Modeling the Risk of Wrong-Way Driving at Freeway Exit Ramp Terminals

by

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Abstract

Wrong-way driving (WWD) crashes are a critical safety issue on freeways. Although these crashes are rare in nature, they often result in severe injuries and/or fatalities. Typically, exit ramp terminals are the initial point of entry for most wrong-way drivers on freeways. Therefore, it is important for the transportation agencies to identify the exit ramp terminals with high risk of WWD and adopt a systemic safety approach to reduce the probability of their occurrence proactively before a crash happens. However, the rare nature of WWD crashes and the difficulty in identifying the actual entry points make it hard to assess the risk of WWD at a particular exit ramp terminal. To overcome this issue, in this study, logistic regression models have been calibrated for predicting the risk of WWD at the exit ramp terminals of full diamond and partial cloverleaf (parclo) interchanges. The geometric design features, usage of traffic control devices (TCDs), traffic volume, and area type were used as the potential predictors of WWD. To evaluate the performance of the calibrated models, they were used as a network screening tool to rank the exit ramp terminals of full diamond and parclo interchanges in Alabama from high to low risk of WWD and the occurrences of WWD events was observed over a 48-hour period using video cameras. The observation of WWD incidents at high-risk locations demonstrates strong evidence that the models calibrated in this study are capable of identifying the exit ramp terminals with high risk of WWD. Transportation agencies can use these models to assess the risk of WWD at the exit ramp terminals within their jurisdictions and identify the high-risk locations for countermeasures implementation.

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I would also like to thank my dissertation committee members, Dr. Turochy, Dr. LaMondia, and Dr. Zech, for their insightful comments, questions, and guidance through this process. They challenged me with intriguing questions, which allowed me to explore my research abilities. My sincere thanks also goes to Dr. Ana Franco-Watkins for reading and reviewing my dissertation.

I dedicate this dissertation to my loving mother, who has always been the core source of my inspiration to work hard and to peruse my dreams.

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List of Abbreviations

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADAS	Advanced Driver Assistance System
ADOT	Arizona Department of Transportation
AIC	Akaike Information Criterion
ALDOT	Alabama Department of Transportation
ATSSA	American Traffic Safety Services Association
BAC	Blood Alcohol Concentration
BIC	Bayesian Information Criterion
CalTrans	California Department of Transportation
CARE	Critical Analysis and Reporting Environment
DMS	Dynamic Message Signs
DUI	Driving Under the Influence
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GOL	Generalized Ordered Logit
GPS	Global Positioning System
HCTRA	Harris County Toll Road Authority
HSIS	Highway Safety Information Systems

HUD	Heads-up Display
IDOT	Illinois Department of Transportation
ILD	Inductive Loop Detectors
ITS	Intelligent Transportation Systems
KYTC	Kentucky Transportation Cabinet
MCA	Multiple Correspondence Analysis
MLE	Maximum Likelihood Estimation
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
NDS	Naturalistic Driving Study
NTSB	National Transportation Safety Board
NTTA	North Texas Tollway Authority
NYSDOT	New York State Department of Transportation
Parclo	Partial Cloverleaf
PO	Proportional Odds
PPO	Partial Proportional Odds
OBU	Onboard Unit
OR	Odds Ratio
RFB	Rapid Flashing Beacon
RRFB	Rectangular Rapid Flashing Beacons
RRPM	Retroreflective Raised Pavement Markings
RSU	Roadside Units

SPF	Safety Performance Function
TCD	Traffic Control Device
TMC	Traffic Management Center
TxDOT	Texas Department of Transportation
TTI	Texas A&M Transportation Institute
VIF	Variance Inflation Factor
VIP	Video Image Processing
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WSDOT	Washington State Department of Transportation
WWD	Wrong-Way Driving

1 Introduction

1.1 Background

Wrong-way driving (WWD) crashes have been a critical safety issue since the introduction of the interstate system, which causes 300 to 400 fatalities per year in the United States (FHWA, 2017). By definition, WWD is the act of driving against the legal direction of traffic flow on high-speed limited access facilities (e.g., freeways, expressways, and multilane divided highways). Although a WWD event is rare, it is a serious traffic safety issue due to the severity of outcomes associated with WWD crashes. Typically, WWD crash is head-on or opposite direction sideswipe collision at high-speeds resulting in multiple fatalities and/or severe injuries. During the period of 2004–2011, an average of 269 WWD fatal crashes resulted in 359 fatalities annually in the United States, which accounts for 1.34 fatalities per WWD fatal crash compared with 1.10 fatalities for all types of fatal crashes (Baratian-Ghorghi et al., 2014a).

Entering through an exit ramp is the primary and most common origin of WWD events on freeways. Although WWD movements sometimes originate from making a U-turn on the mainline and at median crossovers, they account for only a small portion of all WWD events. A study in Illinois, for example, showed that only 6.5% of 217 confirmed WWD crashes occurred from wrong-way drivers making a U-turn on the mainline, while the other 93.5% occurred from drivers entering freeways through an exit ramp (Zhou et al. 2012). Therefore, if we had some quantitative techniques to identify the exit ramp terminals that are prone to WWD, a more informed decision can be made to implement countermeasures and a significant amount of those WWD events can probably be reduced. Unfortunately, we do not have such quantitative techniques. May be that is why the WWD fatalities remain unchanged over the past years, although the overall fatalities from the traffic crashes are experiencing a declining trend, as shown in Figure 1.1.

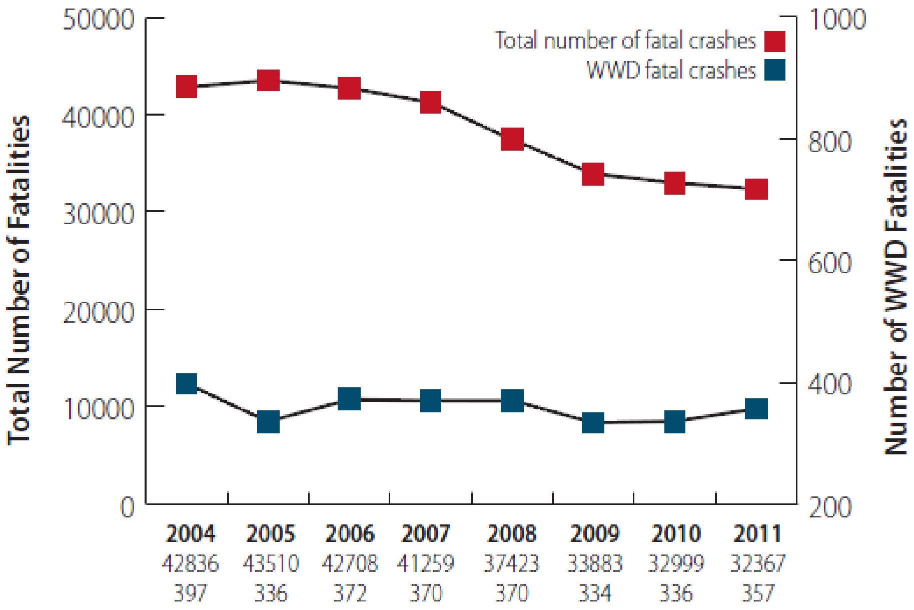
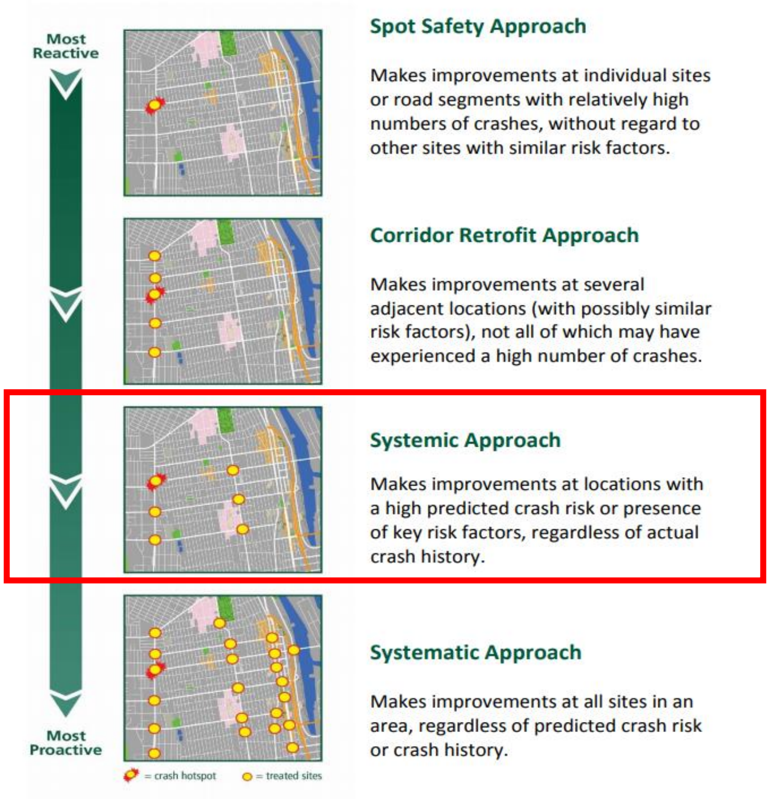


Figure 1.1 U.S. overall fatalities and WWD fatalities (Baratian-Ghorghi et al., 2014a)

Transportation agencies often select locations for safety improvements based on crash history and/or engineering judgements. However, it is challenging to select locations for WWD countermeasures based on crash history alone due to the rareness of this type of crashes. In addition, the selection of locations for WWD countermeasures based on engineering judgements alone may not be sufficient in most cases since the occurrences of WWD events often result from a wide range of contributing factors including geometric design features, TCDs, and traffic characteristics. The complex relationship among all these contributing factors cannot be accounted by engineering judgements alone. Therefore, it is necessary to develop a proactive approach to combat the WWD issue on freeways based on quantitative techniques to identify locations with high-risk of WWD.

Systemic approach to safety is such a proactive approach, which involves making improvements at locations with a high-predicted crash risk or presence of key risk factors, regardless of the actual crash history (FHWA, 2019). As shown in Figure 1.2, it is a more proactive approach than a spot safety or a corridor retrofit approach that focus only on treating specific locations with a crash history and less costly than systematic approach that makes improvements at all sites in an area, regardless of predicted crash risk or crash history (Thomas et al. 2018). Therefore, a systemic approach could be an ideal tool for transportation agencies to mitigate WWD issue on freeways within their jurisdiction by acting proactively before a crash happens.



Spot Safety Approach

Makes improvements at individual sites or road segments with relatively high numbers of crashes, without regard to other sites with similar risk factors.

Corridor Retrofit Approach

Makes improvements at several adjacent locations (with possibly similar risk factors), not all of which may have experienced a high number of crashes.

Systemic Approach

Makes improvements at locations with a high predicted crash risk or presence of key risk factors, regardless of actual crash history.

Systematic Approach

Makes improvements at all sites in an area, regardless of predicted crash risk or crash history.

Figure 1.2 Approaches for implementing safety countermeasures (Thomas et al. 2018)

A systemic safety approach for reducing WWD on freeways would involve the seven steps shown in Figure 1.3. Step 1 involves defining the project scope. Depending on the interest of a particular transportation agency, the project scope can be the exit ramp terminals along a specific segment of a freeway or all the exit ramp terminals along the freeways within their jurisdiction. After defining the scope of the project, steps 2-4 helps to identify and verify the locations (i.e., the exit ramp terminals) having highest risk of WWD. Steps 5-7 involves selecting potential countermeasures to reduce WWD risk at the locations identified in steps 2-4, implementing those countermeasures, and evaluating their impacts on reducing the risk of WWD.

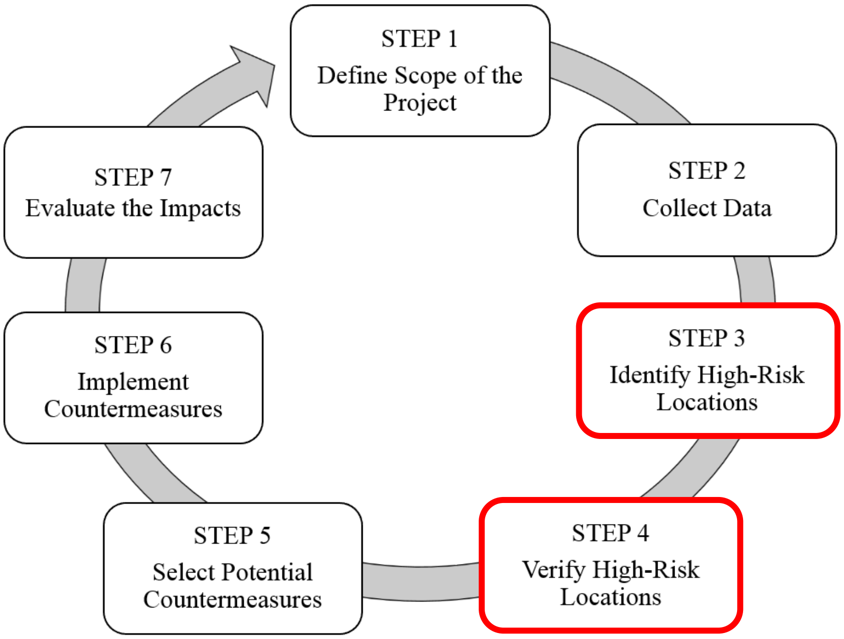


Figure 1.3 Systemic safety approach for reducing WWD on freeways

The most challenging parts in adopting such a systemic safety approach are identifying high-risk ramp terminals without crash history (Step 3) and verifying the risk of WWD at those high-risk ramp terminals (Step 4). There is a paucity of research in identifying and verifying the locations with high risk of WWD. Existing research primarily focused only on predicting WWD risk on a roadway segment. For instance, Sandt et al. (2017) identified WWD hotspots segments by modeling crash risk and analyzing traffic management response times. Similar WWD crash risk models were developed for the South Florida area as well (Rogers et al. 2016). Earlier, Rogers et al. (2015) conducted a study to model the risk of WWD crashes for Interstates/toll facilities and counties in Florida based on statewide WWD crashes, citations, and 911 calls. Baratian-Ghroghi et al. (2014b) predicted the probability of WWD incidents at a signalized exit ramp terminal of a parclo interchange. Pour-Rouholamin and Zhou (2016a) calibrated a logistic regression model to study the effect of various geometric design elements on the probability of WWD entries at parclo interchanges. However, no previous research described a complete process to identify and verify locations with high risk of WWD. To fill this gap, logistic regression models have been calibrated in this study to predict the risk of WWD at the exit ramp terminals of different interchange types, which may help in identifying the exit ramp terminals with high risk of WWD within a transportation jurisdiction.

