)
- The number of lanes on the off-ramp is two (ERnumlane_2)

Cloud 3

- Traversable channelized island on the off-ramp (ERChantran_1)
- The non-traversable median on the crossroad (CRMediantran_0)
- The number of lanes on the crossroad at the ramp side is two (CRLaneonrampside_2)
- Lighting around ramp terminal (NEARLIG_1)

Similarly, there are three clouds near the "WWD_1", indicating that if the geometric design features included in these clouds appeared at one parclo interchange terminal, it might have recurring WWD incidents. Cloud 1 shows that the uncontrolled ramp terminal intersections with no street lighting on the two-lane crossroad are more likely to have WWD incidents. According to Cloud 2, poor pavement marking conditions, the wide median between the on and off-ramp, and the acute angle between ramps and the crossroad are likely to increase the risk of WWD. Cloud 3 describes a location with poor signage and a 50 – 100 ft. non-traversable channelized island on the off-ramp are tends to have WWD. The variables in Clouds 1-3 for "WWD_1" are as follows:

Cloud 1

- Uncontrolled intersection type at ramp terminal (INType_0)
- The number of lanes on the crossroad is at ramp side 1 (CRLaneonrampside_1)
- The corner radius is less than 50 ft (INRAD_0)
- No lighting around the ramp terminal (NEARLIG_0)

Cloud 2

- Pavement markings are not in good condition (PAVCOND_0)
- The median width between on and off-ramp is larger than 60 ft (ERMedwid_2)
- The acute angle between the off-ramp and the crossroad (INANGLE_2)

Cloud 3

- Traffic signs do not meet the minimum requirements of MUTCD (SignEnhanced_0)
- Non-traversable channelized island at the off-ramp terminal (ERChantran_0)
- The length of the channelized island on the off-ramp is between 51 to 100 ft. (ERChanLen_2)

4.4 Prediction of recurring WWD incidents at parclo interchange terminals

The MCA analysis can provide a general idea of what kind of design features at parclo interchange terminals, while working together, may cause or deter WWD. However, the MCA analysis can only explore limited data dimensions and variable categories, it can not quantify the effect of each design feature on WWD nor conduct predictions at specific locations. In this section, the XGboost and Lasso-logistic regression are applied in order to answer these questions.

4.4.1 eXtreme Gradient Boosting

Same as the MCA method, the dataset contains 75 locaitons with design features and WWD information was applied to conduct the XGboost analysis. To optimize the model and obtain the accuracy for classification of the parclo interchange terminals, we conducted parameter tuning to identify the optimal hyperparameters via grid search. The final hyperparameter values used in the model are shown in **Table 4.11**.

Table 4.11 Hyperparameters for eXtreme Gradient Boosting

Hyperparameters	Description	Value
Subsample	Percentage of data used for training	0.75
Min child weight	Minimum instance for new partition	1.00
Max depth	Maximum tree depth	3.00
eta	Learning rate	0.10

As a result, the XGBoost model classifying parclo interchange having recurring or nonrecurring WWD incidents based on design features achieved an average accuracy of 80% on the test data set. The mean SHAP values used for representing the influence of each feature are shown in **Figure 4.15** in descending order. The top-10 features are 1) median on the crossroad did not cover the off-ramp at all, 2) existence of three or more enhanced WW-related signs, 3) median on the crossroad fully covered the off-ramp, 4) two driveways on the ramp side of the crossroad, 5) streetlights available, 6) the length of channelizing island on the off-ramp is less than 50 ft., 7) nearby access point existed within 51– 500 ft., 8) off-ramp terminal is looped, 9) the traffic volume of off-ramp is higher than on-ramp, and 10) the length of channelizing island on the off-ramp is 51–100 ft.

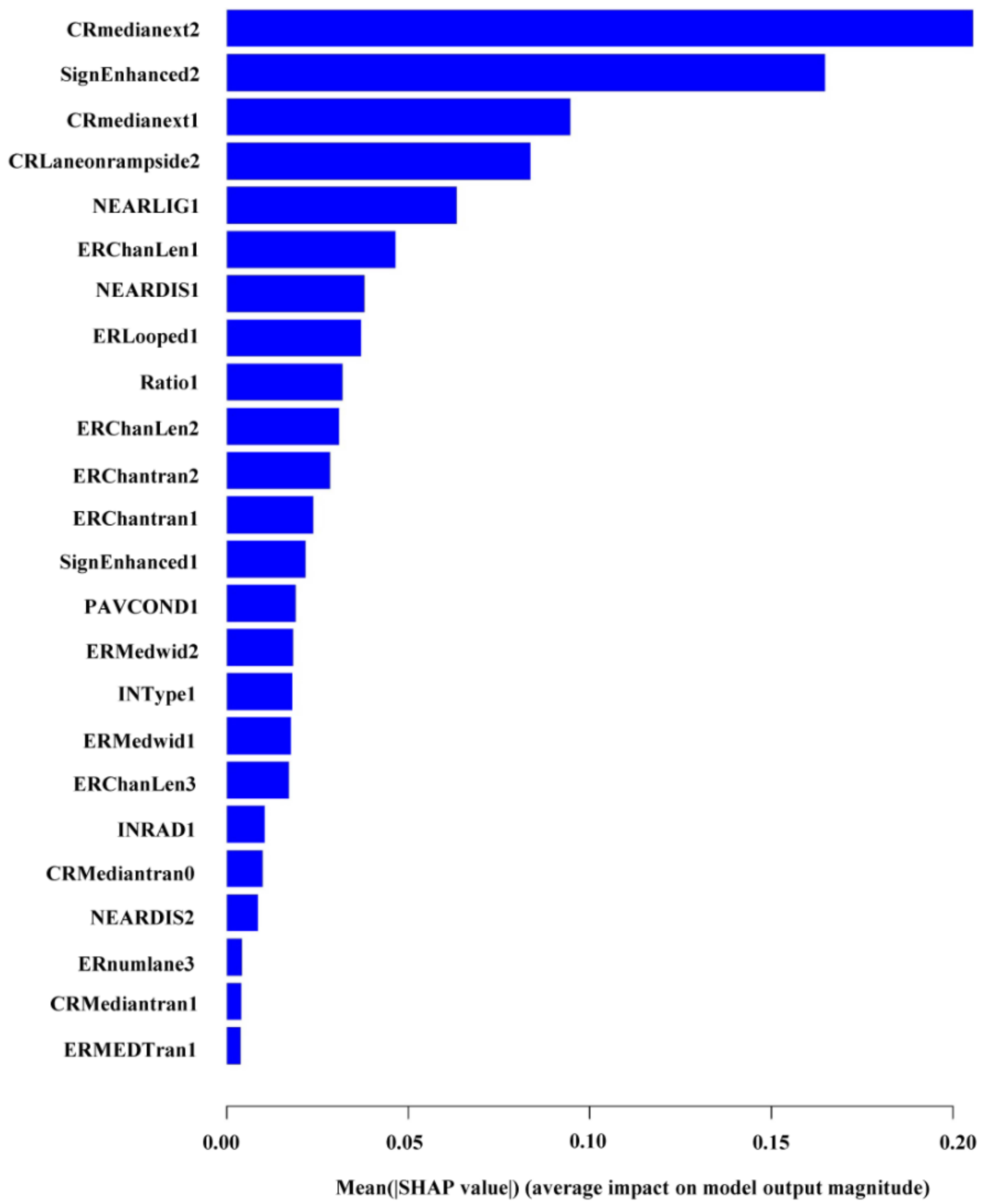

Figure 4.15 Ranking of geometric design and TCD features based on their impact on the occurrence of WWD

To further specify whether the features are positively or negatively related to the occurrence of the recurring WWD incidents, the SHAP values for each influential feature are plotted in **Figure 4.16**. In this analysis, the existence of each feature category can be either recorded as “yes (1)” or “no (0)” represented by the purple and yellow dots. The corresponding horizontal axis value for each point represents the computed SHAP value of each feature during the modeling period.

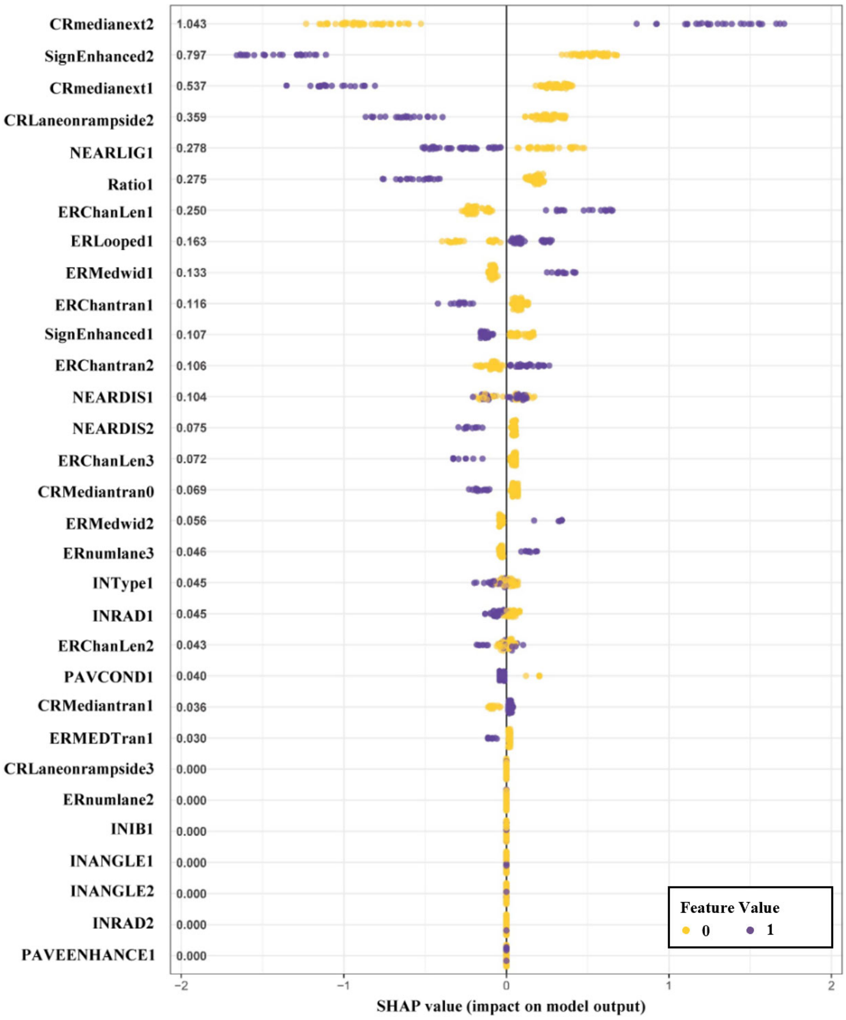

Figure 4.16 Effect of geometric design and TCD features

For example, when feature “CRmedianext2” (median on the crossroad did not extend into the intersection functional area to cover the off-ramp) exists at a specific parclo interchange terminal, the record would be “yes” for “CRmedianext2” and represented by “1”; in **Figure 4.16**, it would be plotted as a purple dot. Then, the corresponding SHAP value for the purple dot on the horizontal axis is shown as a positive value, which illustrates that if the crossroad median did not extend into the intersection functional area to cover the off-ramp, it might increase the risk of WWD. In contrast, when the existence of "CRmedianext2" is recorded as "no" and represented by "0" (indicated as a yellow dot), the corresponding SHAP value is shown negative value, which indicates that covering the off-ramp by extending the median on the crossroad can help in reducing WWD. In summary, it is more likely to have recurring WWD incidents if the median on the crossroad does not extend into the intersection functional area to block the left-turn access to the off-ramp. Based on what we discussed, **Table 4.12** summarizes the design features which may reduce or increase the risk of WWD incidents at parclo interchange terminals, according to **Figure 4.16**.