Although impaired driving (i.e., driving under the influence (DUI) of drugs and/or alcohol) has been identified as one of the major contributing factors to WWD (NTSB, 2012), geometric features and traffic control devices (TCDs) at the exit ramp terminals can also have a significant impact. While properly designed geometric features can physically obstruct drivers from entering the wrong-way, proper use of wrong-way related TCDs can help them to differentiate between exit and entrance ramps. In the previous literature, certain geometric design features were reported to have a significant effect on the WWD crashes including intersection angle, turning radius from crossroad to two-way ramps, type of median on the crossroad, type of channelizing island, type and width of median between the exit and entrance ramp, intersection balance at the exit ramp terminals, tangency of corner radius to crossroad edge, and the distance to nearby access points (Pour-Rouholamin and Zhou, 2016a; Zhou and Pour-Rouholamin, 2014). Along with geometric characteristics of exit ramp terminals, other factors such as wrong-way related TCDs, area type (i.e., urban/rural), and Annual Average Daily Traffic (AADT) on the exit ramp, the entrance ramp, and the crossroad are reported to have significant effect on WWD. Therefore, the geometric design features, TCDs, traffic volume, and area type were considered to be the potential predictors of the risk of WWD at the exit ramp terminals.

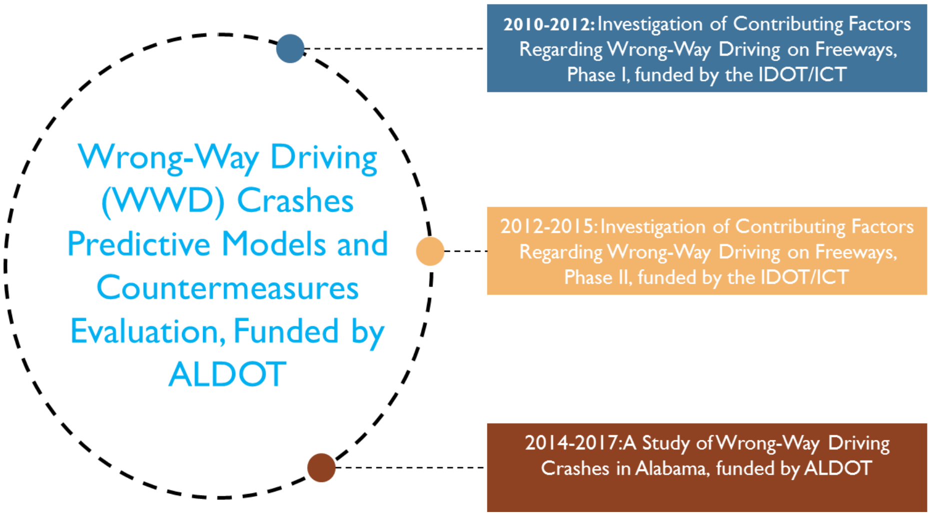


Figure 1.4 WWD related research efforts

This study is based on the project, "Wrong-Way Driving Crashes Predictive Models and Countermeasures Evaluation" funded by ALDOT (Zhou and Atiquzzaman, 2018), which built on three previous project from our research team, as shown in Figure 1.4. While the three previous project focused on studying the characteristics of WWD crashes in Alabama and Illinois, the latest project focused on calibrating models to predict the risk of WWD at freeway exit ramp terminals and evaluating the effect of WWD countermeasures in reducing the WWD crashes. The research efforts related to calibrating the models to predict the risk of WWD at the exit ramp terminals have been documented in this dissertation, which was solely carried out by the author of this dissertation.

1.2 Research Objectives

Past studies found that parclo interchanges are more susceptible to WWD when compared with other interchange types due to the presence of closely spaced parallel entrance and exit ramps (i.e., two-way ramps). On the other hand, full diamond interchanges are the most widely used service interchanges (79% of all interchanges fall in this category) in the United States (MoDOT, 2017). Although they are less susceptible to WWD events than parclo or trumpet interchanges (Moler, 2002; Braam, 2006; Neuman et al., 2008; Morena and Leix, 2012; Zhou et al. 2015), the origins of a major portion of WWD crashes are attributed to the exit ramp terminals of diamond interchanges (Zhou et al., 2012). Together these two interchange types are responsible for approximately 44% of the WWD crashes on freeways (Zhou et al., 2012). Therefore, the assessment of WWD risk at full diamond and parclo interchanges using predictive models may help in reducing a significant portion of WWD crashes within the jurisdiction of a particular transportation agency. In addition, the sample size may not be sufficient to develop mathematical models for other less commonly used interchange types. Thus, the focus of this study was limited to calibrating predictive models for full diamond and parclo interchanges only.

The predictive models were used as a network screening tool to rank the exit ramp terminals of full diamond and parclo interchanges in Alabama from high to low risk of WWD. Then the high-risk ramp terminals were monitored by video cameras for 48-hours to evaluate the performance of the predictive models by observing the occurrences of WWD events. The duration of video monitoring was selected to be 48-hours because the maximum battery life of the available cameras in our laboratory is 48-hours. To ensure the best use of available cameras, the video monitoring of WWD events was conducted during 48-hours of weekends (i.e., from Friday 5 pm to Sunday 5 pm) as the previous studies suggested that the WWD crashes are more likely to occur during early morning hours of weekend days (Zhou et al., 2015).

To sum up, the specific research objectives are as follows:

1. To calibrate models for predicting the risk of WWD at the exit ramp terminals of full diamond and parclo interchanges.

2. To evaluate the performance of the calibrated predictive models by observing WWD events at high-risk exit ramp terminals identified by the model prediction.

1.3 Dissertation Organization

This dissertation is consisted of seven chapters. Chapter 1 discusses the background, research objectives, and organization of the dissertation. A comprehensive review of existing research on WWD crashes is provided in Chapter 2. The study methodology is documented in Chapter 3, which includes detailed discussions on data collection efforts, model development procedures, and model evaluation techniques. Chapter 4 discusses the results of predictive modeling for WWD risks at the exit ramp terminals of full diamond and parclo interchanges. Chapter 5 presents the findings of model evaluation efforts. Chapter 6 documents the conclusions and recommendations. Chapter 7 discusses the limitations of this study and the need for future research.

2 Literature Review

The first effort in understanding the characteristics of WWD crashes started in California in the 1950s (Tamburi, 1969; Sicking and Lechtenberg, 2009). In 1968, the National Transportation Safety Board (NTSB) started investigating this issue when multi-fatality WWD crash happened in Baker, California (NTSB, 1968; NTSB, 2012). In 1970 and 1988, NTSB conducted investigations on two other WWD crashes in Dulles airport access road and Carrolton, Kentucky, respectively (NTSB 1971; NTSB 1989). Apart from these studies, the research on WWD crashes was limited before the 2000s. However, since the early 2000s, it has drawn a lot of attention from a diverse group of researchers. Based on the focus of this study, the previous research efforts on WWD have been summarized into the following three categories: 1) contributing factors in WWD crashes; 2) development and evaluation of WWD safety countermeasures; and 3) development of WWD risk prediction models. In addition, a few research efforts on the application of systemic approach has been summarized to provide a context to the readers about the suitability of systemic approach in addressing WWD crashes on freeways.

2.1 Contributing Factors in WWD Crashes

Understanding the contributing factors in WWD crashes has been a primary focus of much WWD research for the past several decades. The following paragraphs summarizes some of the most recent research efforts on identifying the contributing factors in WWD crashes. Since this dissertation used crash data from two U.S. states and aimed to develop crash risk prediction models specific to U.S. freeways only, the focus of the literature search was limited to U.S. based studies.

Cooner and Ranft (2008) studied four years of WWD crashes along Texas freeways and developed a WWD crash profile. No particular statistical method is specified rather a collection of data is shown, which is stratified with respect to driver's age, sex, influence of drugs or alcohol etc. The independent variable included main lane/ramp, arterial/frontage, time of day, driver's age, driver's sex, and influence of drugs or alcohol to predict WWD crashes. They found that most of the collisions occurred in the inside lane (i.e., left-lane) of the correct direction. Another important finding indicated that the problem occurs when a one-way street, typically in a downtown area, transitions directly into a freeway section. It was reported that the majority of WWD crashes occurred in major urban areas, with slightly more than 60% in the three largest metropolitans. This study also documents best practices nationwide and provides recommended guidelines for use of the most effective WWD countermeasures.

Lathrop (2010) explored medical data of crash fatalities caused by WWD to identify risk factors and formulate prevention strategies. Categorical variables were compared using Chi-square tests or Fisher exact tests, and continuous variables were analyzed using Wilcoxon rank-sum tests or t-tests as appropriate. Decedent demographics, driver/passenger status, seatbelt use, blood alcohol concentration (BAC), weather and light at time of occurrence, and types of vehicles were extracted from the data source to predict WWD fatality. WWD crashes were significantly more likely to occur during darkness and involved intoxicated drivers, with 63% of the wrong-way drivers tested having BACs above the legal limit for driving, compared to 5.6% of right-way drivers and 19% of drivers from other types of fatal interstate crashes. Demographics plays a significant role, for instance, Native Americans had a higher risk of being a deceased wrong-way driver in an interstate collision compared to drivers of other races and ethnicities.

Zhou et al. (2015) aimed to characterize the statistical features of WWD crashes from three aspects (i.e., crash, driving person, and vehicle) using six years crash data from Illinois. First, for crash context, temporal distributions, geographical distribution, roadway characteristics, and crash characteristics were analyzed. In case of temporal distributions, 28.6% of WWD crashes occurred on weekends from midnight to 5:00 am. Urban area was found to be more prone to WWD crashes. Most (67%) of the multiple-vehicle WWD crashes were head-on and opposite direction sideswipe crashes. Road surface condition did not significantly contribute more to WWD crashes compared to other freeway crashes. Compressed diamond interchanges, SPUI, parclo interchanges, and freeway feeders had the highest WWD crash rates. Second, for vehicle context, wrong-way driver demographic information, driver physical condition, and driver injury severity were analyzed. Approximately 50-percent of WWD crashes were confirmed to be impaired by alcohol. Third, for vehicle context, vehicle characteristics, vehicle operation, and collision results were analyzed for WWD vehicles. Nearly 70-percent of WWD vehicles were found to be passenger cars.

Pour-Rouholamin and Zhou (2016b) utilized three different ordered-response models including ordered logit or proportional odds (PO), generalized ordered logit (GOL), and partial proportional odds (PPO) model in order to investigate the effect of various confounding variables on the injury severity being sustained by the at-fault drivers in a WWD crash. This study analyzed at-fault drivers' injury severity using the dataset of 398 cases from the 10-year crash records in Illinois and 5-year crash records in Alabama. Driver's age, condition (i.e., intoxication), seatbelt use, time of day, airbag deployment, type of setting, surface condition, lighting condition, and type of crash were found to have a significant effect on the severity of a WWD crash. In addition, the outcomes were validated through three different models used in this study. The results corroborate that the PPO model outperforms the other two models in terms of modeling injury severity. The authors found that several risk factors at the driver, temporal, vehicle, and crash levels that significantly change the probability of at fault driver injury severity. Accordingly, driver age and condition, seatbelt use, time of day, airbag status, type of setting, surface condition, lighting condition and type of crash show significant association with driver injury severity in WWD crashes. Surprisingly, WWD crashes in rural areas were found to have a higher probability of more severe injuries. WWD head-on crashes are clearly the most influencing factor on the severity of the injury, as this kind of crash increases the probability of fatalities by more than two times. Crashes that caused airbag deployment show decreased probability of severities and WWD crashes on wet surfaces have also shown a lower possibility of minor and severe injuries. Based on the findings, several countermeasures at the engineering, education, and enforcement levels were recommended. The study mentioned a small sample size and human error as a limitation.

Pour-Rouholamin et al. (2016) and Zhou et al. (2017) explored the various effect of the identified variables and recommended several countermeasures for policymakers in order to reduce the WWD issue on Alabama Interstates. The authors utilized 5-years crash data on Alabama freeways, which contained 18 explanatory variables representing the driver, temporal, vehicle, and environmental characteristics. This study calibrated a Firth’s penalized-likelihood logistic regression model to examine the influence of the explanatory variables on the dichotomous dependent variable (the type of crash, i.e., WWD vs. non-WWD), while the authors also used a standard binary logistic regression to make a comparison with the result of Firth’s model. The explanatory variables including the month of the year, time of the day, driver age, driver mental and physical condition, driver’s residence distance, vehicle age, vehicle damage, towing condition, airbag deployment status, and roadway condition were found to characterize WWD crashes. This study used odds ratio (OR) to indicate the influence of individual explanatory variables. For example, drivers who cause WWD crashes are more likely to be 65 and older (OR = 9.07), to be physically impaired (OR = 56.47), to be under the influence of alcohol and drugs (OR = 8.64), to drive during the evening (OR = 2.85) or night (OR=5.50), and to drive vehicles older than 15 years (OR=2.15). The generalizability of the study might fall in question because the data used in this study is just from one U.S. state.

Das et al. (2018a) investigated various factors in the WWD crashes on the basis of five years crash data utilizing the association rules ‘Eclat’ algorithm to determine the interactions between different factors that result in WWD crashes. The authors defined WWD crashes in broader perspective (both WWD crashes on freeways where the wrong-way driver originated from exit ramps and on low speed roadways due to median crossover) and utilized several variables, including two-lane undivided roadways, exit ramps, head-on crashes, male drivers, impaired driving, improper and inadequate pavement markings, inadequate signs and alert systems, and nighttime crashes to predict WWD crashes. The findings provided strong evidence that the proper signings and improvement in pavement marking are essential in reducing such crashes because majority of these crashes happened on rural two-lane undivided roadways. Additionally, fatal WWD crashes tend to be involved with male drivers and off-peak hours. Driver impairment was found as a critical factor among the top twenty rules, which is consistent with the findings of the previous research efforts.