Table 4.12 Design Features Preventing/Leading to WWD Incidents by XGBoost

Design features preventing WWD incidents	
Coding name	***Description***
SignEnhanced2	*Existence of three or more enhanced WW-related signs*
CRmedianext1	*Median on the crossroad fully covered the off-ramp*
CRLaneonrampside2	*Two driveways on the ramp side of the crossroad*
NEARLIG1	*Existence of streetlighting*
Ratio1	*Higher traffic volume on the off-ramp than on the on-ramp*
ERChantran1	*Channelizing island traversable on the off-ramp*
SignEnhanced1	*Existence of one or two enhanced WW-related signs*
NEARDIS2	*The nearest access point is further than 500 ft.*
ERChanLen3	*The length of the channelizing island is longer than 100 ft.*
CRMediantran0	*Median on the crossroad non-traversable*
INTYPE1	*All-way stop control or signalized ramp terminal*
INRAD1	*Corner radius between 50 to 100 ft.*
PAVCOND1	*Pavement markings in good condition*
Design features leading to WWD incidents	
Coding name	***Description***
CRmedianext2	*Median on the crossroad not covering the off-ramp*
ERChanLen1	*The length of the channelizing island is less than 50 ft.*
ERLooped1	*Looped off-ramp*
ERMedwid1	*The median width on the ramp is between 31 and 60 ft.*
ERChantran2	*No channelizing island on the off-ramp*

NEARDIS1	*Existence of a nearby access point within 51–500 ft*
ERMedwid2	*The width of the median on the ramp is longer than 60 ft.*
ERnumlane3	*Three or more driveways existed on the off-ramp*
CRMediantran1	*Median on the crossroad traversable*

4.4.2 Lasso-logistic regression

Considering the impact of different design features on the occurrence of recurring WWD incidents, the Lasso regression was used to select the most important features. The fivefold cross validation was conducted to identify the misclassification error based on different feature combinations. As shown in **Figure 4.17**, the upper *x*-axis represents the number of features included in the model, while the lower *x*-axis represents the corresponding value of λ, and the *y*-axis represents the misclassification error. Based on the previous study, the proper number of features should be chosen between two dash lines ($\lambda \in [0.02, 0.12]$) shown in **Figure 4.17** to achieve the best performance since the range has the lowest misclassification error with a relatively low fluctuation range (*0*). By increasing the value of λ, fewer features will be selected to keep in the final model. As we want to keep more detailed features as well as have higher accuracy in the final model, the Lasso-logistic model was tuned by using λ from 0.02 to 0.12 with a step of 0.01. The results showed that, when $\lambda = 0.04$, the model achieved the best accuracy at 78% with 11 design features kept.

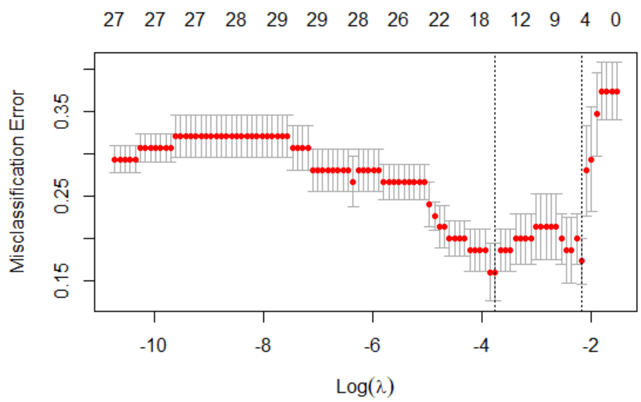

Figure 4.17 Misclassification error for different number of features

Table 4.13 lists all the features that had been selected and the corresponding coefficients for the Lasso-logistic regression model. It should be noticed that all of these variables have the same positive or negative effects on the occurrence of the recurring WWD incidents in comparison with the XGBoost model.

Table 4.13 Design Features Preventing/Leading to WWD Incidents by Lasso-Logistic Regression

(Intercept)		*-0.481*
Design features preventing WWD incidents		
Variables	**Description**	**Coefficients**
SignEnhanced2	*Existence of three or more enhanced WW-related signs*	-1.283
CRmedianext1	*Median on the crossroad fully covered the off-ramp*	-1.277
CRLaneonrampside2	*Two driveways on the ramp side of the crossroad*	-0.969
INRAD2	*Corner radius longer than 100 ft.*	-0.603
ERChanLen3	*The length of the channelizing island is longer than 100 ft.*	-0.588
Ratio1	*Higher traffic volume on the off-ramp than on the on-ramp*	-0.281
NEARDIS2	*The nearest access point is further than 500 ft.*	-0.123
Design features leading to WWD incidents		
Variables	**Description**	**Coefficients**
ERMedwid2	*The width of the median on the ramp is longer than 60 ft.*	1.996
CRmedianext2	*Median on the crossroad not covering the off-ramp*	1.632
ERChanLen1	*The length of the channelizing island is less than 50 ft.*	0.450
ERMedwid1	*Width of median on ramp is between 31 and 60 ft.*	0.392

As shown in **Table 4.13**, the negative sign before the coefficients indicate the design features may reduce the risk of WWD incidents, while the positive sign indicates the design features may increase the risk of WWD incidents. The final fitted Lasso-logistic regression can be represented as **Equation 4-1**, where *P* represents the possibility of the dependent value equal to 1 (a parclo interchange terminal has recurring WWD incidents), and the feature's value inside the bracket is equal to 1 if the feature existed; otherwise, the feature's value shown is counted as 0.

$$\begin{aligned} log(P) = {} & -0.481 - 1.283\ (SignEnhanced2) - 1.277\ (CRmedianex1) \\ & - 0.969\ (CRlaneonrampside2) - 0.603\ (INRAD2) - 0.588\ (ERChanLen3) \\ & - 0.281\ (Ratio1) - 0.123\ (NEARDIS2) + 1.996\ (ERMedwid2) \\ & + 1.632\ (CRmedianext2) + 0.45\ (ERChanLen1) \\ & + 0.392\ (ERMedwid1) \qquad (4-1) \end{aligned}$$

According to **Equation 4-1**, a field design checklist can be created using Excel. As shown in **Figure 4.18**, all the design features considered in the Lasso-logistic regression model were included in the checklist. For a specific parclo interchange terminal, users can easily select the corresponding design features from each dropdown list and estimate the risk of the current terminal having recurring WWD incidents.

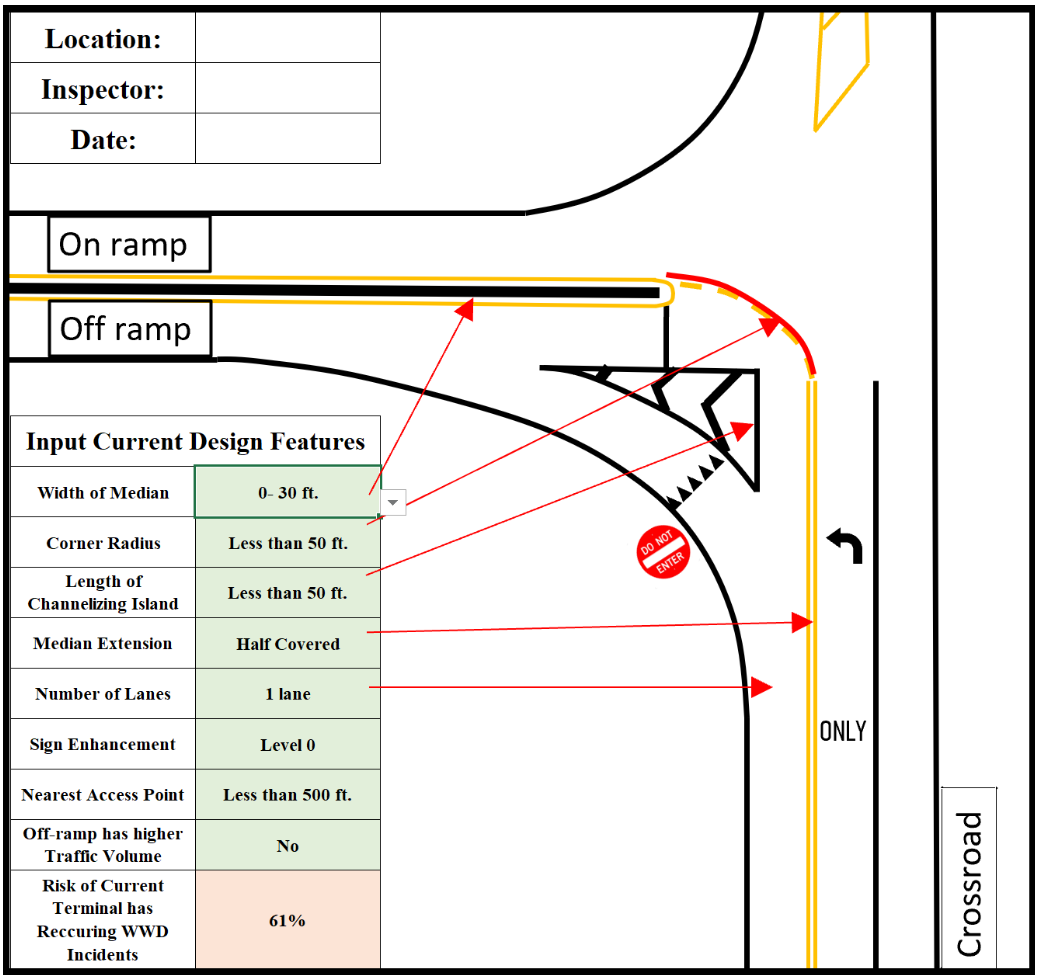

Figure 4.18 Field review checklist

4.4.3 Effects of different design features on WWD

The design features used for modeling were collected based on five aspects: crossroad design, off-ramp design, intersection design, traffic sign, and pavement marking. The results will be presented sequentially.

Crossroad Design

The median on the crossroad plays an important role in deterring WWD, as extending the median into the intersection area and covering the off-ramp opening can efficiently block/limit the WW left turn. This is especially true when there is an exclusive right-turn lane on the off-ramp, which is usually regarded as an on-ramp by WW drivers. WWD incidents are less likely to happen if there are two driveways existing on the ramp side of the crossroad because WW drivers have to drive a long distance from the right path to the wrong path. Previous studies also recommended using a non-traversable median to block the early left turn on the crossroad, while this study further pointed out the proper placement of the median on the crossroad (Atiquzzaman, and Zhou, 2022; Pour-Rouholamin and Zhou, 2016; Zhou and Pour-Rouholamin, 2014; AASHTO, 2011).

Ramp Design

The channelizing island on the off-ramp can reduce the width of the ramp opening, and the non-traversable channelizing island is recommended by current guidelines (Zhou and Pour-Rouholamin, 2014). However, the length of the channelizing island is also important for preventing WWD. The longer length of the channelizing island can causally extend the length of the exclusive right-turn lane; as a result, the exclusive right-turn lane can be closer to parallel with the crossroad. In contrast, a shorter exclusive right-turn lane will have a larger angle with the crossroad, which makes the opening face toward potential left-turn drivers on the crossroad and encourages them to make an early left turn. Based on the results, the length of the channelizing island is recommended to be longer than 100 ft.

The results also showed that the looped off-ramp is more likely to have WWD incidents since the looped off-ramp is always located in the same direction left-turn drivers tend to go. For example, a driver coming from the south and trying to enter the westbound of the freeway is expecting to go west. While the ramps of a parclo interchange terminal can be either built on the west or east side of a crossroad. If the ramps were built on the west side (same as the driver's expectation), the off-ramp would appear first to a driver, and it is looped. It might confuse a driver if he/she does not realize the on-ramp is actually located behind the off-ramp. In contrast, if the ramps were built on the east side of the crossroad (opposite to a driver's expectation), the on-ramp would appear first to a driver, and it would be looped. In this scenario, a driver will have less of a chance to enter the WW.

Although the guidelines developed by IDOT recommended the minimum width of the median on the ramp should be 50 ft., another recent study suggested that the minimum median width should be reduced to the range of 31 to 40 ft. (Pour-Rouholamin and Zhou, IDOT, 2010). However, in this study, the risk of WWD incidents may slightly increase when the width of the ramp on the ramp is between 31 to 60 ft. and rapidly increases when the median is wider than 60 ft. There is no doubt that separating the parallel spaced on-ramp from the off-ramp would reduce driver confusion, but it could be more difficult for drivers to find the on-ramp if it was placed too far away. Another reason causing different results could be the data applied. The previous studies grouped parclo interchange terminals based on WWD crash history; however, parclo interchange terminals without WWD crashes may also have existing recurring WWD incidents. Therefore, engineering judgment should be applied in the real case regarding the width of the median on the ramps.

Intersection Design

The existence of streetlights can help prevent WWD incidents at parclo interchange terminals because they provide better visibility during the night, while the signalized or all-way stop-controlled terminal also provides more reaction time for drivers.

The XGBoost revealed that a corner radius from the left-turn lane to the off-ramp between 51 to 100 ft. could slightly reduce the risk of WWD compared to the locations with shorter or larger turning radius, which remains consistent with the previous guidance (IDOT, 2010). It should be noticed that the Lasso-logistic regression revealed that a corner radius longer than 100 ft. will reduce the chance of WWD incidents, which seems to conflict with previous guidance that recommended the design corner radius from crossroad should be a maximum of 80 ft. (IDOT, 2010). However, based on the concept of feature selection in Lasso-logistic regression, the intersection control type and intersection angle had not been considered to reduce the multicollinearity between features. As a result, a parclo interchange terminal with a corner radius larger than 100 ft. usually represents a large intersection with signalized control or obtuse intersection angle, which could, in tandem, reduce the risk of WWD incidents.

A previous study reveals that the existence of an access point within 600 ft. could increase the chance of WWD. The results represented by this study indicated that the minimum nearest access point could be reduced to 500 ft. (Pour-Rouholamin et al., 2016). Last, if the off-ramp has a higher traffic volume than the on-ramp, the risk of WWD could be decreased. This result remains similar to those in the previous study by showing that the potential WWD incidents will increase when left-turn volume toward an entrance ramp increases and stopped vehicles at an exit ramp decrease (Atiquzzaman et al., 2022; Atiquzzaman et al., 2020; Baratian-Ghorghi et al., 2015).

Traffic Sign

The model results indicated that the enlarged, low-mounted DNE signs, red retroreflective tape on the sign pole, and extra guide signs could reduce the risk of WWD incidents. This finding is consistent with the existing guidelines developed by the state and local agencies.

Pavement Marking

Based on the mathematical model, the pavement marking did not show a significant effect on the occurrence of WWD incidents. This is because 93% of monitored locations are well maintained.

Chapter 5 Proposed Guidelines for Preventing WWD

5.1 WW signs and WW arrow implementation

WW signs and WW arrows are widely adopted traditional-TCDs for deterring WWD. According to the current MUTCD section 2B.41, at least one WW sign should be placed at the off-ramp facing potential WW drivers. However, the current MUTCD does not specify the installation positions for the WW sign or WW arrow. Based on this study, the following design guidance can be proposed, as shown in **Figure 5.1**:

- **Place the first set of WW sign(s)/arrows within 100 ft of the DNE sign.**

The study results from **Section 4.1.2** have shown that placement of the first set of WW sign(s) closer to the DNE sign could reduce the average WWD distance. A cross-sectional comparison found that WWD distance is significantly shorter at off-ramps where the first set of WW signs are located approximately 100 ft from the DNE sign.

- **Consider using a second or third set of WW signs along off-ramps.**

The study results from **Section 4.1.1** found that a second set and third set of WW signs can stop approximately 12% and 5% of WWD, respectively, with approximately 80% of WW drivers turning around before the first set of WW signs. A second or third set of WW-related countermeasures should be placed at high-risk locations such as parclo interchange terminals with recurring WWD incidents. Typically, a distance of approximately 350 ft was commonly used between two consecutive sets of WW sign(s), so the second and third pair of WW-related countermeasures should be placed at 450 ft. and 800 ft. from the end of the off-ramp, respectively.

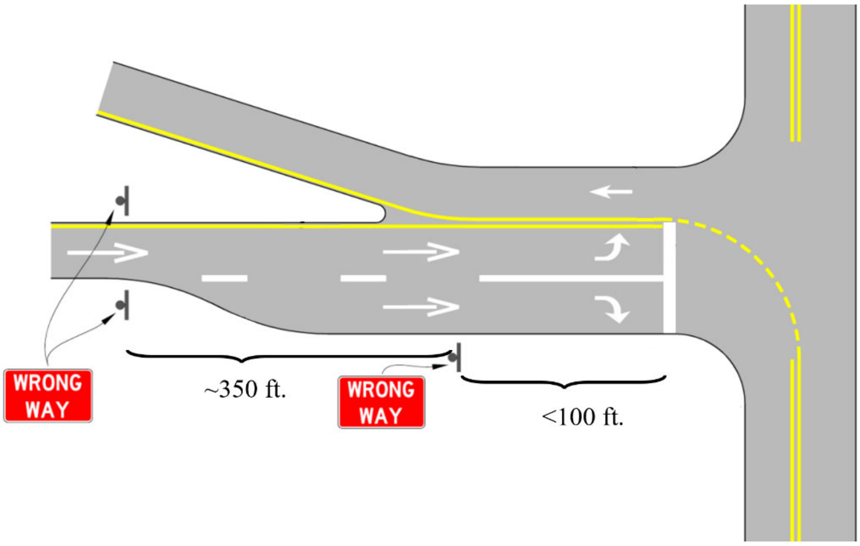

Figure 5.1 Placement of WW sign(s) and WW arrow(s)

5.2 Geometric design elements

Geometric design elements play an important role in causing/deterring WWD. This study investigated the effects of geometric design elements on WWD at parclo interchange terminals, and the design guidelines are proposed in this section.

Deterring WWD incidents entering through ELT:

Based on the results from **Section 4.2.1**, a majority of WWD (77%) entered through ELT at the locations with channelizing islands. Three engineering solutions can be developed by blocking potential WWD routes or slowing down vehicle speeds at parclo off-ramp terminals:

- **Use of a longer channelizing island at the throat of the off-ramps and make the exclusive right-turn lane near parallel to the crossroad to discourage the ELT.**

  The opening of the off-ramp right-turn lanes facing to the left-turning drivers is one of the most important factors causing ELT. Based on the relationships between potential WWD route and off-ramp channelizing islands developed by **Section 4.2.1**, longer channelizing islands (>100 ft.) should be considered for parclo interchange terminals. For the locations with multiple driveways at the crossroad, the length of channelizing island can be reduced correspondently based on **Equation 4-1**.

- **Use a non-traversable median on the crossroad, such as a quick curb or low-mounted concrete barrier, instead of the double yellow line to block the existing potential WWD route, especially at Parclo B interchange terminals.**

  Instead of conducting geometric design modifications such as extending the length of channelizing islands, a non-traversable median on the crossroad could be considered to physically block the potential of ELT.

- **Use of all-way stop control at the terminal, forcing drivers to slow down and stop instead of making a permissive left-turn when there is an acceptable gap from the opposite direction of traffic.**

  A controlled intersection could force vehicles to stop close to the functional area of the intersection, which could eliminate the risk of making ELT.

Deterring WWD incidents entering through LT:

- **The median on the crossroad should be extended into the functional area to block the off-ramp opening to prevent WW left turn.**

  Due to the parallel spaced on- and off-ramp of parclo interchange terminals, vehicles may enter the off-ramp instead of the on-ramp. Regarding this issue, the median on the crossroad for left-turning drivers can be extended into the intersection functional area, providing better guidance for left-turning drivers while entering the on-ramp.

- **When the number of lanes on the off-ramp side is more than two, narrow the off-ramp opening to prevent WW left turn caused by a large turning radius.**

When the number of lanes on the off-ramp of parclo interchange terminals is more than two (which usually appeared at urban areas), the opening of the off-ramp will be too wide for vehicles making WW left turn. Channelizing island should be considered to narrow the opening by adding a bypass for right-turn traffics.

Other

- **Consider median opening between on- and off-ramp to help WW motorist back to the right route.**

  Making a U-turn after entering the off-ramp cloud be challenging and dangerous for WW drivers; an opening on the median between on- and off-ramp should be considered for parclo interchange terminals for them to make the correction. The results from **section 4.1.1** show that the average WWD distance is 38 ft. before stopping; the median opening should be considered to be placed further than 38 ft. from the end of the crossroad.

Chapter 6 Conclusions

This study aims to utilize WWD incident data to estimate the effects of different design features on WWD and predict the risk of WWD at parclo interchange terminals, providing practical design guidance for deterring WWD and evaluating the effectiveness of low-cost wrong-way-related countermeasures. The literature review showed that the WWD incident data was rarely used or studied in the past. In order to come up with solid solutions, there is a need to analyze such kinds of events to understand the generation of WWD better. A total of 5,984 hours of videos were collected at 75 parclo interchange terminals in 13 states, and 410 cases of WWD incidents were captured at 28 locations. The study results have proven the effectiveness of low-cost WW-related countermeasures and several design deficiencies that haven't been well addressed in the past studies. Three machine-learning methods, including MCA, XGBoost, and Lasso-logistic regression, were adopted to describe the design features or combinations that could cause/deter WWD at parclo interchange terminals. The design checklist developed based on the results of Lasso-logistic regression can be utilized to efficiently predict the risk of WWD at parclo interchange terminals during the network screening process. Below are the conclusions from each section:

Effectiveness of WW sign(s) and WW arrow(s)

The analysis of WWD incidents suggested that a large percentage (80%) of drivers were stopped and made corrective turn-around before the first set of WW sign(s) or WW arrow(s). However, the second pair of WW signs should still be considered since approximately 20% of WWD vehicles drove past the first pair of WW sign(s). Around 9% of WW drivers passed all the WW signs and WW arrows on the off-ramp and never turned around. Apparently, advanced ITS technologies may be considered for preventing these 9% WW drivers from entering the freeway mainline. The WWD distance analysis revealed that placing the first set of WW-related TCDs within 100 ft. from the end of the off-ramp could significantly reduce the WWD distance. This implies that the WW-related TCDs should be placed closer to the end of the off-ramp to help drivers make the corrective turn-around maneuver.

WWD entering through ELT and LT

Based on 175 WWD incidents at 17 parclo interchange terminals, it was found that approximately 77% of WWD experienced an ELT from the crossroad to the exclusive right-turn lane on the off-ramp. The study revealed that the design of the exclusive right-turn lane generated by a channelizing island on the off-ramp that directly merges into the crossroad with a large angle could appeal to left-turn drivers for making wrong-way ELT. The following is a combination of design features that can cause wrong-way ELT at parclo interchange terminals with an exclusive right-turn lane on an off-ramp:

- The connection angle between the off-ramp right-turn lane and crossroad is too large, which can generate a smooth WWD route.
- Use of traversable median on the crossroad at off-ramp terminals.
- Permissive left turns from the crossroad to the on-ramp.