Das et al. (2018b) also investigated the contribution factors of WWD in unbiased statistical perspective using five years (2010–2014) data of WWD crashes in Louisiana. Multiple correspondence analysis (MCA) was used to analyze the data instead of general approach including descriptive statistics or logistic regression. Independent variables were set in sixteen significant clusters as different locality types, roadways at dark with no lighting at night, roadways with no physical separations, and roadways with higher posted speed, roadways with inadequate signage and markings, and older drivers. The authors concluded that crashes with open country condition and higher posted speed emerged as severe. Rural areas with no lighting at night, full access control, divided facilities are associated with higher number of WWD crashes. Roadways with no control and roadways with no physical separation are more likely to be associated with WWD crashes. Types of locality play a dominant role in WWD crashes. Open country, urban residential areas, and industrial zones show different types of key associations. Targeted law enforcement at problem areas should help discourage intentional violations, and traffic calming countermeasures may help alleviate the severity of these crashes. Jalayer et al. (2018) also identified contributing factors of WWD crashes in Illinois and Alabama using the MCA approach.

Ponnaluri (2018) studied WWD crashes on arterial corridors as well as on freeway systems. Also, this study compares WWD and non-WWD crashes, and fatal and non-fatal WWD crashes with the help of univariate and multivariate analyses. Age of the driver, physical defect, lighting, rural and urban region, weather, time of incident, traffic volume, purpose of using the vehicle, and number of vehicles involved were considered to predict WWD crashes on arterials and freeways. The current study extends previous findings on the arterials-based WWD crashes by introducing several exogenous variables including driver age, BAC, their underlying physical defects, and non-use of seatbelt tend to have a large impact on WWD crashes. Lighting, weather, rural and urban locations, median and shoulder widths, divided and undivided roads, time of crash, traffic volumes, and vehicle use also impact WWD Crashes. It was suggested that not only engineering countermeasures but also educational campaigns could mitigate WWD in the most efficient manner possible.

In an earlier research effort, Ponnaluri (2016) investigated the factors that cause WWD crashes and fatalities. This study used binomial regression model to evaluate the impact of several independent variables on WWD crashes and fatalities. The study parameters included driver’s age, gender, licensing state, physical defect, BAC, vehicle use, seatbelt compliance, day and time of crash, roadway lighting, facility type, weather conditions, road geometrics, and traffic volumes. Individual variable analysis of 23 parameters and the model development process included the determination of odds ratios and statistical tests for the predictive power and goodness-of-fit. The odds ratio results show that driver’s age, gender, BAC, driving license state - a proxy to residence, physical defect, seatbelt use, the purpose for which vehicle was used, facility type, roadway lighting, area of crash, day and time of crash, traffic volume and other geometric characteristics have a significant influence on WWD crashes and fatalities.

To sum up, the studies on characteristics of WWD crashes collectively concluded that older drivers, younger drivers, male drivers, driving under the influence (DUI) of alcohol or drugs, poor lighting conditions, urban areas, early morning hours, weekend days, severe weather conditions, and traffic characteristics contribute to WWD crashes (Copelan, 1989; Cooner et al., 2004; Braam, 2006; Lathrop et al., 2010; Morena and Leix, 2012; Zhou et al., 2012; Zhou et al., 2015; Pour-Rouholamin et al., 2016; Ponnaluri, 2016; Das et al., 2018a; Das et al., 2018b). Additionally, a few studies identified that some interchange types are more susceptible to cause driver confusion and may contribute to WWD. For instance, Copelan (1989) and Zhou et al. (2015) reported that the interchanges with short sight distances, parclo interchanges, trumpet interchanges, half and full diamond interchanges, buttonhook ramps, slip ramps, four-legged intersections near exit ramps, left-side exit ramps, and scissors exit ramps are more likely to cause driver confusion. Cooner et al. (2004) reported that left-side exit ramps and one-way streets transitioning into freeways are more likely to cause WWD. Additionally, previous studies reported that two-quadrant parclo, trumpet, tight diamond, and full diamond interchanges are more susceptible to WWD (Braam, 2006; Morean and Leix, 2012; Zhou et al., 2014).

2.2 WWD Safety Countermeasures

While impaired driving accounts for over 60% of WWD crashes, studies also found that inconsistency in location, angle, and size of wrong-way related traffic signs, lack of pavement markings, and improper geometric design may have significant effect on the occurrences of WWD crashes. Therefore, some previous studies investigated different engineering safety countermeasures to reduce the chances of WWD at the exit ramp terminals along freeways. These safety countermeasures can be divided into three categories: a) geometric design features; b) application of TCDs; and c) application of intelligent transportation systems (ITS). The following sections discuss some of the notable recent research efforts related to improving engineering countermeasures to reduce WWD crashes on freeways.

2.2.1 Geometric Design Features

Geometric features should be designed with careful consideration to reduce the risk of WWD at an exit ramp terminal. Based on the interchange type, the application of geometric elements may vary significantly. Thus, the previous studies provided specific recommendations for different types of interchanges. Since, the focus of this study is developing models to predict WWD risk at the exit ramp terminals of full diamond and parclo interchange, the following paragraphs only discuss the geometric design elements that are specific to these two interchange types.

At the exit ramp terminals of full diamond interchanges, the use of a right-angle connection to the crossroad is preferred, which makes the wrong-way right-turning maneuvers uncomfortable to the motorists. Additionally, the crossroad median is recommended to be non-traversable to physically deter wrong-way left-turns and the connection between left edge of exit ramp and right edge of the crossroad is recommended to be angular to deter wrong-way right-turns from crossroad (AASHTO, 2011). A non-traversable channelizing island is also reported to be an effective design to deter WWD, as it reduces the traversable width of exit ramp throat (WSDOT, 2013; Zhou and Pour-Rouholamin, 2014).

Previous studies also reported numerous geometric features to be effective in deterring WWD entries at the exit ramp terminals of parclo interchanges (IDOT, 2010; AASHTO, 2011; WSDOT, 2013; Zhou and Pour-Rouholamin, 2014). Generally, a right angle connection to crossroad is considered a good design practice for this type of interchange. Similar to diamond interchanges, the non-traversable median on crossroad and the non-traversable channelizing island on exit ramp throat provides physical barrier to the potential WWD movement at the exit ramp terminals of parclo interchange. In addition, Zhou and Pour-Rouholamin (2014) suggested that the channelizing island on entrance throat should be avoided to increase traversable width of pavement on entrance ramp and provide better visibility. A wide non-traversable median between exit and entrance ramps is also desirable. Regarding that, Illinois Department of Transportation (IDOT) (2010) recommended that the median between entrance and exit ramp should be at least 50 feet to reduce the chance of WWD at locations with closely space parallel ramps. IDOT (2010) manual also suggested that the corner radius from crossroad to entrance ramp should be maximum 80 feet, which makes a sharp left-turning maneuver to the entrance ramp; thus, it is difficult for drivers to enter the exit ramp by making a sharper left-turning maneuver. The corner radius from exit ramp to crossroad is recommend to be within 100 feet (IDOT, 2010).

Washington State Department of Transportation (WSDOT) introduced the term called intersection balance to provide a perception of sight distance at the exit ramp terminals of parclo interchange. It is the ratio of the distance between stop bar for left-turning vehicles from the crossroad and centerline of median on two-way ramp to the distance between stop bar at two opposing direction of the crossroad. Figure 2.1 further illustrates the definition of intersection balance by WSDOT. An intersection balance of 51% to maximum 60% is likely to provide a clear view of both exit and entrance ramps to the left-turning drivers from crossroad and thus reduces WWD caused by inadequate sight distance (WSDOT, 2013). While this recommendation was purely based on engineering judgement, a recent study by Wang and Zhou (2018) evaluated the effect of intersection on driver behavior at parclo interchange using Naturalistic Driving Study (NDS) data and found that the intersection balance of less than 60% provides better sight distance and reduces driver confusions. Another study found that the intersection balance less than 40% may also contribute to a higher likelihood of WWD (Pour-Rouholamin and Zhou, 2016a).

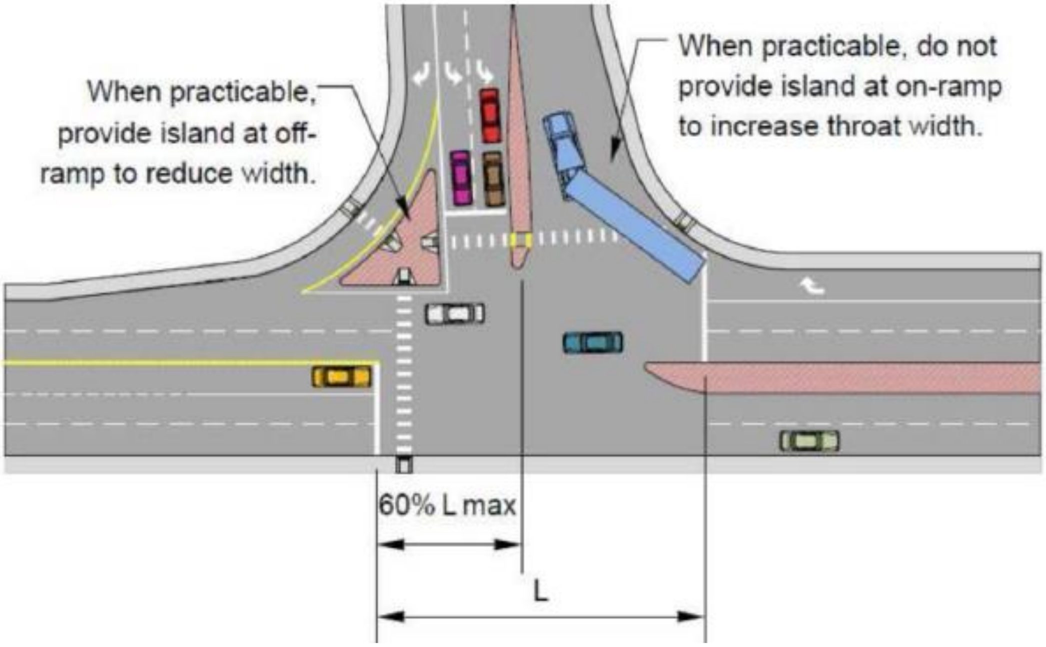


Figure 2.1 Intersection balance defined by WSDOT (2013)

Previous studies also reported that the presence of access points/driveways within close proximity of exit ramp terminals are likely to increase driver confusions, which may lead to WWD movements (Zhou et al. 2008; Zhou and Pour-Rouholamin, 2014; Pour-Rouholamin and Zhou, 2016a). Zhou et al. (2008) recommended that the minimum distance of access points/driveways should be at least 600 feet from an exit ramp terminal to avoid driver confusions and resulting WWD movements. Pour-Rouholamin and Zhou (2016a) also found that the exit ramp terminals with access points within 600 feet has a higher chance of WWD compared to those without any access points within 600 feet.

Interestingly most of the recommendations for geometric design features are purely based on engineering judgements alone. There is a scarcity of research on the quantitative evaluation of the effect of various geometric design elements on the risks of WWD at the exit ramp terminals. This study made a significant contribution to fill this research gap, since the effect of various design elements have been evaluated quantitatively with the help of mathematical modeling.

2.2.2 Signs, Pavement Markings, and Signals

Application of TCDs to deter WWD entries at the exit ramp terminals are important in reducing WWD. Over the years, wrong-way related TCDs experienced a significant evolution. A recent study by Baratian-Ghorghi and Zhou (2017) have documented the historical evolution of wrong-way related TCDs and discussed the basis on which the changes in TCDs were made over the years. Manual on Uniform Traffic Control Devices (MUTCD) only requires the use of at least one WRONG WAY sign and DO NOT ENTER sign, facing to the potential wrong-way drivers, along the exit ramp terminals (MUTCD, 2009). Additionally, ONE WAY, turn prohibition (NO LEFT/RIGHT TURN), and Keep Right (between closely spaced exit and entrance ramp of partial cloverleaf interchanges) signs are commonly used to deter WWD entries. Recently, the use of oversized and low-mounted signs are reported to be effective (Cooner et al., 2004; Pour-Rouholamin et al., 2015). Red retroreflective strips on wrong-way related sign posts and flashing LED borders are recommended to increase nighttime visibility (MUTCD, 2009; Pour-Rouholamin, et al. 2015). The use of wrong-way arrow, in addition to the lane use marking, is also recommended (MUTCD, 2009). Furthermore, the signalized exit ramp terminals provide more regulated traffic flow and are likely to reduce the occurrences of WWD entries.

More recently, researchers evaluated the effectiveness of several enhancements of WWD driving countermeasures and found interesting results. For instance, the red Rectangular Rapid Flashing Beacons (RRFBs), Wigwag Flashing Beacons, detection-triggered blank-out signs that flash "WRONG WAY", and detection-triggered LED lights around "WRONG WAY" signs were found to be effective in mitigating WWD at freeway exit-ramps (Lin et al., 2017; Ozkul and Lin, 2017; Lin et al., 2018). In another study, the LED "WRONG WAY" signs and Rapid Flashing Beacon (RFB) "WRONG WAY" signs were found to be effective in reducing WWD movements (Kayes et al., 2018). The Texas Department of Transportation (TxDOT) had experienced a 30% reduction in WWD incident frequency after adding Flashing LEDs to "DO NOT ENTER" and "WRONG WAY" sign borders (Clay, 2011). North Texas Tollway Authority (NTTA) reported that the application and improvement of pavement marking at problematic locations resulted in reduction of WWD incidents by 40% (Ouyang, 2013). Another study evaluated the driver's understanding of red retroreflective raised pavement markings (RRPMs) through survey. This study found that replacing supplemental RRPMs with supplemental arrows can always improve the rate of correct responses for all roadway configurations (Miles et al., 2014).

Although some of the current practices for WWD safety countermeasures were found to be effective for normal drivers, their effectiveness for alcohol-impaired drivers are still largely unknown. In 2014, two closed-course studies were conducted to determine the effectiveness of selected WWD countermeasures on alcohol-impaired drivers. Results suggest that lowering the height of the white-on-red signs, making the signs larger (i.e., oversized), adding a red retroreflective sheeting on the sign support, or adding red flashing LEDs around the border of the sign did not improve the ability of alcohol impaired drivers to locate WRONG WAY signs (Finley et al., 2014).