An equation was developed to test the existence of a potential WWD route at parclo interchange terminals by using the radius generated by the curve of the channelizing island and the angle between the off-ramp right-turn lane and the crossroad. The intrusion distance on the crossroad can be calculated, which can be used to determine the existence of a potential WWD route from the crossroad to the off-ramp right-turn lane.

Comparing the parclo interchange terminals with a high frequency of WWD incidents versus the locations with a low frequency of WWD incidents, the parclo type B design was revealed to be the primary cause. This is because the parclo type B terminal has a similar configuration to diamond interchange terminals (off-ramp located in the same direction as the traveler's expected direction). In real practice, the practitioners should pay more attention to the parclo type B interchange terminals as it could cause way more WWD incidents than type A.

Prediction of recurring WWD incidents at parclo interchange terminals

Three machine learning techniques were used to explore the effect of design features on WWD incidents. The results indicated that those design features and TCDS could reduce the risk of WWD incidents: (1) median extension on the crossroad that fully covers the off-ramp opening; (2) enlarged, lower-mounted WW-related signs with red reflective tape and extra guidance signs; (3) street lighting at ramp terminals; (4) higher vehicle occupancy on off-ramp than on-ramp; (5) for the two-direction crossroad, having two driveways on the ramp side; (6) ramp terminal signalized or all-way stop-controlled; (7) a corner radius from the crossroad to the off-ramp between 50 to 100 ft.; (8) no nearby access point within 51 to 500 ft.; and (9) having the channelizing island on the off-ramp opening longer than 100 ft. The design features that may increase the risk of WWD incidents include the median on the crossroad not covering the off-ramp opening, the parclo type B terminal, the length of the channelizing island on the off-ramp opening less than 50 ft. and no channelizing island on the off-ramp. The results generated by MCA could provide a general idea of what kind of parclo interchange terminals may cause/deter WWD. The results generated by XGBoost were visualized based on the SHAP value, which evaluated more design features regarding the occurrence of WWD incidents. Engineers could take advantage of these results to improve off-ramp terminal design to deter WWD. The results generated by Lasso-logistic regression were represented as an expression, and the probability of whether a parclo interchange terminal has recurring WWD incidents could be calculated by inputting the specific design features. The engineers could apply these results to conduct evaluations and safety diagnoses in the field.

Chapter 7 Limitations and Future Study

This study aims to evaluate the effects of geometric design features and traditional traffic control devices at parclo interchange terminals on WWD incidents. Furthermore, the prediction model was developed to estimate the risk of recurring WWD incidents at specific locations. In this chapter, the limitations and the future study needed of this study are discussed.

WWD incidents are rare; although some interchange terminals have recurring WWD incidents, it usually won't appear more than one incident per day. As a result, manually identifying WWD incidents from normal traffic monitoring videos is a very challenging task. In this study, the author and his colleagues manually reviewed around 6,000 hours of videos in order to find evidence of WWD, which is very time-consuming. Now the research team is developing computer-vision-based algorithms in order to automatically identify WWD incidents from normal traffic monitoring videos. Currently, the most challenging task is how to recognize vehicles precisely from the videos during the nighttime.

Due to the time, budget, and limitations of current portable traffic cameras, most of the study locations were monitored for 50-72 hours to determine whether WWD incidents are occurring. Although the team tried to monitor during the weekend (which has more chance of capturing WWD), whether the WWD incident can be captured or not could be affected by regression to mean error. In the future study, the monitoring time frame should be extended if the time, budget and equipment permit.

This study focuses on parclo interchange terminals since this type of design was reported to have more WWD crashes than other types of interchange terminals. In order to eliminate WWD crashes, estimating the risk of WWD for other types of interchange terminals is still needed. On the other hand, the relationships between WWD incidents and crashes should be further explored in order to conduct an economic analysis. Knowing the benefits of eliminating the recurring WWD incidents at interchange terminals will help local practitioners conduct countermeasures selection and economic appraisal while dealing with WWD issues.

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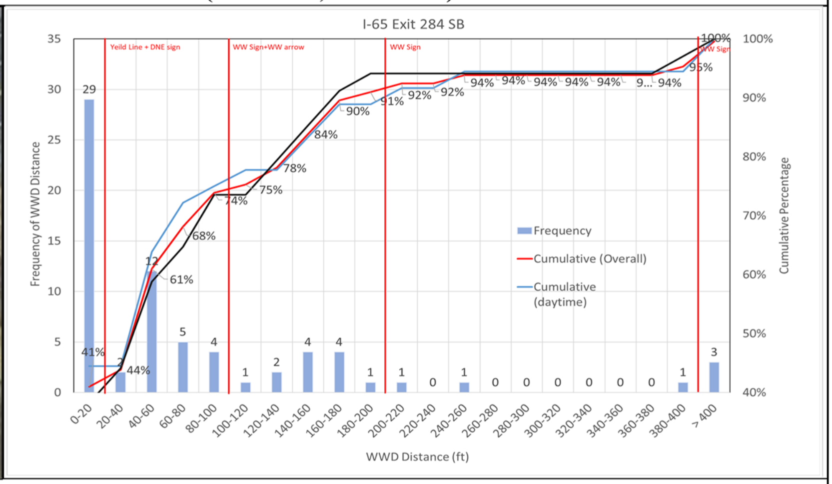
Appendix: Summary of 28 Locations with Recurring WWD

AL I65 Exit 284 SB (33.847815, -86.828421)								



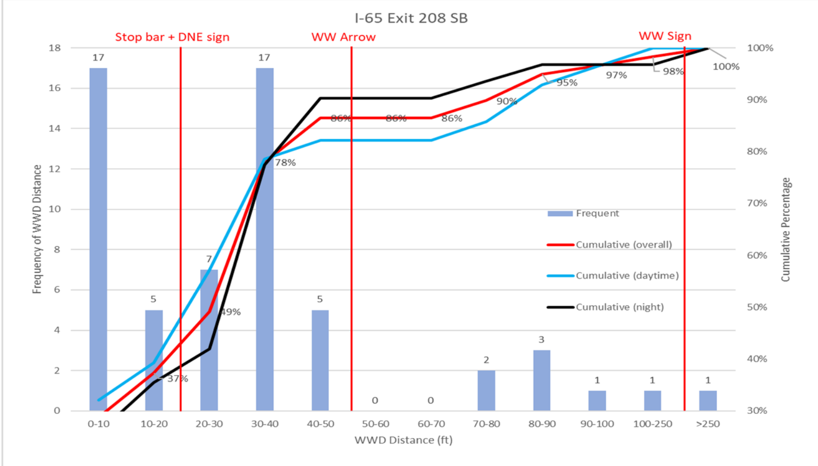
Site Geometric Design Information								
Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		0			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	1	0	1	25 ft	1	0	5 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		38%		Straight		25 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		1		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	0		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	369 ft				0			
AADT	Exit ramp				Entrance ramp			
	1070				7270			

WWD Incidents at AL I65 Exit 284 SB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	3.4	12.0	90	Night	Sunny
2	3.5	13.2	40	Night	Sunny
3	3.9	1.5	50	Night	Sunny
4	3.5	24.1	124	Dawn	Sunny
5	4.1	2.2	60	Daylight	Sunny
6	6.6	36.7	118	Daylight	Sunny
7	2.5	0.8	10	Daylight	Sunny
8	3.0	0.8	10	Daylight	Sunny
9	2.7	1.6	8	Night	Sunny
10	6.4	10.1	5	Night	Sunny
11	5.5	10.7	100	Night	Sunny
12	2.9	4.6	5	Dawn	Sunny
13	5.8	5.7	20	Daylight	Sunny
14	3.2	2.5	15	Daylight	Sunny
15	3.6	0.5	5	Daylight	Sunny
16	2.6	1.9	20	Daylight	Sunny
17	4.3	8.2	50	Night	Sunny
18	4.6	9.0	45	Daylight	Cloudy
19	8.6	49.2	255	Daylight	sunny
20	4.7	17.4	60	Daylight	Rain
21	4.0	10.4	70	Daylight	Sunny
22	4.2	4.0	50	Dusk	Sunny
23	7.0	12.4	90	Daylight	Sunny
24	3.3	4.8	10	Daylight	Sunny
25	3.3	7.9	5	Daylight	Cloudy
26	13.3	43.5	480	Daylight	Sunny
27	4.4	1.8	10	Daylight	Sunny
28	6.4	17.8	160	Daylight	Cloudy
29	4.7	1.3	15	Daylight	Sunny
30	3.3	9.7	47	Dusk	Sunny
31	3.6	1.6	5	Daylight	Sunny
32	5.9	5.9	56	Daylight	Sunny
33	4.0	7.2	60	Daylight	Sunny
34	9.0	16.1	210	Daylight	Sunny
35	10.4	44.5	180	Daylight	Sunny
36	3.1	3.5	10	Daylight	Sunny

37	2.4	4.5	10	Daylight	Sunny
38	6.2	5.1	15	Dusk	Sunny
39	7.1	24.6	80	Daylight	Sunny
40	6.2	6.9	70	Daylight	Sunny
41	99999	99999	99999	Daylight	Sunny
42	13.0	22.0	180	Night	Sunny
43	9.9	20.1	160	Night	Sunny
44	6.1	3.0	15	Night	Sunny
45	7.0	17.8	160	Daylight	Sunny
46	5.2	5.4	170	Daylight	Sunny
47	4.5	2.6	5	Night	Sunny
48	2.1	5.3	10	Night	Sunny
49	12.3	61.8	60	Night	Sunny
50	3.3	6.7	50	Daylight	Sunny
51	9.7	4.2	60	Daylight	Sunny
52	3.5	6.1	10	Night	Sunny
53	8.2	24.7	550	Night	Sunny
54	2.7	1.7	10	Daylight	Sunny
55	3.8	9.1	15	Night	Rain
56	4.7	10.3	80	Night	Rain
57	6.9	25.6	400	Night	Rain
58	4.5	12.2	90	Night	Rain
59	4.8	16.3	160	Night	Sunny
60	4.4	8.0	190	Night	Rain
61	12.8	30.2	125	Night	Rain
62	3.9	6.5	40	Night	Rain
63	4.9	11.5	20	Night	Rain
64	2.5	10.7	5	Daylight	Rain
65	4.6	22.4	70	Night	Rain
66	4.9	18.5	20	Night	Rain
67	3.5	10.7	10	Night	Rain
68	4.3	7.9	5	Night	Rain
69	2.2	5.5	5	Daylight	Sunny
70	5.1	38.8	180	Night	Sunny

Notes: 99999 = No data available since the vehicle never came back

AL I65 Exit 208 SB (32.843625, -86.597013)



Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		0			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	3	0	N	N	0	0	100 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		40%		Straight		32 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	0		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	136 ft				0			
AADT	Exit ramp				Entrance ramp			
	1270				1390			

WWD Incidents at AL I65 Exit 208 SB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	4.3	37.3	50	Dusk	Sunny
2	5.8	32.2	20	Night	Sunny
3	2.5	2.5	10	Night	Sunny
4	3.9	6.6	30	Night	Sunny
5	6.8	21.7	40	Night	Sunny
6	3.4	12.3	40	Night	Sunny
7	4.6	17.7	30	Night	Sunny
8	4.4	15.5	40	Night	Sunny
9	3.2	11.8	10	Night	Sunny
10	3.8	11.4	40	Daylight	Sunny
11	6.1	17.8	10	Dusk	Sunny
12	3.6	15.4	20	Night	Sunny
13	7.0	5.5	10	Night	Sunny
14	7.2	19.9	40	Night	Sunny
15	3.3	13.7	20	Daylight	Sunny
16	2.7	2.0	10	Daylight	Sunny
17	4.7	18.7	90	Daylight	Sunny
18	4.5	28.2	10	Daylight	Cloudy
19	7.1	19.8	95	Daylight	Rain
20	5.4	57.9	40	Night	Foggy
21	7.2	45.5	40	Daylight	Sunny
22	5.3	3.7	10	Daylight	Sunny
23	2.6	1.9	5	Daylight	Sunny
24	4.5	10.2	40	Daylight	Sunny
25	2.9	7.0	5	Daylight	Sunny
26	6.9	20.2	30	Daylight	Sunny
27	4.7	3.0	10	Daylight	Sunny
28	4.5	23.2	15	Daylight	Sunny
29	4.8	19.4	40	Dawn	Sunny
30	3.8	13.8	5	Dawn	Sunny
31	5.3	22.5	30	Daylight	Sunny
32	5.6	65.3	40	Night	Sunny
33	3.4	2.0	10	Daylight	Sunny
34	4.8	49.9	10	Night	Sunny
35	5.4	15.0	15	Night	Sunny
36	7.4	43.4	40	Night	Sunny
37	7.9	19.6	40	Night	Sunny

38	7.9	63.1	80	Night	Sunny
39	5.4	17.1	40	Night	Sunny
40	2.9	2.4	10	Daylight	Sunny
41	5.3	11.8	45	Daylight	Sunny
42	3.9	37.2	40	Night	Sunny
43	3.1	13.9	10	Night	Sunny
44	2.2	3.2	5	Daylight	Sunny
45	2.7	4.3	30	Daylight	Sunny
46	4.9	15.5	50	Night	Sunny
47	7.0	16.4	90	Night	Sunny
48	3.1	15.7	40	Daylight	Sunny
49	10.3	82.3	85	Daylight	Sunny
50	6.0	20.9	40	Daylight	Sunny
51	7.3	27.0	45	Night	Sunny
52	11.7	12.7	300	Night	Sunny
53	5.8	12.3	30	Daylight	Rain
54	7.5	191.1	230	Daylight	Rain
55	4.5	24.0	30	Daylight	Windy
56	3.1	21.5	10	Night	Sunny
57	4.4	17.4	40	Daylight	Windy
58	3.5	14.6	45	Dawn	Sunny
59	9.5	86.9	80	Daylight	Sunny

AL I65 Exit 208 NB (32.843393, -86.593240)

Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		0			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	2	0	N	N	0	0	73 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		42%		Acute		50 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	1	1		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	0		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				0			
AADT	Exit ramp				Entrance ramp			
	1040				1320			

WWD Incidents at AL I65 Exit 208 NB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	3.5	8.5	30	Night	Sunny

<table>
<tr><th colspan="9">TX I635 Exit 15 SB (32.894497, -96.712814)</th></tr>
<tr><td colspan="9"></td></tr>
<tr><th colspan="9">Site Geometric Design Information</th></tr>
<tr><th rowspan="2">Crossroad Design</th><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">2</td><td colspan="3">3</td></tr>
<tr><th rowspan="2">Exit Ramp</th><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>3</td><td>3</td><td>0</td><td>N</td><td>N</td><td>0</td><td>0</td><td>10 ft</td></tr>
<tr><th rowspan="2">Intersection</th><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">1</td><td colspan="2">50%</td><td colspan="2">Straight</td><td colspan="2">68 ft</td></tr>
<tr><th rowspan="2">Signs</th><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td colspan="2">0</td><td colspan="2">1</td><td>1</td></tr>
<tr><th rowspan="2">Pavement Markings</th><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><th rowspan="2">Nearby Environment</th><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">0 ft</td><td colspan="4">1</td></tr>
<tr><th rowspan="2">AADT</th><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">5120</td><td colspan="4">8487</td></tr>
</table>

WWD Incidents at TX I635 Exit 15 SB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	4.5	14.7	40	Light	Sunny
2	3.5	0.8	10	Light	Sunny
3	2.0	4.0	10	Light	Sunny

<table>
<tr><th colspan="9">TX I35 Exit 370 NB (32.045427, -97.093228)</th></tr>
<tr><td colspan="9"></td></tr>
<tr><th colspan="9">Site Geometric Design Information</th></tr>
<tr><th rowspan="2">Crossroad Design</th><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">2</td><td colspan="3">2</td></tr>
<tr><th rowspan="2">Exit Ramp</th><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>0</td><td>52 ft</td><td>1</td><td>0</td><td>50 ft</td></tr>
<tr><th rowspan="2">Intersection</th><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">0</td><td colspan="2">50%</td><td colspan="2">Straight</td><td colspan="2">76 ft</td></tr>
<tr><th rowspan="2">Signs</th><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td colspan="2">0</td><td colspan="2">0</td><td>0</td></tr>
<tr><th rowspan="2">Pavement Markings</th><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><th rowspan="2">Nearby Environment</th><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">300 ft</td><td colspan="4">1</td></tr>
<tr><th rowspan="2">AADT</th><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">945</td><td colspan="4">1154</td></tr>
</table>

WWD Incidents at I35 Exit 370 NB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	6.5	7.8	70	Night	Sunny

MS I20 Exit 1A WB (32.312072, -90.899609)

Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			3		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	1	1	0	157 ft	1	0	16.7 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	1		43%		Straight		69 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	1	0		1		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				1			
AADT	Exit ramp				Entrance ramp			
	3100				8700			

WWD Incidents at MS I20 Exit 1A WB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	4.2	10.5	25	Night	Sunny

MS I59 Exit 97 SB (31.697750, -89.118541)

Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	1	1	0	91 ft	1	0	21 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		51%		Straight		41 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		1		1
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				1			
AADT	Exit ramp				Entrance ramp			
	1700				7600			

WWD Incidents at MS I59 Exit 97 SB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	1.9	5.5	10	Night	Sunny
2	3.1	9.5	85	Daylight	Sunny
3	2.5	4.5	20	Daylight	Sunny
4	2.5	5.5	85	Daylight	Sunny
5	11.7	9.3	200	Daylight	Sunny

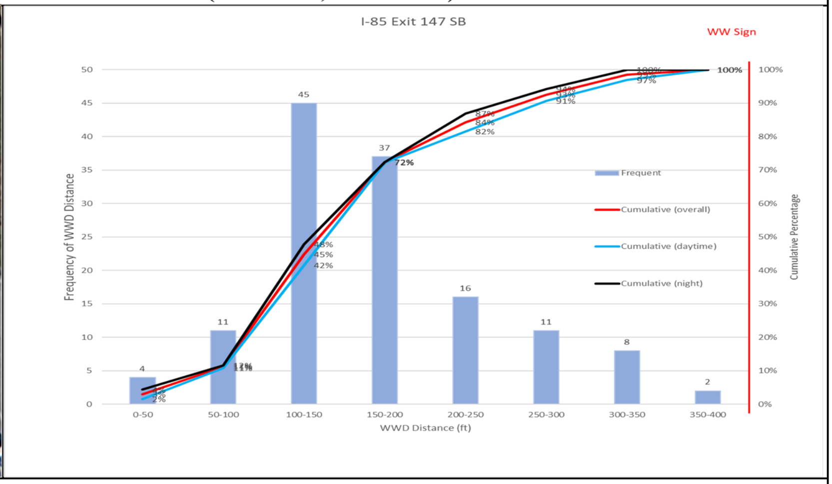
MS I22 Exit 85 EB (34.302079, -88.723865)

Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	3	0	N	N	0	0	13 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		53%		Straight		47 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	0	0	0	0		1		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				0			
AADT	Exit ramp				Entrance ramp			
	1800				2600			

WWD Incidents at MS I22 Exit 85 EB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	3.8	15.5	30	Daylight	Sunny

GA I85 Exit 147 SB (34.230977, -83.500435)



Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	1	0	0	40 ft	1	1	8 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		59%		Straight		47 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				0			
AADT	Exit ramp				Entrance ramp			
	970				2460			

WWD Incidents at GA I85 Exit 147 SB

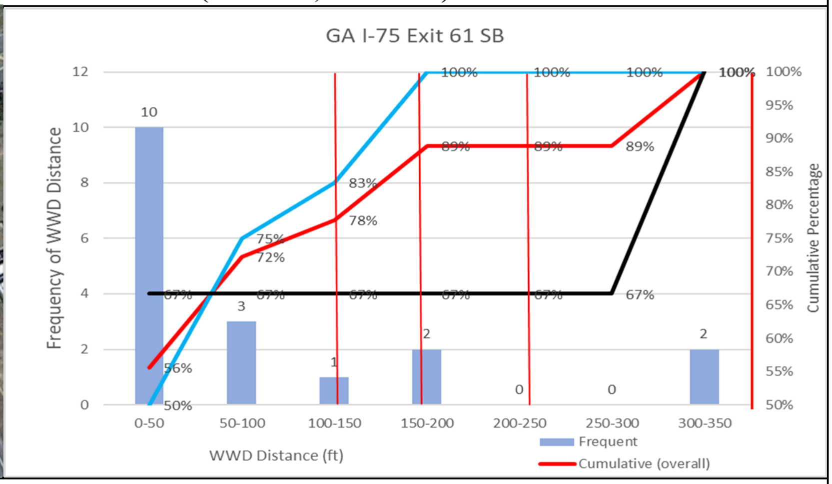
NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	0.0	0.0	140	Night	Sunny
2	6.4	0.0	170	Night	Sunny
3	0.0	0.0	100	Night	Sunny
4	0.0	0.0	110	Night	Sunny
5	4.3	0.0	65	Night	Sunny
6	0.0	0.0	160	Night	Sunny
7	3.5	10.7	40	Dawn	Sunny
8	0.0	0.0	110	Daylight	Sunny
9	0.0	0.0	190	Daylight	Sunny
10	2.7	5.5	30	Daylight	Sunny
11	0.0	0.0	80	Daylight	Sunny
12	0.0	0.0	120	Daylight	Sunny
13	11.5	8.2	390	Daylight	Sunny
14	7.6	0.8	260	Daylight	Sunny
15	0.0	0.0	230	Daylight	Sunny
16	0.0	0.0	170	Daylight	Sunny
17	0.0	0.0	210	Daylight	Sunny
18	0.0	0.0	170	Daylight	Sunny
19	0.0	0.0	130	Night	Sunny
20	7.8	2.1	340	Night	Sunny
21	0.0	0.0	210	Night	Sunny
22	0.0	0.0	170	Night	Sunny
23	0.0	0.0	160	Daylight	Sunny
24	0.0	0.0	210	Daylight	Sunny
25	5.4	0.7	200	Daylight	Sunny
26	0.0	0.0	180	Daylight	Sunny
27	4.7	0.5	300	Daylight	Sunny
28	0.0	0.0	200	Daylight	Sunny
29	3.7	0.0	100	Night	Sunny
30	9.6	1.5	350	Night	Sunny
31	12.0	1.0	330	Night	Sunny
32	0.0	0.0	260	Night	Sunny
33	0.0	0.0	160	Night	Sunny
34	6.3	0.0	230	Night	Sunny
35	0.0	0.0	180	Night	Sunny
36	0.0	0.0	110	Night	Sunny
37	9.1	1.0	140	Night	Sunny
38	0.0	0.0	100	Night	Sunny