2.2.3 ITS Countermeasures

ITS technologies have been recently used by many transportation agencies to develop WWD countermeasures. These ITS-based WWD countermeasures primarily consist of detecting wrong-way drivers using various sensors, sending alerts to wrong-way and nearby right-way drivers using the existing ITS infrastructure, and alerting the traffic management system and law enforcement (Simpsom, 2013; Zhou and Pour-Rouholamin, 2014; ATSSA, 2014). Detection step can be accomplished using a variety of different detectors such as Inductive Loop Detectors (ILD), Video Image Processing (VIP) Systems, Microwave Radar-based Traffic Detection Systems, Infrared Detection Systems, and others. Regarding the warning step, different methods can be employed to warn both wrong-way and right-way drivers. In-pavement warning lights, flashing wrong-way signs, warning lights, and Dynamic Message Signs (DMS) are some examples of these warning systems. Action can be taken by patrol units or other responsible parties after receiving an alert from the traffic management center (TMC) or some centralized dispatches to intercept wrong-way drivers. A typical scheme of ITS detection and warning system for WWD can be found in Figure 2.2.

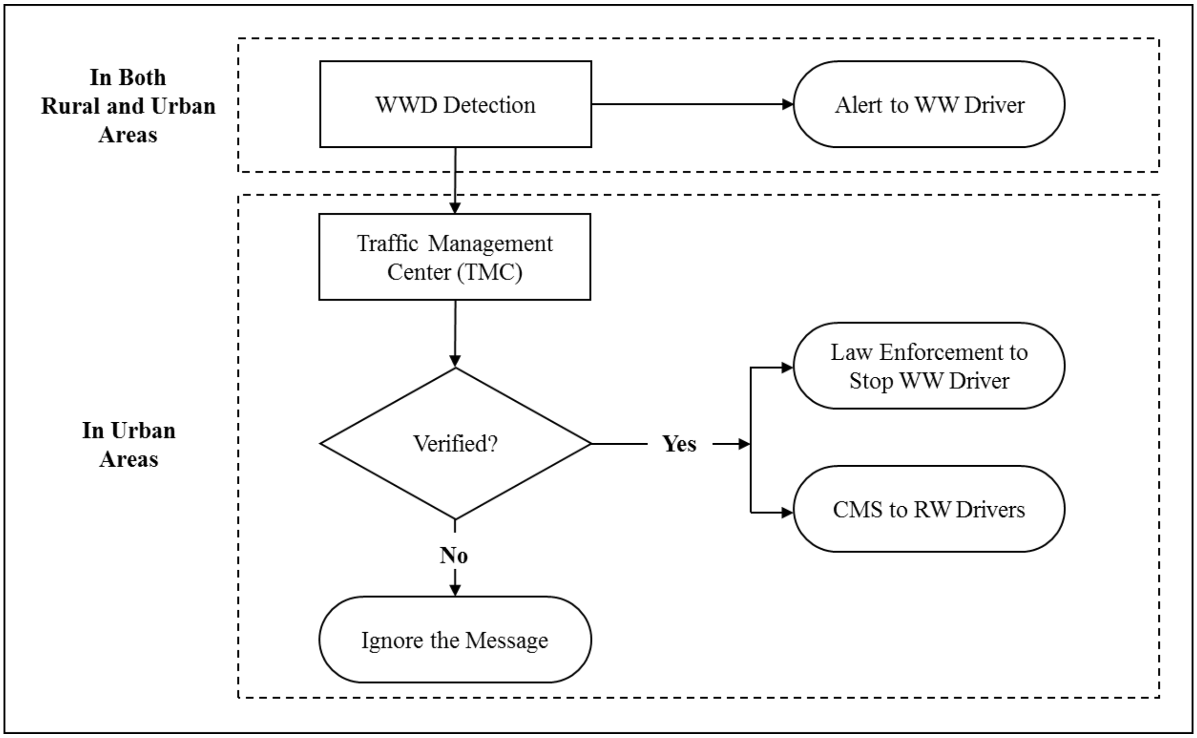


Figure 2.2 Typical scheme of WWD detection and warning system

Recently, the Arizona Department of Transportation (ADOT) adopted $4 million worth of thermal-detection technology, which includes 90 thermal-detection cameras, to detect WWD in the Interstate 17 corridor. Recently, it was reported that the thermal-detection technology detected 15 WWD events so far (AZCentral, 2018). Earlier, ADOT developed a conceptual system "*to detect a wrong-way driver upon entry, inform the errant driver of their mistake, notify the ADOT Traffic Operations Center (TOC) and law enforcement instantly, track the wrong-way vehicle on the highway system, and warn right-way drivers in the vicinity of the oncoming vehicle*" (Simpson and Bruggeman, 2015).

The California Department of Transportation (Caltrans) deployed dual-radar based wrong-way driver detection system in Sacramento and San Diego areas, which activates red flashing lights bordering the WRONG WAY signs when a wrong-way driver is detected. In addition, it sends real-time notification about the wrong-way driver to Traffic Management Centers (TMC)

(Caltrans, 2016). Harris County Toll Road Authority (HCTRA) implemented a radar-based WWD detection system at 12 exit ramps in Houston, Texas. According to HCTRA, 30 WWD incidents were detected in 2012 (HCTRA, 2012). In 2014, the Florida Department of Transportation (FDOT) deployed radar and camera-based detection technology, which detects a wrong-way driver, alerts them by flashing signs, and sends alerts to the authorities (Trischitta and Sentinel, 2018).

In addition to the traditional ITS application, several studies explored the application of connected and autonomous vehicle technologies, which uses vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication, for developing wrong-way driver detection and warning system. In 2016, the Texas A&M Transportation Institute (TTI) developed an initial concept for a connected vehicle WWD detection and management system, which would detect WWD vehicles, notify the TxDOT and law enforcement personnel, and alert affected travelers (Finley et al., 2016). Earlier, Zeng et al. (2012) proposed a connected vehicle wrong-way warning system, which has four major components – a) roadside units (RSUs); b) an onboard unit (OBU); c) a detection unit; and d) a Global Positioning System (GPS). This system requires all the vehicles to be equipped with OBUs. When the detection unit detects a wrong-way driver, the RSUs receives that information and sends it to the OBUs of the vehicles in the vicinity. Other examples of wrong-way driver detection and warning system based on V2I communications includes an agent-based paradigm proposed by Conesa et al. (2013). In another study, Jalayer et al. (2019) explored the application of unmanned aerial vehicle to inspect and inventory interchange asset to mitigate WWD entries.

In 2007, a driver assistance program was developed in Germany, which uses the in-vehicle navigation system to automatically recognize when a driver enters the wrong direction in a roadway and provides a series of audible and visual warnings in the Heads-up Display (HUD).

Using V2V communication, the program was also capable of warning other motorists within 2000 feet of the wrong-way driver. The V2I technology was used for communicating information to vehicles in a wider area, in which the wrong-way vehicle sends its position to a service center, and the service center disseminates this information to other vehicles (Brigl, 2007). Realizing the danger associated with WWD, the European automotive industry is including wrong-way warnings modules as part of the advanced driver assistance system (ADAS). Such wrong-way warning modules will take advantage of high-accuracy navigation system, road geometry, and/or machine vision to detect wrong-way drivers and use V2V and/or V2I technology to send a warning to both the wrong-way and right-way drivers (Automotive Business Review, 2013; Brigl, 2007).

2.3 Modeling WWD Crash Risk

Only a handful of previous studies attempted to predict WWD risks at certain interchanges, roadway segments, or within a specific jurisdiction. The studies conducted by Baratian-Ghroghi et al. (2014b), Pour-Rouholamin and Zhou (2016a), Sandt et al. (2017), Rogers et al. (2016) and Rogers et al.(2015) are some notable examples of research in this area. These research efforts are briefly discussed in the following paragraphs.

Baratian-Ghorghi et al. (2014b) used VISSIM simulation models, calibrated by field observations, to predict the number of potential WWD maneuvers at a signalized parclo interchange terminal in Illinois. The probability of WWD maneuvers was computed by using Poisson distribution. The results indicated that the number of potential WWD maneuvers increases when the left-turn volume toward an entrance ramp increases and stopped vehicles at an exit ramp decrease. The developed Poisson distribution model can estimate the probability of the number of potential WWD maneuvers at defined time periods.

Pour-Rouholamin and Zhou (2016a) calibrated a logistic regression model to study the effect of various geometric design elements on the probability of WWD entries at parclo interchanges. In this study, 15-year crash data were used to identify exit ramp terminals with a history of WWD entry. The geometric design elements of exit ramp terminal with a history of WWD entry was compared with those without a history of WWD entry. Some geometric design elements were found to have a significant effect on the probability of WWD entry, including turning radius from crossroad to two-way ramps, type and width of median between the exit and entrance ramp, intersection balance at the exit ramp terminals, and the distance to nearby access points.

Sandt et al. (2017) reported two approaches to identify WWD hotspots in central Florida. In the first approach, a Poisson regression model was calibrated to predict the number of WWD crashes in a road segment based on WWD citations, 911 calls, traffic volume, and interchange designs. The Poisson regression model revealed that WWD citations, 911 calls, partial diamond interchanges, trumpet interchanges, major directional interchanges, and AADT volumes on the crossroad significantly affect the number of WWD crashes in a road segment. In the second approach, WWD hotspots were identified based on time spent responding to WWD events, which can be used when WWD citations and 911 calls are not available. Rogers et al. (2016) conducted a similar study for south Florida. Earlier, Rogers et al. (2015) conducted a study to model the risk of WWD crashes for Interstates/toll facilities and counties in Florida based on statewide WWD crashes, citations, and 911 calls.

In summary, although a few studies attempted to predict the risk of WWD crashes, the focus was mainly on the macroscopic level. The scarcity of research in this area can be attributed to the rareness and random nature of WWD events along with the difficulty to determine the true entry points of WWD crashes. To fill this gap, this study calibrated microscopic models to predict WWD risks at individual exit ramp terminals based on its geometric design features, usage of TCDs, AADT data, and area types.

2.4 Studies on Systemic Safety Approach

In recent years, systemic approach has drawn a lot of attention among the traffic safety professionals. It involves making safety improvements based on high-risk roadway features or high-predicted crash risk correlated with particular severe crash types. FHWA (2019) reported that the systemic approach offers following benefits:

1. It can reduce overall fatal and severe injury crashes of certain types within a jurisdiction more effectively than applying safety improvements at locations with high crash frequency in the past;
2. Systemically implemented countermeasures are typically low-cost improvements;
3. It helps the transportation agencies to broaden their safety efforts and consider other risk factors in addition to crash history when identifying locations for potential safety improvement; and
4. Systemic approach can bolster public confidence because it allows the agency to implement a proactive safety program.

Over the past years, several states introduced the application of a systemic approach to enhance their efforts towards traffic safety within their jurisdiction. Following paragraphs briefly discusses some of these efforts.

Minnesota Department of Transportation (MnDOT) followed the procedure of systemic approach to safety to reduce lane-departure and intersection related crashes along rural segments and curves, rural intersections, and urban signalized intersections. The network screening and prioritization of candidate locations for safety improvements were based on factors such as AADT, access density, presence of fixed object, and roadside condition of no usable shoulder. After identifying candidate locations, a comprehensive list of potential countermeasures was assembled as options for safety improvements at particular locations (FHWA, 2013a; Preston et al., 2013).

The Kentucky Transportation Cabinet (KYTC) applied systemic approach in five counties of Kentucky. The focus was on reducing roadway departure crashes along rural county roads. Potential risk factors reported in this study includes horizontal curve density, shoulder type, shoulder width, lane width, and speed limit. Because of this study, a set of cost-effective countermeasures was implemented along the horizontal curves to reduce the roadway departures crashes on rural county roads (FHWA, 2013b; Chandler, 2011).

A systemic approach was applied in Thurston County, Washington to explore the benefits of proactive safety planning. The focus was to reduce roadway departure crashes along horizontal curves. The screening of candidate locations for safety improvements was based on nine potential risk factors identified in this study. Some low-cost, low-maintenance countermeasures were implemented at the horizontal curves with potential risk factors (FHWA, 2013c).

The New York State Department of Transportation (NYSDOT) used the systemic approach to identify sites where high-risk crashes could be reduced by implementing low-cost roadway countermeasures. The focus of this systemic approach was to reduce lane-departure crashes along the two-lane rural state highways with a posted speed limit of 55 mph. NYSDOT compared the severity of crashes at locations with similar risk factors and discovered that three characteristics were over-represented, which includes AADT between 3,000 and 5,999, curve radii between 100 and 300 feet, and (c) shoulder width between 1 and 3 feet. Finally, NYSDOT assembled an initial, comprehensive list of countermeasures relative to lane-departure crashes (Storm et al., 2013).

More recently, Thomas et al. (2018) proposed a systemic pedestrian safety approach to reduce pedestrian crashes. Four real-world examples of systemic pedestrian safety process used by state and local DOTs are presented in this study. For instance, Seattle DOT used network-wide data for all intersections to develop pedestrian safety performance functions (SPFs) for different crash types. The crash prediction models were used to identify high-risk sites. Additional field investigations were conducted to confirm potential problems and plan countermeasures implementation at several intersections to address the identified risks.

2.5 Gaps in Previous Research and Proposed Work

The existing literature shows that some transportation agencies started to adopt a systemic approach to reduce certain types of crashes (e.g., lane-departure, roadway departure, intersection-related, and pedestrian crashes). According to FHWA (2019), a systemic approach is appropriate for reducing specific types of severe crashes, which indicates that this approach could be ideal for reducing WWD crashes as these crashes are typically severe in nature. However, to the best of author's knowledge, none of the previous studies attempted to use systemic approach to reduce WWD crashes. Typically, most transportation agencies select locations for WWD countermeasures based on spot safety approach, which depends on previous crash history. For example, FDOT used corridor retrofit approach to implement WWD countermeasure along some of their limited-access highways. Similarly, IDOT used systematic approach to improve wrong-way related signs along all their limited access facilities. Ponnaluri (2016b) formulated a policy-oriented framework toward addressing WWD in a systematic manner and suggested a systemic discipline is required for transforming policy objectives to actionable outcomes. However, no transportation agencies, to-date, used a systemic approach to address WWD issue on freeways or other limited-access facilities. This can be attributed to the lack of quantitative models to identify high-risk ramp terminals based on the predicted crash risk. To overcome this limitation, this study calibrated logistic regression models (similar to safety performance functions) to predict the risk of WWD at full diamond and parclo interchanges. In addition, a systemic approach have been proposed, which takes advantage of the calibrated models to identify high-risk ramp terminals through network screening and verify high-risk ramp terminals using video data.

3 Methodology

This chapter consisted of three major sections. The first section describes the efforts in collecting required data for modeling the risk of WWD at the exit ramp terminals of full diamond and parclo interchanges. The second section discusses the details of statistical methods for modeling the risk of WWD. The third section discusses the procedure for evaluating the performance of the predictive models calibrated in this study.

3.1 Data Collection

Because WWD crashes are relatively infrequent events on freeways, the sample size may not be large enough to develop reliable logistic regression models if the WWD crash data were collected from only one state. Therefore, to increase the sample size, WWD crash data on the freeways in two states (i.e., Alabama and Illinois) were collected for a period of five years (2009–2013). The steps involved in the data collection efforts are shown in Figure 3.1. Highway Safety Information Systems (HSIS) and Critical Analysis and Reporting Environment (CARE) was the primary source of crash data for Illinois and Alabama, respectively. It was realized that some of the crashes described as WWD crash in HSIS and CARE database may not be actual WWD crashes. Therefore, the crash reports were collected from Alabama Department of Transportation (ALDOT) and IDOT for the crashes that are denoted as WWD crash in CARE and HSIS databases. These crash reports were reviewed thoroughly to confirm the actual WWD crashes. The final crash dataset only includes those crashes that were originated from entering freeways through exit ramps.

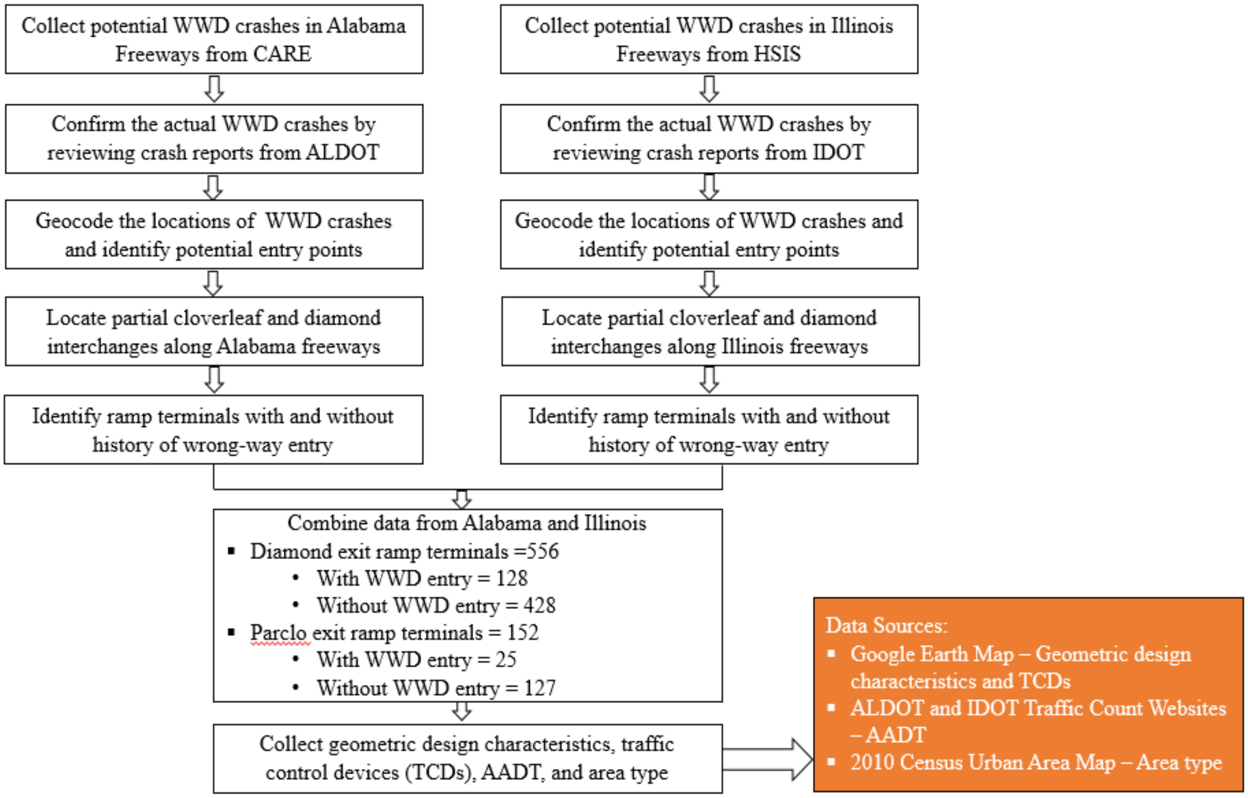


Figure 3.1 Steps in data collection and sources of data

Identifying the exit ramp terminals with histories of WWD crash is critical to model the risk of WWD. However, after locating the WWD crash locations in Google Maps and reviewing the crash reports, it was found that the initial entry point (i.e., exit ramp terminals) for a significant portion of the crashes are not reported in the crash reports. To overcome this issue, the crash data was divided into two groups: 1) WWD crashes with confirmed entry points determined from the crash narratives, 2) WWD crashes without confirmed entry points based on the crash reports. No special treatment was required for the WWD crashes for which it was possible to determine, from the crash narratives, the exit ramp terminals where the driver initially went wrong-way. However, for the crashes with unknown initial entry points, an estimation methodology, proposed by Zhou et al. (2012), was used to estimate the exit ramp terminals where the driver initially went wrong-way. After determining the confirmed and estimated entry points for the WWD crashes in the study period, the full diamond and parclo exit ramp terminals in Illinois and Alabama were divided into two categories: 1) exit ramp terminals with history of WWD and 2) exit ramp terminals without history of WWD.

After combining the data from Alabama and Illinois, there were a total of 556 full diamond and 152 parclo exit ramp terminals. Then the exit ramp terminals were investigated using Google Earth aerial and street views to collect the geometric design features and TCDs usage information. Initially, the 2017 Google Earth imagery was used for data collection. Then, the data were cross-checked with the imagery of crash year or closest year available to verify if improvements/modifications were made at the study locations. If any improvements/modifications were noticed, the data were adjusted to ensure that it portrays the crash year's geometric and signage conditions. ALDOT and IDOT traffic count map was used as the source of AADT data. The type of area (urban/rural) was determined using the 2010 Census Urban Area Map. A comprehensive discussion of the collected data for full diamond and parclo interchanges is presented in the following sections.

3.1.1 Data Collection for Exit Ramp Terminals of Full Diamond Interchanges

For full diamond interchanges, a total of 128 exit ramp terminals were identified to have at least one WWD crash during the study period (2009-2013). Additionally, there were a total of 428 exit ramp terminals with no WWD crashes during the same period. Altogether, 556 exit ramp terminals were selected for data collection for the modeling of WWD risks at the full diamond interchanges. Summaries of collected categorical and continuous variables for full diamond interchange are presented in Tables 3.1 and 3.2, respectively.

Seven geometric design features at full diamond interchanges, defined in Figure 3.2, were collected, including intersection angle, type of median on crossroad, type of channelizing island, distance of nearest access point from the exit ramp terminals, tangency of corner radius to the crossroad edge, and number of lanes on the exit ramps and crossroads. Based on past studies and existing geometric guidelines, these geometric design features may have considerable effect on the probability of WWD (Zhou and Pour-Rouholamin, 2014; AASHTO, 2011). The definitions of these geometric design elements are discussed in the following paragraphs.

Intersection angle is the angle between the centerline of a ramp and the centerline of crossroad median, measured from the right side of the ramp (Eyler, 2005). In this study, the intersection angle was categorized as either an acute, right, or obtuse angle. Previous studies revealed that a 5-degree deviation from a right angle is typically indistinguishable by drivers (Caltrans, 2014). Therefore, in this study, the intersection angle is defined as follows: acute – <85 degrees; right – 85 to 95 degrees; and obtuse – >95 degrees.

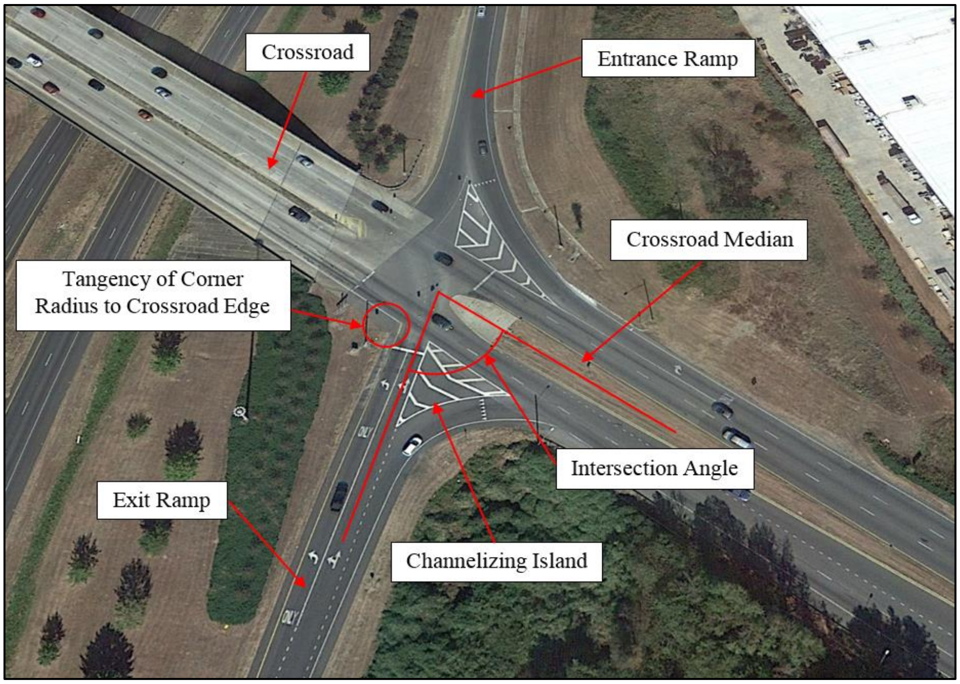


Figure 3.2 Geometric design features at full diamond exit ramp terminals

Table 3.1 Summary of categorical variables for full diamond interchanges

Variable	Category	With History of WWD crashes (*n*=128, 23%)		Without History of WWD crashes (*n*=428, 77%)	
		Frequency	**Percent**	**Frequency**	**Percent**
Intersection Angle					
	Acute	35	27.34%	54	12.62%
	Right	41	32.03%	125	29.21%
	Obtuse	52	40.63%	249	58.18%
Median on Crossroad					
	Non-traversable	55	42.97%	277	64.72%
	Traversable	73	57.03%	151	35.28%
Channelizing Island					
	Non-traversable	72	56.25%	307	71.73%
	Traversable	56	43.75%	121	28.27%
Distance to Nearest Access Point					
	200 ft. and less	13	10.16%	38	8.88%
	201 to 400 ft.	36	28.13%	84	19.63%
	401 to 600 ft.	29	22.66%	67	15.65%
	601 to 800 ft.	15	11.72%	119	27.80%
	More than 800 ft.	35	27.34%	120	28.04%
Is Corner Radius Tangent to Crossroad?					
	Yes	69	53.91%	127	29.67%
	No	59	46.09%	301	70.33%
Distance of WRONG WAY sign from Crossroad					
	200 ft. and less	32	25.00%	280	65.42%
	More than 500 ft.	96	75.00%	148	34.58%
Usage of DO NOT ENTER Sign					
	One (right/left side of exit ramp)	10	7.81%	29	6.78%
	Two (channelizing island and right/left side of exit ramp)	26	20.31%	61	14.25%
	Two (both side of exit ramp)	78	60.94%	319	74.53%
	Three (channelizing island and both side of exit ramp)	14	10.94%	20	4.67%
Exit Ramp Signalization					
	Signalized	54	42.19%	127	29.67%
	Unsignalized	74	57.81%	301	70.33%
Area Type					
	Rural	49	38.28%	268	62.62%
	Urban	79	61.72%	160	37.38%

Table 3.2 Summary of continuous variables for full diamond interchange

Variable	Maximum	Minimum	Mean	Median	Standard Deviation
Exit ramp AADT	27200	125	2825	1500	3485
Crossroad AADT	50440	374	9545	5525	10035

The type of median on crossroads and channelizing islands on exit ramps are two important design features for deterring WWD entries. A non-traversable raised median on the crossroad makes the wrong-way left-turn from a crossroad less likely (AASHTO, 2011). Similarly, a non-traversable channelizing island reduces WWD entries by narrowing the exit ramp throat (Zhou and Pour-Rouholamin, 2014). The presence of access points close to exit ramp terminals increases the chance of WWD entries at parclo interchanges (Pour-Rouholamin and Zhou, 2016a). The distance of nearest access points from exit ramp terminals was collected with an aim to understand its effect on WWD entries at full diamond interchanges. Existing guidelines stressed using an angular connection at the intersection of the left edge of exit ramps and right edge of crossroads, thus making the corner radius non-tangent to crossroad edge, to discourage WWD (AASHTO, 2011; WSDOT, 2013). However, no existing literature quantitatively measured the effect of this geometric feature on WWD. In addition to the geometric features discussed above, the number of lanes on an exit ramp and crossroad were collected as potential variables to be included in the model.

Wrong-way related signs and intersection signalization at the exit ramp terminals are also critical for reducing WWD. However, there is no guidance on proper placement of these signs to ensure that drivers can see the signs properly as well as have enough time to perceive and react. The MUTCD only suggests that there should be at least one WRONG WAY sign and one DO NOT ENTER sign along exit ramps to inform drivers about the exit ramp and prevent them from going wrong-way (FHWA, 2009). The impact of WRONG WAY signs placement, number and location of DO NOT ENTER signs, and signalization on WWD has not been studied in depth. Hence, the author collected the distance of WRONG WAY signs from crossroads (as shown in Figure 3.3), the number and location of DO NOT ENTER signs at the exit ramp throat (as shown in Figure 3.4), and intersection signalization information to be included in the model to predict the risk of wrong-way entry.