39	12.0	0.0	300	Night	Sunny
40	0.0	0.0	150	Daylight	Sunny
41	0.0	0.0	120	Daylight	Sunny
42	0.0	0.0	270	Daylight	Sunny
43	0.0	0.0	130	Daylight	Sunny
44	0.0	0.0	130	Daylight	Sunny
45	0.0	0.0	200	Daylight	Sunny
46	0.0	0.0	200	Daylight	Sunny
47	0.0	0.0	140	Daylight	Sunny
48	0.0	0.0	150	Daylight	Sunny
49	0.0	0.0	120	Daylight	Sunny
50	0.0	0.0	170	Daylight	Sunny
51	0.0	0.0	170	Daylight	Sunny
52	7.1	0.6	290	Daylight	Sunny
53	4.5	0.5	200	Daylight	Sunny
54	0.0	0.0	180	Daylight	Sunny
55	0.0	0.0	280	Daylight	Sunny
56	0.0	0.0	160	Daylight	Sunny
57	0.0	0.0	110	Daylight	Sunny
58	0.0	0.0	200	Daylight	Sunny
59	11.0	1.1	350	Daylight	Sunny
60	0.0	0.0	150	Daylight	Sunny
61	4.5	0.6	120	Night	Light rain
62	3.1	13.5	20	Night	Light rain
63	7.2	1.1	240	Night	Sunny
64	0.0	0.0	230	Night	Sunny
65	3.5	2.7	200	Night	Sunny
66	11.1	0.8	210	Night	Sunny
67	2.9	3.1	120	Night	Sunny
68	0.0	0.0	140	Night	Sunny
69	0.0	0.0	220	Night	Sunny
70	0.0	0.0	200	Night	Sunny
71	0.0	0.0	230	Night	Sunny
72	5.1	1.9	120	Night	Sunny
73	0.0	0.0	140	Night	Sunny
74	0.0	0.0	140	Daylight	Sunny
75	0.0	0.0	140	Night	Sunny
76	0.0	0.0	140	Night	Sunny
77	0.0	0.0	120	Night	Sunny
78	0.0	0.0	100	Night	Sunny
79	0.0	0.0	170	Night	Sunny

80	0.0	0.0	140	Night	Sunny
81	0.0	0.0	170	Night	Sunny
82	0.0	0.0	180	Night	Sunny
83	9.5	1.5	290	Night	Sunny
84	15.2	2.5	330	Night	Sunny
85	9.7	11.1	400	Daylight	Sunny
86	0.0	0.0	180	Daylight	Sunny
87	9.1	12.1	140	Daylight	Sunny
88	3.2	5.1	120	Daylight	Sunny
89	5.5	1.2	200	Daylight	Sunny
90	10.7	0.5	300	Daylight	Sunny
91	11.1	0.3	310	Daylight	Sunny
92	0.0	0.0	170	Daylight	Sunny
93	9.3	2.2	290	Night	Sunny
94	0.0	0.0	120	Night	Sunny
95	0.0	0.0	210	Night	Sunny
96	0.0	0.0	110	Night	Sunny
97	4.0	0.0	0	Night	Sunny
98	0.0	0.0	120	Night	Sunny
99	0.0	0.0	180	Night	Sunny
100	0.0	0.0	190	Daylight	Sunny
101	0.0	0.0	220	Daylight	Sunny
102	0.0	0.0	120	Daylight	Sunny
103	0.0	0.0	100	Daylight	Sunny
104	0.0	0.0	140	Daylight	Sunny
105	0.0	0.0	100	Daylight	Sunny
106	5.4	2.1	110	Daylight	Sunny
107	8.9	1.7	210	Daylight	Sunny
108	0.0	0.0	300	Night	Sunny
109	0.0	0.0	140	Night	Sunny
110	11.5	0.5	200	Night	Sunny
111	9.3	0.8	210	Night	Sunny
112	0.0	0.0	140	Night	Sunny
113	0.0	0.0	180	Night	Sunny
114	0.0	0.0	200	Night	Sunny
115	0.0	0.0	150	Night	Sunny
116	0.0	0.0	120	Night	Sunny
117	0.0	0.0	170	Night	Sunny
118	0.0	0.0	200	Night	Sunny
119	0.0	0.0	150	Night	Sunny
120	0.0	0.0	140	Night	Sunny

121	5.4	0.7	120	Night	Sunny
122	0.0	0.0	180	Night	Sunny
123	7.2	0.9	210	Night	Sunny
124	19.2	12.5	330	Daylight	Sunny
125	0.0	0.0	240	Daylight	Sunny
126	5.4	2.3	200	Daylight	Sunny
127	0.0	0.0	100	Daylight	Sunny
128	0.0	0.0	120	Daylight	Sunny
129	0.0	0.0	110	Daylight	Sunny
130	0.0	0.0	100	Daylight	Sunny
131	4.5	3.1	100	Daylight	Sunny
132	11.2	9.8	330	Daylight	Sunny
133	0.0	0.0	130	Daylight	Sunny
134	0.0	0.0	130	Night	Sunny

GA I75 Exit 61 SB (31.442102, -83.526120)								



Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	3	1	N	N	0	1	5 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		36%		Straight		35 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	0	0	0	0		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				1			
AADT	Exit ramp				Entrance ramp			
	960				1510			

WWD Incidents at GA I75 Exit 61 SB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	2.2	5.1	25	Day	Cloudy
2	6.1	19.3	155	Day	Cloudy
3	3.5	3.1	35	Day	Cloudy
4	8.7	12.5	190	Day	Cloudy
5	4.3	2.1	45	Day	Cloudy
6	5.5	8.9	65	Day	Cloudy
7	1.3	1.6	5	Day	Cloudy
8	1.9	2.1	20	Day	Cloudy
9	3.1	4.9	20	Night	Cloudy
10	0.5	1.1	0	Night	Cloudy
11	0.3	0.5	0	Night	Cloudy
12	9.1	17.1	400	Night	Cloudy
13	7.5	9.8	320	Night	Cloudy
14	3.8	15.1	50	Night	Cloudy
15	4.1	2.9	80	Day	Sunny
16	4.5	9.1	20	Day	Sunny
17	5.8	11.1	90	Day	Sunny
18	5.7	17.8	140	Day	Sunny

AR I40 Exit 260 WB (35.13178, -90.4856)

Site Geometric Design Information

<table>
<tr><td rowspan="2">Crossroad Design</td><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">2</td><td colspan="3">1</td></tr>
<tr><td rowspan="2">Exit Ramp</td><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td>0</td><td>31 ft</td><td>0</td><td>0</td><td>5 ft</td></tr>
<tr><td rowspan="2">Intersection</td><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">0</td><td colspan="2">40%</td><td colspan="2">Straight</td><td colspan="2">42 ft</td></tr>
<tr><td rowspan="2">Signs</td><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>1</td><td>0</td><td>0</td><td colspan="2">0</td><td colspan="2">0</td><td>0</td></tr>
<tr><td rowspan="2">Pavement Markings</td><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><td rowspan="2">Nearby Environment</td><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">151 ft</td><td colspan="4">0</td></tr>
<tr><td rowspan="2">AADT</td><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">2000</td><td colspan="4">1800</td></tr>
</table>

WWD Incidents at AR I40 Exit 260 WB

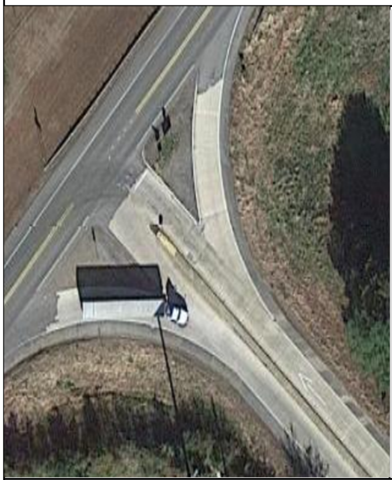
NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	3.5	5.5	60	Daylight	Sunny
2	4.1	13.5	65	Daylight	Sunny
3	3.6	24.5	70	Daylight	Sunny
4	5.3	19.1	70	Night	Sunny
5	6.2	26.5	70	Night	Sunny

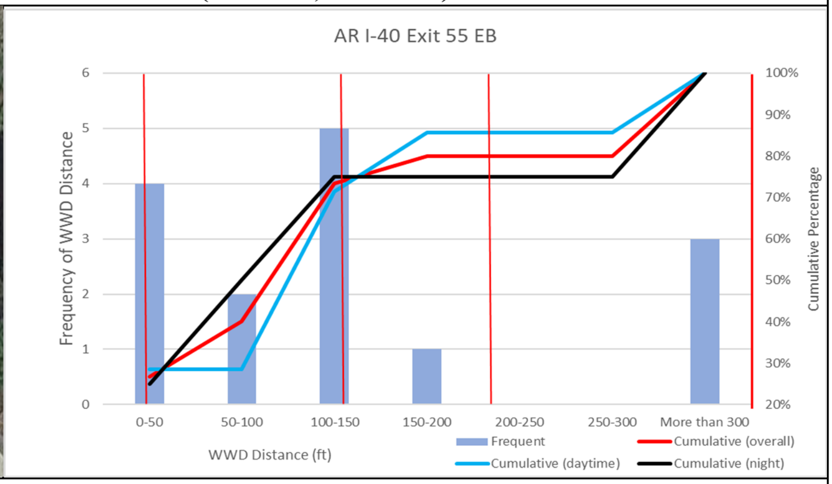
AR I40 Exit 94 WB (35.253728, -92.936994)								

Site Geometric Design Information								
Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	3	1	N	N	0	0	5 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		50%		Straight		46 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	1		1		1
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		1			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	100 ft				1			
AADT	Exit ramp				Entrance ramp			
	1400				1900			

WWD Incidents at AR I40 Exit 94 WB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	0.5	0.5	10	Daylight	Sunny

AR I40 Exit 55 EB (35.464278, -93.521989)								





Site Geometric Design Information								
Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		0			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	1	0	1	64 ft	1	1	5 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		56%		Straight		20 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	1		0		1
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		1			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	127 ft				1			
AADT	Exit ramp				Entrance ramp			
	1200				2500			

WWD Incidents at AR I40 Exit 55 EB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	99999	0.0	99999	Daylight	Sunny
2	5.5	33.1	150	Daylight	Sunny
3	2.7	36.5	25	Daylight	Sunny
4	11.4	15.5	200	Daylight	Sunny
5	6.8	18.9	150	Daylight	Sunny
6	5.1	24.4	120	Daylight	Sunny
7	3.9	6.0	20	Daylight	Sunny
8	0.5	0.2	5	Light	Sunny
9	6.3	5.7	70	Light	Sunny
10	4.2	22.1	120	Light	Sunny
11	9.4	0.0	99999	Light	Sunny
12	3.1	17.6	80	Light	Sunny
13	3.3	30.9	50	Light	Sunny
14	5.2	0.0	99999	Light	Sunny
15	5.6	22.2	130	Light	Sunny
Notes: 99999 = No data available since the vehicle never came back					

AR I40 Exit 47 WB (35.497975, -93.661278)