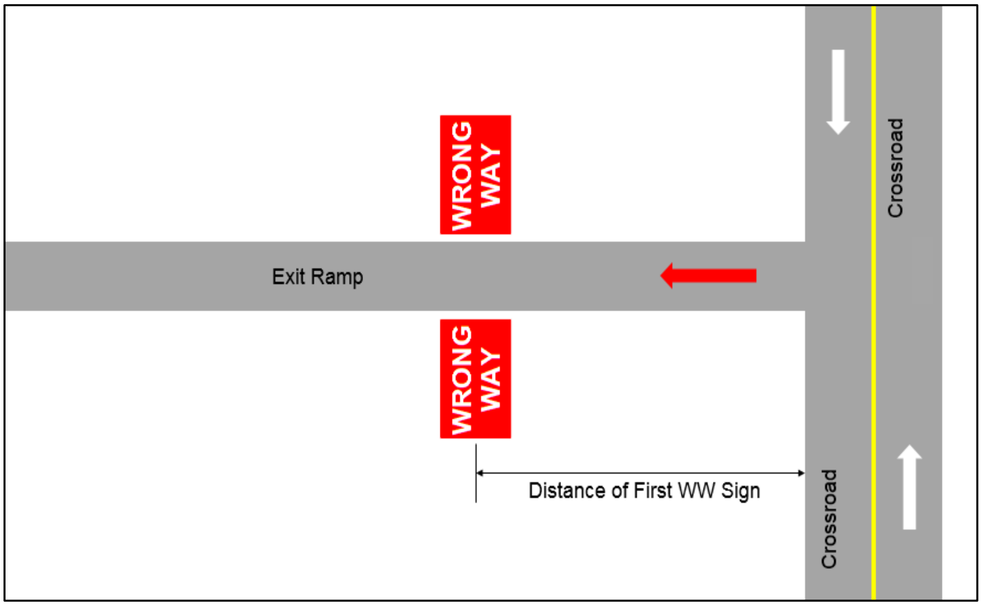


Figure 3.3 Distance of the first set of WRONG WAY sign from the crossroad

Figure 3.4 Number and locations of DO NOT ENTER signs

The area types (i.e., urban/rural) of the study interchanges were recorded using the 2010 Census Urban Area map, as previous studies indicated that the interchanges in urban areas are typically over-represented in WWD crashes. In addition, the AADT on the exit ramp and the crossroad may play a significant role in the risk of WWD. Therefore, AADT on exit ramps and crossroads were collected from ALDOT and IDOT traffic count websites.

3.1.2 Data Collection for the Exit Ramp Terminals of Parclo Interchanges

There were 25 exit ramp terminals of parclo interchanges with a history of at least one WWD crash during the study period (2009–2013) in the two states. The geometric design features and wrong-way related TCDs at these 25 exit ramp terminals were collected using Google Earth's aerial and street view imagery. In addition, as a comparison group, similar information was collected for 127 exit ramp terminals of parclo interchanges with no history of WWD crashes during the same period. Summary of collected categorical and continuous variables for parclo interchange are presented in Tables 3.3 and 3.4, respectively.

Based on the literature review results, the geometric design features having potential effects on the WWD at the parclo interchanges (Figure 3.5) include: (a) intersection angle, (b) corner radius to and from crossroad, (c) type of median on crossroad, (d) type and width of median between entrance and exit ramp, (e) channelizing island, (f) intersection balance, and (g) distance to nearest access point in the vicinity of interchange terminals (AASHTO, 2011; Zhou and Pour-Rouholamin, 2014; Pour-Rouholamin and Zhou, 2016a). A brief discussion of these geometric elements is presented below.

Similar to diamond interchanges, the intersection angle for parclo interchange was defined as follows: acute – less than 85 degrees; right – 85 to 95 degrees; and obtuse – more than 95 degrees. Corner radius from crossroad to two-way ramp plays an important role in reducing the chances of WWD at the parclo interchange terminals. The IDOT design manual suggests that the corner radius from crossroad to on ramp should be a maximum of 80 feet. Similarly, the corner radius from exit ramp to crossroad is suggested to be a maximum of 100 feet (IDOT, 2010). These suggestions, as presented in the IDOT manual, are based on experiences and engineering judgment. No scientific research was found to support these guidelines.

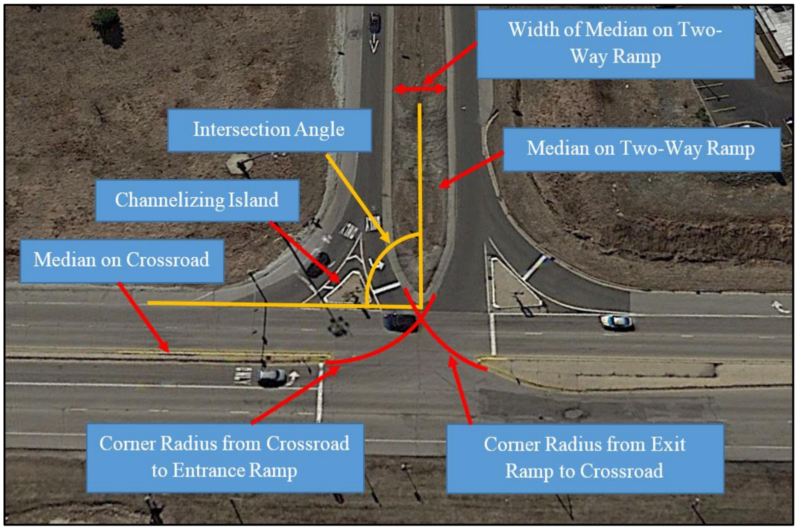


Figure 3.5 Geometric design features at parclo exit ramp terminals

The type of median on crossroads is an important design feature for reducing the probability of WWD entries. A non-traversable median on the crossroad works as a physical obstruction to the wrong-way left-turns from the crossroad and makes the exit ramp terminal less susceptible to WWD entry (AASHTO, 2011).

Type and width of median between entrance and exit ramp plays an important role in reducing the WWD at the exit ramp terminals of parclo interchange. Non-traversable medians with a minimum width of 50 feet is suggested by the IDOT manual (IDOT, 2010). Pour-Rouholamin and Zhou (2016a) found that this minimum width can be reduced to 30 feet without increasing the probability of WWD.

Table 3.3 Summary of categorical variables for parclo interchange

Variable	**Category**	**With history of WWD crashes (*n*=25, 16.45%)***		**Without history of WWD crashes (*n*=127, 83.55%)***	
		Frequency	**Percent**	**Frequency**	**Percent**
Intersection angle	Acute	2	8%	26	20%
	Right	17	68%	86	68%
	Obtuse	6	24%	15	12%
Corner radius from crossroad	60 feet or less	5	20%	20	16%
	61 to 80 feet	12	48%	59	46%
	81 to 100 feet	6	24%	36	28%
	More than 100 feet	2	8%	12	9%
Corner radius to crossroad	80 feet or less	9	36%	34	27%
	81-100 feet	9	36%	46	36%
	101-120 feet	5	20%	29	23%
	More than 120 feet	2	8%	18	14%
Median on crossroad	Traversable	11	44%	28	22%
	Non-traversable	14	56%	99	78%
Median between entrance and exit ramp	Traversable	0	0%	4	3%
	Non-traversable	25	100%	123	97%
Width of median between entrance and exit ramp	30 feet or less	14	56%	90	71%
	31 to 50 feet	8	32%	57	45%
	More than 50 feet	3	12%	10	8%
Channelizing island	None	2	8%	7	6%
	Traversable	4	16%	5	4%
	Non-traversable	19	76%	115	91%
Distance to nearest access point	300 feet or less	4	16%	14	11%
	301 to 600 feet	4	16%	33	26%
	601 to 900 feet	10	40%	44	35%
	More than 900 feet	7	28%	36	28%
Intersection balance	31% to 40%	9	36%	35	28%
	41% to 50%	9	36%	41	32%
	51% to 60%	6	24%	34	27%
	More than 60%	1	4%	17	13%
Distance of first WRONG WAY sign from crossroad	200 feet or less	11	44%	58	46%
	More than 200 feet	14	56%	69	54%
DO NOT ENTER sign	One (right/left side of exit ramp)	3	12%	27	21%
	Two (channelizing island and right/left side of exit ramp)	11	44%	33	26%
	Two (both side of exit ramp)	9	36%	45	35%
	Three (channelizing island and both side of exit ramp)	2	8%	22	17%
Presence of wrong-way arrow	Yes	10	40%	81	64%
	No	15	60%	46	36%
Presence of two sets of WRONG WAY signs	Yes	7	28%	60	47%
	No	18	72%	67	53%
Exit ramp signalization	Signalized	9	36%	58	46%
	Unsignalized	16	64%	69	54%
Area type	Rural	8	32%	46	36%
	Urban	17	68%	81	64%

Table 3.4 Summary of continuous variables for parclo interchange

Variable	Minimum	Maximum	Mean	Median	Standard Deviation
Exit Ramp AADT	175	14050	2928	1650	3171
Entrance Ramp AADT	150	15210	3015	1675	3193
Crossroad AADT	640	40100	12165	8900	9666

The type of channelizing island on exit ramps is also an important design feature to reduce the probability of WWD. A non-traversable channelizing island reduces the chance of WWD by narrowing the exit ramp throat (Zhou and Pour-Rouholamin, 2014; WSDOT, 2013).

Intersection balance is the ratio of the distance between the stop bar for left-turning vehicles from the crossroad and centerline of the median on a two-way ramp to the distance between the stop bar at two opposing directions of the crossroad. An intersection balance of 51% to 60% ensures that the left-turning drivers from the crossroad to the two-way ramp can have a good view of the entrance ramp when they stop at the stop line (WSDOT, 2013). A recent study found that an intersection balance of less than 40% may contribute to a higher likelihood of WWD (Pour-Rouholamin and Zhou, 2016).The presence of access points close to the ramp terminals are likely to cause driver confusion and increase the chance of WWD entries at parclo interchanges (Pour-Rouholamin and Zhou, 2016). Zhou et al. (2008), based on a safety and operational study, suggested that the minimum and desirable distance to the access point near interchange terminals should be 600 and 1,320 feet, respectively. Thus, the distance to the nearest access points from the exit ramp terminals, as shown in Figure 3.6, was collected with an aim to understand their effects on WWD.

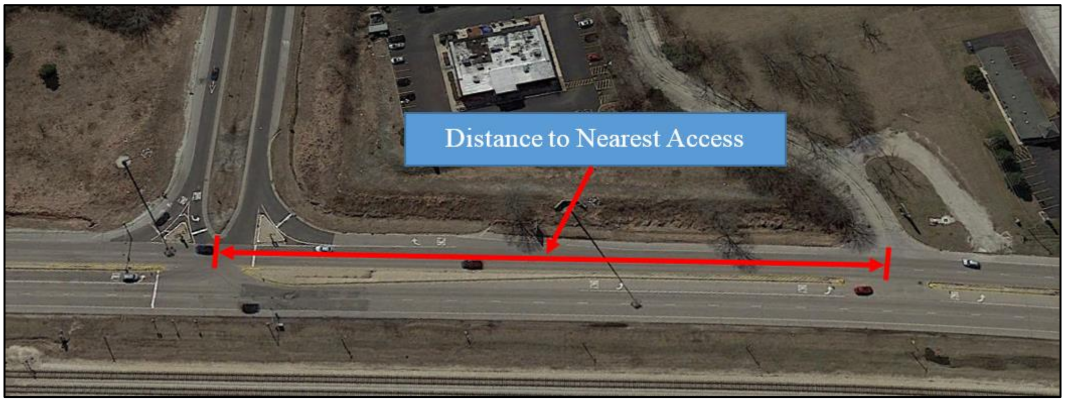


Figure 3.6 Distance to the first access point near an exit ramp terminal

Figure 3.7 Use of Keep Right sign at the nose of median between exit and entrance ramp

In terms of wrong-way related signs, the distance of the first set of WRONG WAY signs from the crossroad as well as the number and location of DO NOT ENTER signs at the exit ramp throat were collected, similar to that of full diamond interchange. In addition, there are certain signs that were specific for parclo interchanges. For instance, Keep Right sign at the nose of median between entrance and exit ramp as shown Figure 3.7 is one such example. The presence of wrong-way arrow on the exit ramp pavement and the presence of two sets of WRONG WAY signs were also included as potential predictors. The intersection signalization was also included to examine if the signalization at the intersections of two-way ramps can reduce the risk of WWD.

Previous studies found that WWD crashes are more likely to occur in urban areas. Therefore, the area type (i.e., urban or rural) was included as a potential predictor of the WWD. Additionally, the traffic volumes at the interchange terminals may have a significant effect on the chances of WWD entries at parclo interchanges. Baratian-Ghorghi et al. (2014b) stated that the number of potential WWD maneuvers, at the interchange terminals of parclo interchanges, increases when left-turn volume toward an entrance ramp increases and stopped vehicles at an exit ramp decrease. In this study, the AADT on the exit ramp, entrance ramp, and crossroad were collected, from the ALDOT and IDOT traffic count website, to be included in the model.

3.2 Modeling the Risk of WWD

The response variable in this study is dichotomous in nature (i.e., exit ramp terminals with or without history of WWD entries). There are several statistical techniques available to model the data with dichotomous response variable such as decision tree, discriminant analysis, support vector machines, and binary logistic regression. Since we have a relatively small sample size, the binary logistic regression is likely to produce better results than decision tree or discriminant analysis. While support vector machines can handle the small sample size issue, it is difficult to understand the effect of individual independent variables to the overall prediction of a model. Binary logistic regression overcomes this issue, since the effect of individual independent variables to the overall prediction of a model can be easily understood. In addition, many previous studies used this technique to study the probability of traffic crashes and the effects of different variables on certain types of crashes (Al-Ghamdi, 2002; Yan et al., 2005; Sarkar et al., 2011; Qin et al., 2013; Torrão et al., 2014; Yu, 2015). Therefore, binary logistic regression was assumed to be the appropriate techniques to model the risk of WWD based on the available data.