<table>
<tr><th colspan="9">Site Geometric Design Information</th></tr>
<tr><td rowspan="2">Crossroad Design</td><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">0</td><td colspan="3">1</td></tr>
<tr><td rowspan="2">Exit Ramp</td><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td>0</td><td>24 ft</td><td>1</td><td>0</td><td>5 ft</td></tr>
<tr><td rowspan="2">Intersection</td><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">0</td><td colspan="2">50%</td><td colspan="2">Straight</td><td colspan="2">14 ft</td></tr>
<tr><td rowspan="2">Signs</td><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td colspan="2">0</td><td colspan="2">0</td><td>0</td></tr>
<tr><td rowspan="2">Pavement Markings</td><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><td rowspan="2">Nearby Environment</td><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">1000 ft</td><td colspan="4">0</td></tr>
<tr><td rowspan="2">AADT</td><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">300</td><td colspan="4">330</td></tr>
</table>

WWD Incidents at AR I40 Exit 47 WB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	7.2	22.5	90	Night	Sunny

TN I40 Exit 182 NB (36.027862, -87.175527)

Site Geometric Design Information

<table>
<tr><td rowspan="2">Crossroad Design</td><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">2</td><td colspan="3">1</td></tr>
<tr><td rowspan="2">Exit Ramp</td><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>1</td><td>3</td><td>0</td><td>N</td><td>N</td><td>0</td><td>0</td><td>5 ft</td></tr>
<tr><td rowspan="2">Intersection</td><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">1</td><td colspan="2">35%</td><td colspan="2">Straight</td><td colspan="2">54 ft</td></tr>
<tr><td rowspan="2">Signs</td><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td colspan="2">0</td><td colspan="2">1</td><td>0</td></tr>
<tr><td rowspan="2">Pavement Markings</td><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">1</td><td colspan="3">0</td></tr>
<tr><td rowspan="2">Nearby Environment</td><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">150 ft</td><td colspan="4">0</td></tr>
<tr><td rowspan="2">AADT</td><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">2000</td><td colspan="4">3000</td></tr>
</table>

WWD Incidents at TN I40 Exit 182 NB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	6.8	20.1	60	Night	Sunny

TN I40 Exit 172 WB (36.020176,-87.336640)

Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			2		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	3	1	1	1	16 ft	0	0	21 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	1		62%		Straight		83 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		1		1
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		1			1		
Nearby Environment	Distance to nearest access point				Lighting condition			
	600 ft				1			
AADT	Exit ramp				Entrance ramp			
	5000				8000			

WWD Incidents at TN I40 Exit 172 WB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	2.5	3.5	20	Daylight	Sunny
2	4.7	9.5	230	Daylight	Sunny
3	4.2	1.8	20	Light	Sunny
4	25.0	170.0	800	Light	Sunny
5	4.5	5.5	200	Light	Rain

TN I40 Exit 182 SB (36.027306, -87.179722)

Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	2	3	0	N	N	0	0	16 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	1		48%		Straight		42 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		1		1
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		1			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				1			
AADT	Exit ramp				Entrance ramp			
	2000				3000			

WWD Incidents at TN I40 Exit 182 SB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	99999	0.0	99999	Daylight	Sunny
2	3.2	1.0	10	Night	Rain
3	11.0	15.0	150	Night	Rain
4	7.5	16.5	70	Night	Rain
5	4.5	22.0	120	Night	Sunny

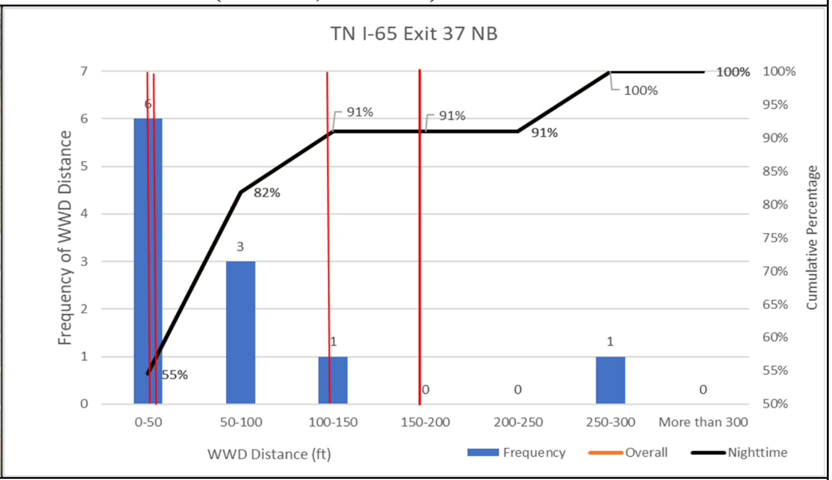
Notes: 99999 = No data available since the vehicle never came back

<table>
<tr><th colspan="9">TN I65 Exit 22 NB (35.30882, -86.88124)</th></tr>
<tr><td colspan="9"></td></tr>
<tr><th colspan="9">Site Geometric Design Information</th></tr>
<tr><th rowspan="2">Crossroad Design</th><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">2</td><td colspan="3">1</td></tr>
<tr><th rowspan="2">Exit Ramp</th><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>1</td><td>3</td><td>0</td><td>N</td><td>N</td><td>0</td><td>0</td><td>8 ft</td></tr>
<tr><th rowspan="2">Intersection</th><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">0</td><td colspan="2">66%</td><td colspan="2">Straight</td><td colspan="2">47 ft</td></tr>
<tr><th rowspan="2">Signs</th><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td colspan="2">0</td><td colspan="2">0</td><td>0</td></tr>
<tr><th rowspan="2">Pavement Markings</th><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">1</td><td colspan="3">0</td></tr>
<tr><th rowspan="2">Nearby Environment</th><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">0 ft</td><td colspan="4">0</td></tr>
<tr><th rowspan="2">AADT</th><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">2000</td><td colspan="4">3000</td></tr>
</table>

WWD Incidents at TN I65 Exit 22 NB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	4.1	2.1	60	Night	Sunny

TN I65 Exit 37 NB (35.51758, -86.89675)



Site Geometric Design Information								
Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	2	0	0	20 ft	1	0	50 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		45%		Straight		52 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				0			
AADT	Exit ramp				Entrance ramp			
	2000				3000			

WWD Incidents at TN I65 Exit 37 NB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	0.9	0.5	0	Night	Sunny
2	2.3	20.1	30	Night	Sunny
3	3.1	26.9	50	Night	Sunny
4	3.3	18.4	60	Night	Sunny
5	0.5	0.5	0	Night	Sunny
6	3.9	30.5	90	Night	Sunny
7	2.7	2.4	60	Night	Sunny
8	1.9	23.1	15	Night	Sunny
9	7.4	59.9	130	Night	Sunny
10	9.8	22.3	270	Night	Sunny
11	2.1	13.8	50	Night	Sunny

TN I24 Exit 49 SB (36.165950,-86.765231)

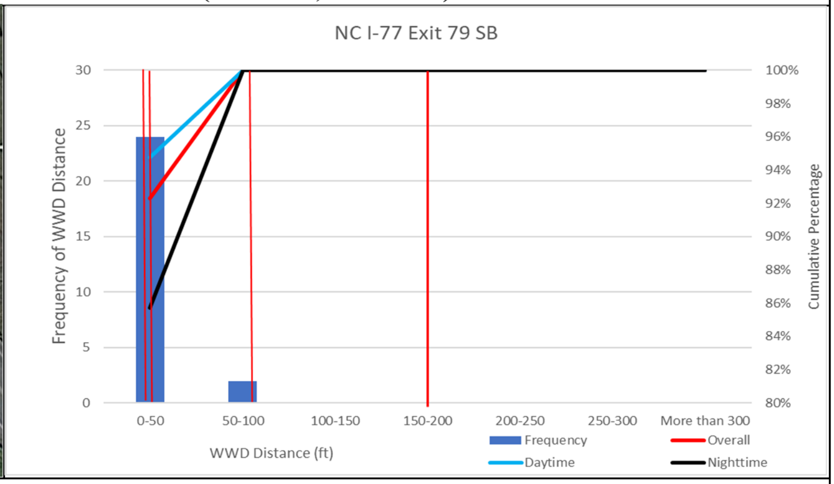
Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			3		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	2	3	0	N	N	0	0	8 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	1		50%		Obtuse		75 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		1		1
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		1			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				1			
AADT	Exit ramp				Entrance ramp			
	5000				8000			

WWD Incidents at TN I24 Exit 49 SB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	3.5	3.0	10	Light	Sunny
2	9.5	16.1	150	Light	Sunny
3	8.9	11.5	110	Light	Sunny
4	11.5	10.5	300	Light	Sunny
5	3.2	9.2	20	Light	Sunny

NC I77 Exit 79 SB (36.198411, -80.812200)



Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		0			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	1	0	0	13 ft	1	0	38 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		56%		Acute		39 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	206 ft				0			
AADT	Exit ramp				Entrance ramp			
	950				550			

WWD Incidents at NC I77 Exit 79 SB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	3.1	13.3	60	Daylight	Sunny
2	2.5	7.1	30	Night	Sunny
3	1.9	4.2	45	Night	Sunny
4	1.7	4.4	30	Daylight	Sunny
5	0.5	5.1	5	Daylight	Sunny
6	2.9	11.3	60	Daylight	Sunny
7	2.2	3.7	50	Daylight	Sunny
8	2.5	3.2	0	Daylight	Sunny
9	1.8	5.4	15	Daylight	Sunny
10	1.2	2.9	5	Daylight	Sunny
11	2.7	1.9	40	Daylight	Sunny
12	1.2	0.2	20	Daylight	Sunny
13	0.8	8.6	10	Daylight	Sunny
14	2.4	3.7	30	Daylight	Sunny
15	2.1	1.9	40	Daylight	Sunny
16	0.3	1.7	0	Daylight	Sunny
17	0.4	3.1	0	Daylight	Sunny
18	1.7	1.5	30	Daylight	Sunny
19	2.1	1.4	30	Daylight	Sunny
20	0.4	1.9	0	Daylight	Sunny
21	0.2	1.2	0	Daylight	Sunny
22	0.5	5.1	10	Daylight	Sunny
23	2.3	2.0	40	Night	Sunny
24	2.1	3.2	40	Night	Sunny
25	1.7	24.1	20	Night	Sunny
26	1.5	11.3	10	Night	Sunny

NC I77 Exit 79 NB (36.195898, -80.810019)

<table>
<tr><th colspan="9">Site Geometric Design Information</th></tr>
<tr><td rowspan="2">Crossroad Design</td><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">0</td><td colspan="3">1</td></tr>
<tr><td rowspan="2">Exit Ramp</td><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>1</td><td>2</td><td>1</td><td>0</td><td>6 ft</td><td>1</td><td>0</td><td>57 ft</td></tr>
<tr><td rowspan="2">Intersection</td><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">0</td><td colspan="2">63%</td><td colspan="2">Straight</td><td colspan="2">36 ft</td></tr>
<tr><td rowspan="2">Signs</td><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td colspan="2">0</td><td colspan="2">1</td><td>0</td></tr>
<tr><td rowspan="2">Pavement Markings</td><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><td rowspan="2">Nearby Environment</td><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">0 ft</td><td colspan="4">0</td></tr>
<tr><td rowspan="2">AADT</td><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">550</td><td colspan="4">1000</td></tr>
</table>