While standard binary logistic regression, which is based on maximum likelihood estimations (MLEs), works well for a balanced sample size, it may produce biased outcome and convergent failures when applied to rare event crash data (Firth, 1993; King and Zeng, 2001; Heinze and Schemper, 2002; Allison, 2008; Van der Paal, 2014; Heinze et al., 2016). Thus, standard binary logistic regression models will be biased when analyzing WWD events because of lack of robust data for rare WWD events. To overcome potential bias, we used Firth's penalized-likelihood logistic regression method because it minimizes the biased probability and convergent failures resulting from the MLEs of rare event.

The MLEs of regression parameters β_n $(n = 1, \dots\dots, k)$ are obtained by solving the score function $\frac{\partial \log L}{\partial \beta_n} \equiv U(\beta_n) = 0$ where L is the likelihood function. For rare events, Firth's proposed a modified score function to reduce the small-sample bias of these estimates, as follows:

$$U(\beta_n)^* = U(\beta_n) + \alpha_n, \qquad n = 1, \dots\dots, k \tag{3.1}$$

Where β_n is the regression parameter (contributing factors that affect the probability of WWD crashes) to be estimated, k is the number of parameters to be estimated, and α_n is the nth entry, which can be formulated as:

$$\alpha_n = \frac{1}{2} tr \left[I(\beta)^{-1} \frac{\partial I(\beta)}{\beta_n} \right], \qquad n = 1, \dots\dots, k \tag{3.2}$$

Where *tr* is the trace function and $I(\beta)^{-1}$ is the inverse of the Fisher's information matrix evaluated at β. The modified score equation $U(\beta)^*$ is associated with the penalized log-likelihood and likelihood functions, $\log L(\beta)^* = \log L(\beta) + 0.5 \log|I(\beta)|$ and $L(\beta)^* = L(\beta)|I(\beta)|^{1/2}$, respectively. In this case, $|I(\beta)|^{1/2}$ is known as Jeffrey's invariant prior. Using this modification, Firth showed that the $O(n^{-1})$ bias of MLEs $\hat{\beta}$ can be removed. A more detailed explanation of Firth's bias reduction technique can be found in Heinze and Schemper (2002) and Firth (1993). More recently, Van der Paal (2014) also reported that the Firth's method is more accurate in computing the regression coefficients and more reliable in computing the confidence intervals in terms of convergence failures.

To develop the models, the dependent variables were assigned a binary indicator that had a value of 0 if there was no history of WWD crashes at an exit ramp terminal and 1 for presence of crash history. The categorical independent variables were also assigned binary indicator of 0 or 1. Among the explanatory variables, AADT was the only continuous variable. The actual value of AADT is large compared with the binary indicators (0 or 1), which may cause skewness. To reduce this skewness, AADT was transformed to logarithmic scale. The "logistf" package in "R-project" was used to carry out the modeling approach (Heinze et al., 2016).

After preparing the data set, a full logistic regression model was fitted at first, which included all the explanatory variables in the primary data set. However, all the variables in this primary data set may not be statistically significant in predicting the probability of WWD. Therefore, in the next step, the backward elimination technique was employed to achieve a reduced final model, which only included the subset of variables that are significant in predicting the probability of WWD. The backward elimination technique produces an Akaike Information Criterion (AIC) value to decide the most parsimonious model. Typically, the most parsimonious and best-fitted model is the one that produces the lowest AIC.

The odds ratio (OR) was computed for each of the independent variables included in the final models using Equation 3.3. By definition, the OR of a certain variable expresses the change in the probability of WWD entry caused by a unit change of that same variable, while other variables remain constant. The OR can range from 0 to infinity, where a value of greater than 1 indicates the increased probability of WWD entry, and a value of less than 1 indicates the decreased probability when compared with the reference group.

$$Odds\ Ratio,\ OR_n = \exp(\beta_n) \tag{3.3}$$

Due to the unbalanced sample size and rareness of WWD crashes, the Firth's penalized-likelihood logistic regression is likely to produce better results than the standard binary logistic regression. Nonetheless, for the sake of making comparison between these two logistic regression models, a standard binary logistic regression model was also fitted to the dataset for full diamond interchange. Two indicators of model fit, namely AIC and Bayesian Information Criterion (BIC), were assessed to make comparison between standard binary logistic regression and Firth's penalized-likelihood logistic regression models. Both AIC and BIC estimates the relative amount of information lost by a given model. Therefore, the lower values of AIC and BIC indicates less information is lost and the quality of the model is better. AIC and BIC can be computed using equations 3.4 and 3.5, respectively.

$$AIC = -2LL_{Full} + 2k \tag{3.4}$$

$$BIC = -2LL_{Full} + \ln(N) \times k \tag{3.5}$$

Where LL_{Full} is the (penalized) log-likelihood of the full model (at convergence) with statistically significant predictor variables, k is the number of estimated parameters in the final model, and N is the number of observations. The model with lower AIC and BIC is considered to be better, when more than one logistic regression models are fitted on the same dataset.

One of the primary assumption of logistic regression model is that there is no intercorrelations (i.e., multi-collinearity) among the independent variables. The presence of collinearity inflates the variances of the parameter estimates, and consequently incorrect inferences about the relationships between independent and dependent variables (Midi et al., 2010). Therefore, it was necessary to check for potential multi-collinearity among the independent variables to ensure that the highly correlated variables has not been included in a model. This can be done by checking the correlation matrix, but may not be sufficient in some cases. Because several variables together may be highly interdependent, although no pairs of variables has a high correlation. To check for multi-collinearity more accurately, a parameter known as variance inflation factor (VIF), which is the reciprocal of tolerance and can be computed using Equation 3.6 (Midi et al., 2010), has been used in this study. VIF value of 4 is generally taken as a cut-off point in statistical modeling, which means a VIF value of 4 or more indicates high multi-collinearity while less than 4 indicates that the independent variables are not highly correlated (Pallant, 2001).

$$VIF = \frac{1}{Tolerance} = \frac{1}{1-R^2} \tag{3.6}$$

Where R^2 is the coefficient of determination for the regression of that explanatory variable on all remaining independent variables.

3.3 Procedure for Evaluation of the Calibrated Models

Due to the small sample size, it was not possible to conduct a traditional validation by keeping a portion of the original data excluded from the model construction and then using that to test the model prediction. Therefore, the author decided to evaluate the performance of the models in a different manner. In this study, the evaluation of model performance included identifying high-risk exit ramp terminals (i.e., network screening) in Alabama based on model prediction and observing WWD incidents at those high-risk locations for 48 hours. The assumption was that the model prediction can be considered successful if some of the high-risk locations experiences one or more WWD incidents within a time period as short as 48-hour. The following sections discusses about the network screening to identify high-risk exit ramp terminals in Alabama and video monitoring to observe WWD incidents.

3.3.1 Network Screening – Case Studies in Alabama

The network screening is a three-steps process as shown in Figure 3.8, which takes advantage of the logistic regression models calibrated for predicting the risk of WWD at the full diamond and parclo exit ramp terminals. To provide examples of network screening based on the calibrated models, case studies were conducted for the exit ramp terminals of full diamond and parclo interchanges along Alabama freeways.

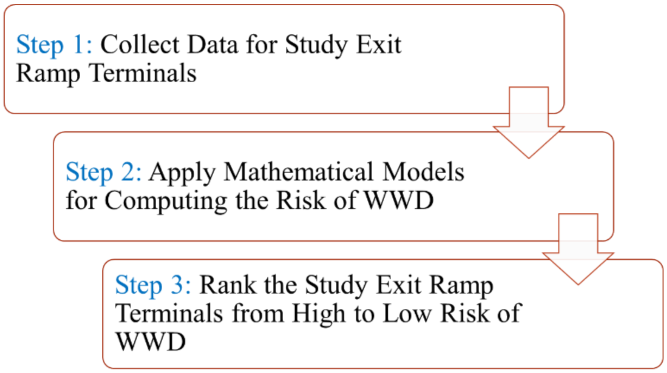


Figure 3.8 Steps involved in network screening for WWD

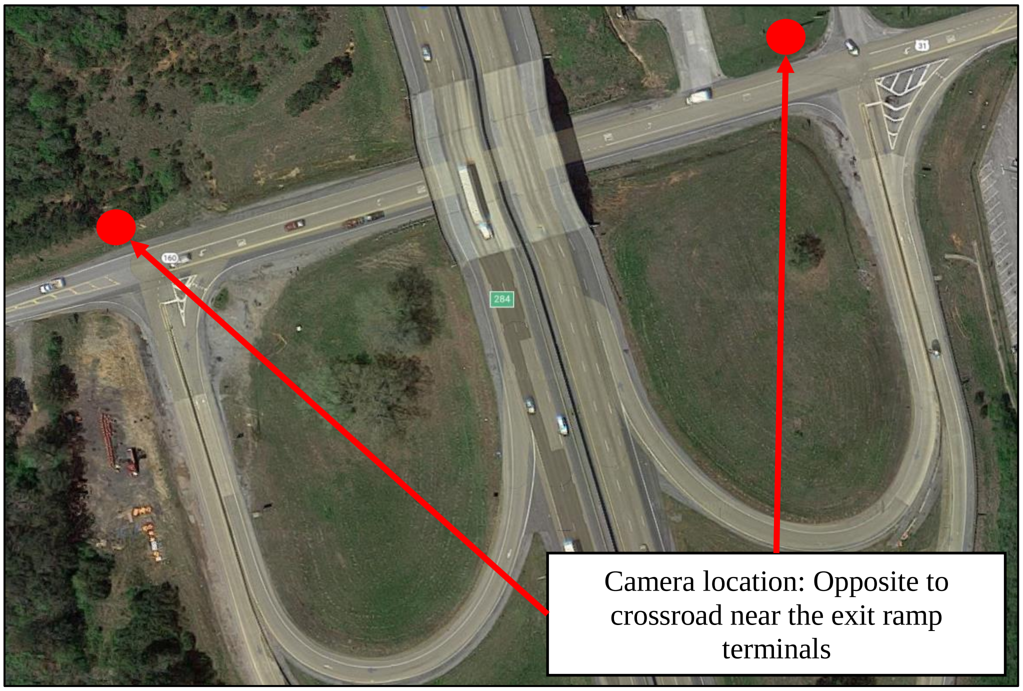
The first step in the network screening process involved collecting data for all the exit ramp terminals of full diamond and parclo interchanges in Alabama. The second step involved applying logistic regression models to predict the risk of WWD. For convenience, the research team integrated the logistic regression models into an automated excel spreadsheet. This excel spreadsheet will enable lay people to compute the probability of WWD at the exit ramp terminals by simply inputting the AADT values and selecting geometric design features and TCDs from drop-down lists. In addition to predicting the probability of WWD, the Excel spreadsheet readily provides a list of potential countermeasures (geometric design elements and/or TCDs) for reducing the probability of WWD at the respective exit ramp terminals. Screenshots of the automated excel spreadsheets are presented in Appendix B. After computing the probability of WWD at individual locations, in the third step, all the exit ramp terminals of full diamond and parclo interchanges were sorted in descending order (i.e., from high to low risk of WWD), which completed the network screening process.

3.3.2 Video Data Collection for Evaluation of the Models

The top-ten high-risk exit ramp terminals of both full diamond and parclo interchanges, identified through network screening of exit ramp terminals along Alabama freeways, were monitored using video cameras during typical (i.e., not affected by any special events, construction, and/or sever weather) weekends. For each location, 48-hour video was recorded from Friday, 5:00 p.m. to Sunday, 5:00 p.m. Later, the collected videos were thoroughly investigated to see if there was any WWD incidents.

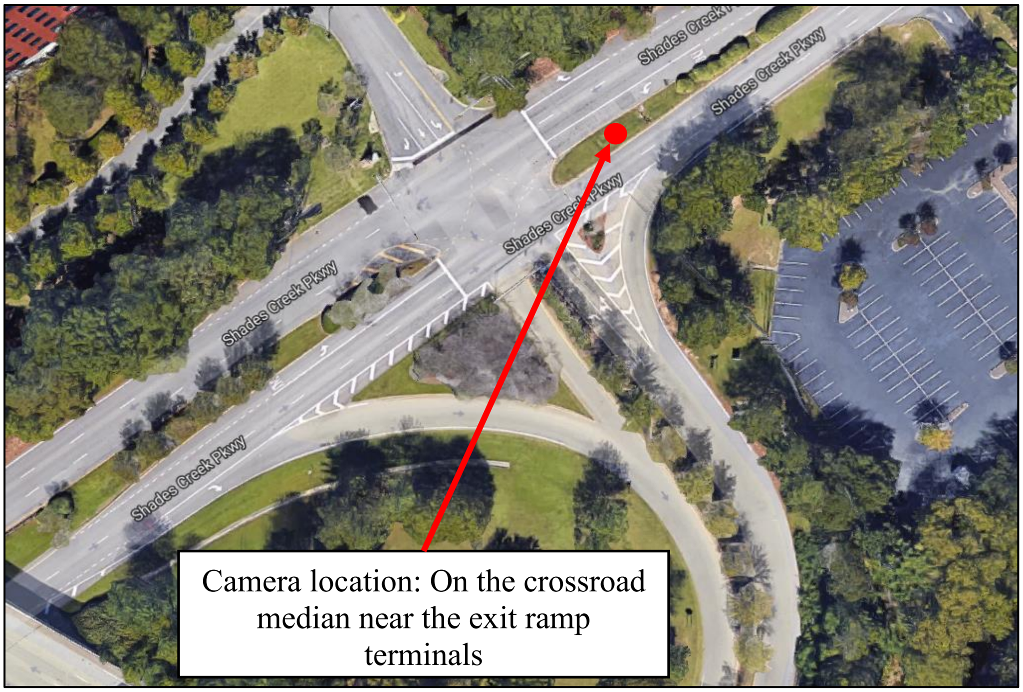
Figure 3.9 shows examples of installing cameras at the exit ramp terminals for collecting video of traffic movements. The cameras were mounted on top of signs with adjustable mounting pool and attached to sign posts with the help of screws and locks. The ideal location for installing camera are typically opposite to the crossroad near exit ramp terminals, as shown in Figure 3.10. However, if the crossroad has multiple lane with a wide median, video camera can be installed on the crossroad median near the exit ramp terminal, as shown in Figure 3.11, to ensure a clear view of the exit ramp throat. The view of the video camera should cover all the possible traffic movements at the exit ramp terminals, as shown in Figure 3.12 where red-dot represents the camera location and shaded-red region represents the expected view of camera.