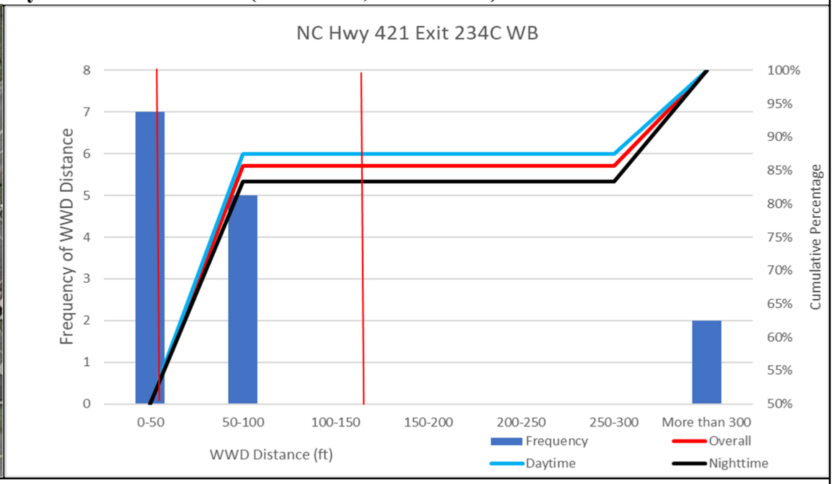
WWD Incidents at NC I77 Exit 79 NB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	3.1	2.9	40	Daylight	Sunny

NC Hwy 421 Exit 242 WB (36.078203, -80.388227)								

Site Geometric Design Information								
Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	0		2			2		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	4	1	1	1	30 ft	0	0	24 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	1		56%		Straight		65 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		1			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				1			
AADT	Exit ramp				Entrance ramp			
	11000				2800			

WWD Incidents at NC Hwy 421 Exit 242 WB					
NO.	**Reaction time (sec)**	**Correction time (sec)**	**Travel distance (ft)**	**Lighting condition**	**Weather**
1	4.2	9.1	25	Night	Sunny

NC Hwy 421 Exit 234C WB (36.092744, -80.268241)



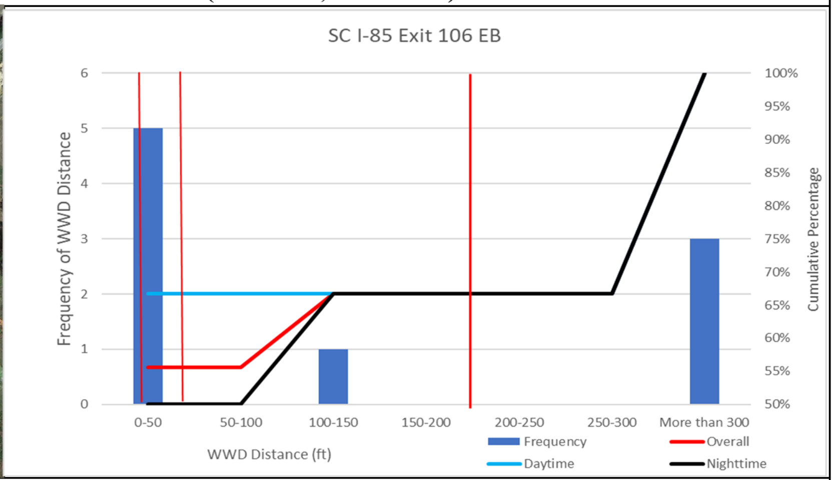
Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	1	0	0	65 ft	1	0	124 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		42%		Acute		58 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	0 ft				1			
AADT	Exit ramp				Entrance ramp			
	4600				6100			

WWD Incidents at NC Hwy 421 Exit 234C WB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	1.5	8.9	10	Light	Sunny
2	1.7	6.4	15	Light	Sunny
3	99999	0.0	99999	Light	Sunny
4	4.7	2.1	60	Light	Sunny
5	3.3	1.9	75	Daylight	Sunny
6	3.9	4.1	60	Daylight	Sunny
7	4.1	2.5	20	Daylight	Sunny
8	5.5	4.9	20	Light	Sunny
9	7.7	13.3	70	Light	Sunny
10	99999	0.0	99999	Daylight	Sunny
11	3.6	6.2	20	Daylight	Sunny
12	4.3	2.2	55	Daylight	Sunny
13	1.9	6.6	10	Daylight	Sunny
14	2.4	3.1	40	Daylight	Sunny
Notes: 99999 = No data available since the vehicle never came back					

<table>
<tr><th colspan="9">SC I85 Exit 106 EB (35.163241, -81.452131)</th></tr>
</table>

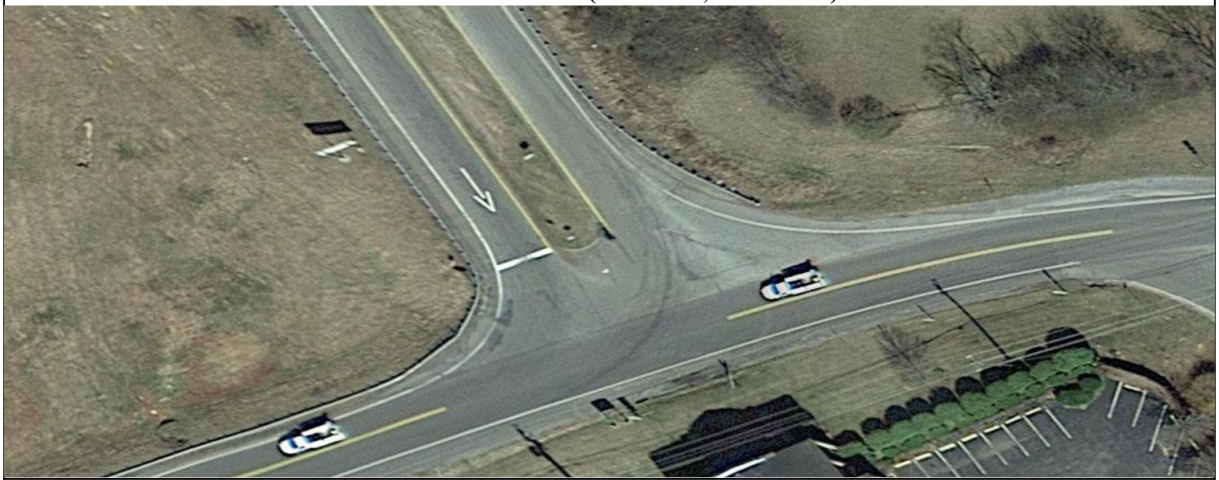


<table>
<tr><th colspan="9">Site Geometric Design Information</th></tr>
<tr><td rowspan="2">Crossroad Design</td><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">1</td><td colspan="3">1</td></tr>
<tr><td rowspan="2">Exit Ramp</td><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td>0</td><td>54 ft</td><td>1</td><td>0</td><td>92 ft</td></tr>
<tr><td rowspan="2">Intersection</td><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">0</td><td colspan="2">40%</td><td colspan="2">Straight</td><td colspan="2">43 ft</td></tr>
<tr><td rowspan="2">Signs</td><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td colspan="2">0</td><td colspan="2">0</td><td>0</td></tr>
<tr><td rowspan="2">Pavement Markings</td><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><td rowspan="2">Nearby Environment</td><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">470 ft</td><td colspan="4">0</td></tr>
<tr><td rowspan="2">AADT</td><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">2000</td><td colspan="4">3000</td></tr>
</table>

WWD Incidents at SC I85 Exit 106 EB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	4.5	4.2	40	Night	Sunny
2	2.7	1.4	20	Daytime	Sunny
3	21	52.5	550	Daytime	Dangerous
4	0.9	19.1	10	Night	Sunny
5	3.2	1.5	10	Daytime	Sunny
6	7.6	3.3	150	Night	Dangerous
7	20.1	233.5	480	Night	Dangerous
8	6.4	9.7	40	Night	Sunny
9	17.8	99999	99999	Night	Sunny
Notes: 99999 = No data available since the vehicle never came back					

VA I-77 Exit41 NB (36.967619, -81.064449)



Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		2			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	3	0	N	N	0	0	24 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		52%		Straight		52 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	1		1		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	240 ft				0			
AADT	Exit ramp				Entrance ramp			
	1800				2300			

WWD Incidents at VA I-77 Exit41 NB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	1.2	2.0	10	Daylight	Sunny

<table>
<tr><th colspan="9">VA I81 Exit 141 SB (37.325497, -80.035030)</th></tr>
</table>

<table>
<tr><th colspan="9">Site Geometric Design Information</th></tr>
<tr><td rowspan="2">Crossroad Design</td><td colspan="2">Median traversable</td><td colspan="3">If the median extended to cover exit ramp</td><td colspan="3">Number of lane on ramp side</td></tr>
<tr><td colspan="2">1</td><td colspan="3">2</td><td colspan="3">2</td></tr>
<tr><td rowspan="2">Exit Ramp</td><td>Number of lane on exit ramp</td><td>Type 1 or 2 or 3</td><td>Ramp side opposite to freeway direction</td><td>Channelized island traversable</td><td>Length of channelized island</td><td>Signs on channelized island</td><td>Median traversable</td><td>Median width</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td>0</td><td>55 ft</td><td>1</td><td>0</td><td>50 ft</td></tr>
<tr><td rowspan="2">Intersection</td><td colspan="2">Control type</td><td colspan="2">Intersection balance</td><td colspan="2">Intersection angle</td><td colspan="2">Corner radius</td></tr>
<tr><td colspan="2">1</td><td colspan="2">48%</td><td colspan="2">Straight</td><td colspan="2">75 ft</td></tr>
<tr><td rowspan="2">Signs</td><td>Condition</td><td>DNE face to driver</td><td>DNE enlarged</td><td colspan="2">DNE lower mounted</td><td colspan="2">Keep right sign at the nose</td><td>Enhanced sign</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td colspan="2">1</td><td colspan="2">0</td><td>1</td></tr>
<tr><td rowspan="2">Pavement Markings</td><td colspan="2">Condition</td><td colspan="3">Left-turn guidance</td><td colspan="3">Enhanced</td></tr>
<tr><td colspan="2">1</td><td colspan="3">1</td><td colspan="3">0</td></tr>
<tr><td rowspan="2">Nearby Environment</td><td colspan="4">Distance to nearest access point</td><td colspan="4">Lighting condition</td></tr>
<tr><td colspan="4">341 ft</td><td colspan="4">1</td></tr>
<tr><td rowspan="2">AADT</td><td colspan="4">Exit ramp</td><td colspan="4">Entrance ramp</td></tr>
<tr><td colspan="4">5600</td><td colspan="4">3200</td></tr>
</table>

WWD Incidents at VA I81 Exit 141 SB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	6.5	4.5	140	Daylight	Sunny
2	7.8	6.5	150	Daylight	Sunny
3	8.3	6.5	190	Daylight	Sunny
4	6.3	12.0	180	Night	Sunny
5	3.5	3.0	10	Night	Sunny

NJ I295 Exit 16B EB (39.81098, -75.27135)

Site Geometric Design Information

Crossroad Design	Median traversable		If the median extended to cover exit ramp			Number of lane on ramp side		
	1		0			1		
Exit Ramp	Number of lane on exit ramp	Type 1 or 2 or 3	Ramp side opposite to freeway direction	Channelized island traversable	Length of channelized island	Signs on channelized island	Median traversable	Median width
	1	2	1	0	13 ft	0	0	7 ft
Intersection	Control type		Intersection balance		Intersection angle		Corner radius	
	0		54%		Straight		51 ft	
Signs	Condition	DNE face to driver	DNE enlarged	DNE lower mounted		Keep right sign at the nose		Enhanced sign
	1	1	0	0		0		0
Pavement Markings	Condition		Left-turn guidance			Enhanced		
	1		0			0		
Nearby Environment	Distance to nearest access point				Lighting condition			
	145 ft				0			
AADT	Exit ramp				Entrance ramp			
	712				788			

WWD Incidents at NJ I295 Exit 16B EB

NO.	Reaction time (sec)	Correction time (sec)	Travel distance (ft)	Lighting condition	Weather
1	2.4	7.6	10	Night	Sunny