Figure 3.9 Installing cameras at the high-risk exit ramp terminals



Camera location: Opposite to crossroad near the exit ramp terminals

Figure 3.10 Camera location for exit ramp terminals connected to two-lane crossroad



Camera location: On the crossroad median near the exit ramp terminals

Figure 3.11 Camera location for exit ramp terminals connected to multi-lane crossroad

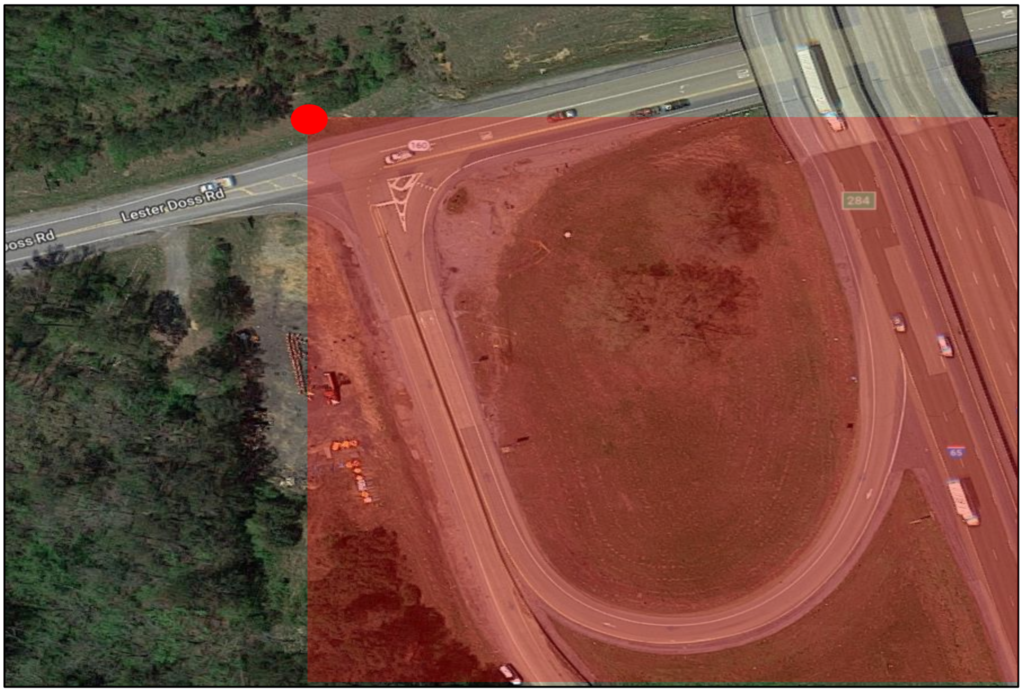


Figure 3.12 Area of coverage by the view of video camera

4 Analysis and Results

This chapter discusses the findings of modeling the risk of WWD at the exit ramp terminals of full diamond and parclo interchanges. In addition, the results of network screening for the exit ramp terminals along the freeways in Alabama has been discussed. Finally, the observation of WWD incidents during 48-hours of video monitoring at the top-ten high-risk ramp terminals of full diamond and parclo interchange have been documented.

4.1 Modeling Results for Full Diamond Interchange

The independent variables were checked for potential multi-collinearity before fitting them using logistic regression models. As shown in Table 4.1, all of the independent variables for full diamond interchange produced a VIF value of less than 4. Therefore, it can be assumed that the independent variables used for modeling the risk of WWD at the exit ramp terminals of full diamond interchange are not highly correlated.

Table 4.1 Test of multi-collinearity among the independent variables for full diamond interchange modeling

Variable	**Collinearity Statistics**	
	Tolerance	**VIF**
Intersection Angle	0.92	1.08
Median on Crossroad	0.44	2.26
Channelizing Island	0.66	1.51
Distance to Nearest Access Point	0.76	1.33
Tangency of Corner Radius	0.56	1.79
Distance of First WRONG WAY Sign	0.74	1.35
Usage of DO NOT ENTER Sign	0.91	1.10
Exit Ramp Signalization	0.37	2.71
Area Type	0.41	2.43
Exit Ramp AADT	0.32	3.13
Crossroad AADT	0.30	3.37

The final data set for modeling consisted of 128 exit ramp terminals with history of WWD and 428 exit ramp terminals with no history of WWD. A base model was fitted using all 556 observations, which included the exit ramp terminals connected to both two-lane and multilane (more than two lanes) crossroads. Further, the final data set was divided into two categories based on the number of lanes on the crossroads (i.e., two-lane and multilane). Two separate models were fitted for the exit ramp terminals connected to two-lane and multilane crossroads. This was done to investigate if particular geometric features and/or TCDs are more important for the exit ramp terminals connected to a two-lane crossroad than a multilane crossroad. Therefore, three models were calibrated, as follows:

- **Model 1** – base model to predict WWD risk regardless of the number of lanes on the crossroads
- **Model 2** – a model to predict WWD risk at the exit ramp terminals connected to two-lane crossroads
- **Model 3** – a model to predict WWD risk at the exit ramp terminals connected to multilane crossroads

4.1.1 Model 1: Base Model for Predicting WWD Risk

The aim of the base model was to predict the probability of WWD regardless of the number of lane(s) on the connecting crossroad. First, a full model was fitted, including all the explanatory variables. A summary of the full model is presented in Appendix A, Table A.1. However, some of the independent variables were not found to be statistically significant in predicting risk of WWD such as channelizing island, distance to nearest access point, and usage of DO NOT ENTER sign. Therefore, a backward elimination technique was employed to achieve a reduced final model, which only considers a subset of independent variables in the data set and minimizes the AIC value. The summary of final Firth's model is presented in Table 4.2. ANOVA test between full and final model shows that the final model was not significantly different from the full model ($\chi^2 = 5.26$, $p = 0.73$). Therefore, it can be stated that the final model has the same predictive power as the full model, although three variables from the full model was excluded in the final model.

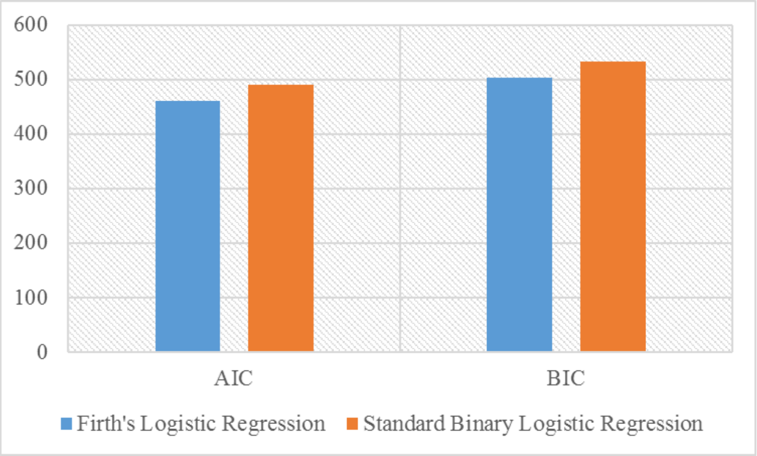


Figure 4.1 Comparison of AIC and BIC values

After fitting Firth's and standard binary logistic regression in the same dataset, a comparison was made between their indicators of model fit. Table 4.2 shows the results of both Firth's and standard binary logistic regression including their parameter estimates as well as the corresponding standard errors and OR. Table 4.2 also shows the AIC and BIC values of fitted Firth's and standard binary logistic regression models. According to the results, there is not much difference between the Firth's and standard binary logistic regression models in terms of parameter estimates, standard errors, and OR of the predictor variables. However, as reported in Table 4.2 and illustrated in Figure 4.1, the Firth's model produced a lower AIC and BIC values compared to the standard binary logistic regression model, indicating that the Firth's model provided a better fit to the dataset compared to the standard binary logistic regression model. As such, the remaining discussions and further modeling in this dissertation only included Firth's penalized-likelihood logistic regression models.

Table 4.2 Summary of Firth’s and standard binary logistic regression for Model 1

Independent Variables	Firth's Model			Traditional Binary Logistic Regression		
	β	**S.E.**	**OR**	**β**	**S.E.**	**OR**
(Intercept)	-4.912	1.365	-	-5.070	1.379	-
Intersection Angle						
Right	Reference			Reference		
Acute	0.273*	0.159	1.31	0.274*	0.159	1.32
Obtuse	-0.646**	0.269	0.52	-0.659**	0.272	0.52
Type of Median on Crossroad						
Non-Traversable	Reference			Reference		
Traversable	0.256*	0.150	1.29	0.256*	0.150	1.29
Corner Radius Tangent to Crossroad Edge?						
No	Reference			Reference		
Yes	1.337***	0.301	3.81	1.379***	0.304	3.97
Distance of First WRONG WAY Sign from Crossroad						
200 feet and less	Reference			Reference		
More than 200 feet	1.438***	0.255	4.21	1.473***	0.258	4.36
The Exit Ramp Terminal Signalized?						
No	Reference			Reference		
Yes	-0.328*	0.186	0.72	-0.330*	0.186	0.72
Area Type						
Rural	Reference			Reference		
Urban	1.334***	0.353	3.80	1.360***	0.357	3.90
log(Exit Ramp AADT)	-0.421*	0.233	0.66	0.425*	0.234	1.53
log(Crossroad AADT)	0.865**	0.430	2.38	0.896**	0.434	2.45
Log-Likelihood	-220.27			-234.66		
AIC	460.54			489.32		
BIC	503.75			532.53		

Significance Codes:

***Significant at the 99% confidence interval

**Significant at the 95% confidence interval

*Significant at the 90% confidence interval

Considering Firth's logistic regression as the model of choice, the fitted logistic regression model is shown in Equation 4.1. In the fitted model, p is the probability of WWD at the exit ramp terminals of a full diamond interchange.

Fitted regression equation for Model 1:

$$\boldsymbol{logit}(\boldsymbol{p}) = -4.912 + 0.273(IA_1) - 0.646(IA_2) + 0.256(MC) + 1.337(CR) + 1.438(WWSD) - 0.328(Signalized) + 1.334(AT) - 0.421\log(exit\ ramp\ AADT) + 0.865\log(crossroad\ AADT) \quad (4.1)$$

Where,

$$IA_1 = \begin{cases} 1, & if\ intersection\ angle\ is\ acute \\ 0, & otherwise \end{cases}$$

$$IA_2 = \begin{cases} 1, & if\ intersection\ angle\ is\ obtuse \\ 0, & otherwise \end{cases}$$

$$MC = \begin{cases} 1, & if\ median\ on\ crossroad\ is\ traversable \\ 0, & otherwise \end{cases}$$

$$CR = \begin{cases} 1, & if\ corner\ radius\ is\ tangent\ to\ the\ edge\ of\ crossroad \\ 0, & otherwise \end{cases}$$

$$WWSD = \begin{cases} 1, & if\ the\ distance\ of\ WW\ sign\ from\ crossroad\ is\ more\ than\ 200\ ft \\ 0, & otherwise \end{cases}$$

$$Signalized = \begin{cases} 1, & if\ the\ exit\ ramp\ terminal\ is\ signalized \\ 0, & otherwise \end{cases}$$

$$AT = \begin{cases} 1, & if\ the\ interchange\ is\ located\ in\ urban\ area \\ 0, & otherwise \end{cases}$$

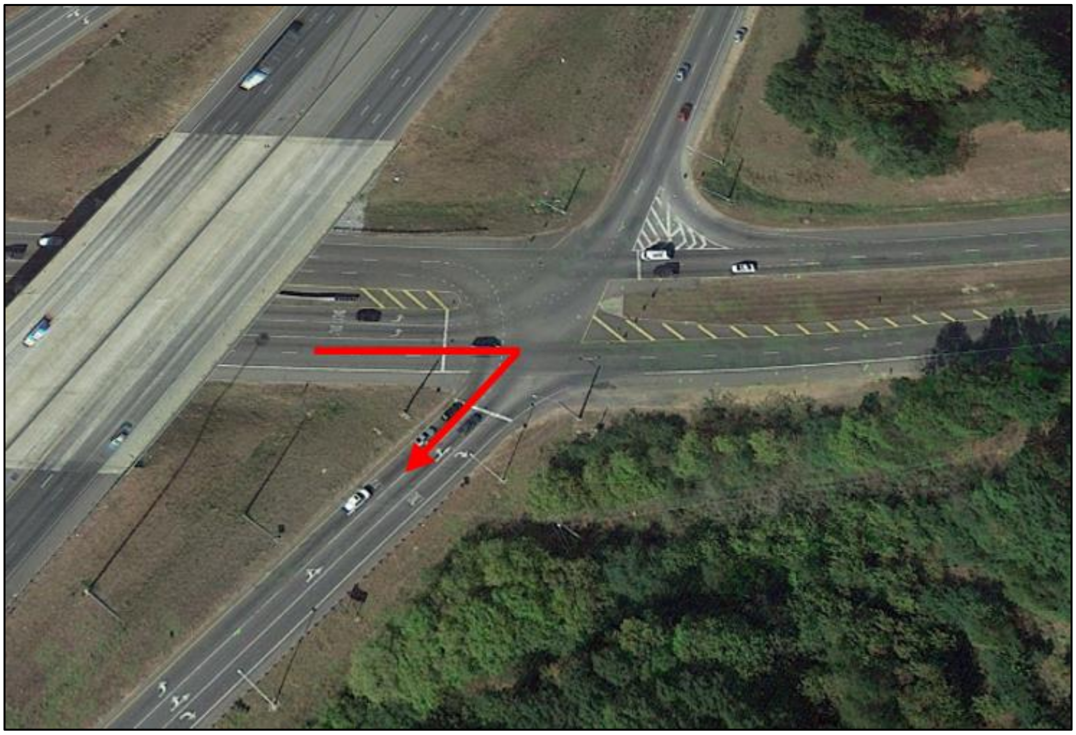
$\log(exit\ ramp\ AADT) = Logarithmic\ value\ of\ exit\ ramp\ AADT$

$\log(crossroad\ AADT) = Logarithmic\ value\ of\ crossroad\ AADT$

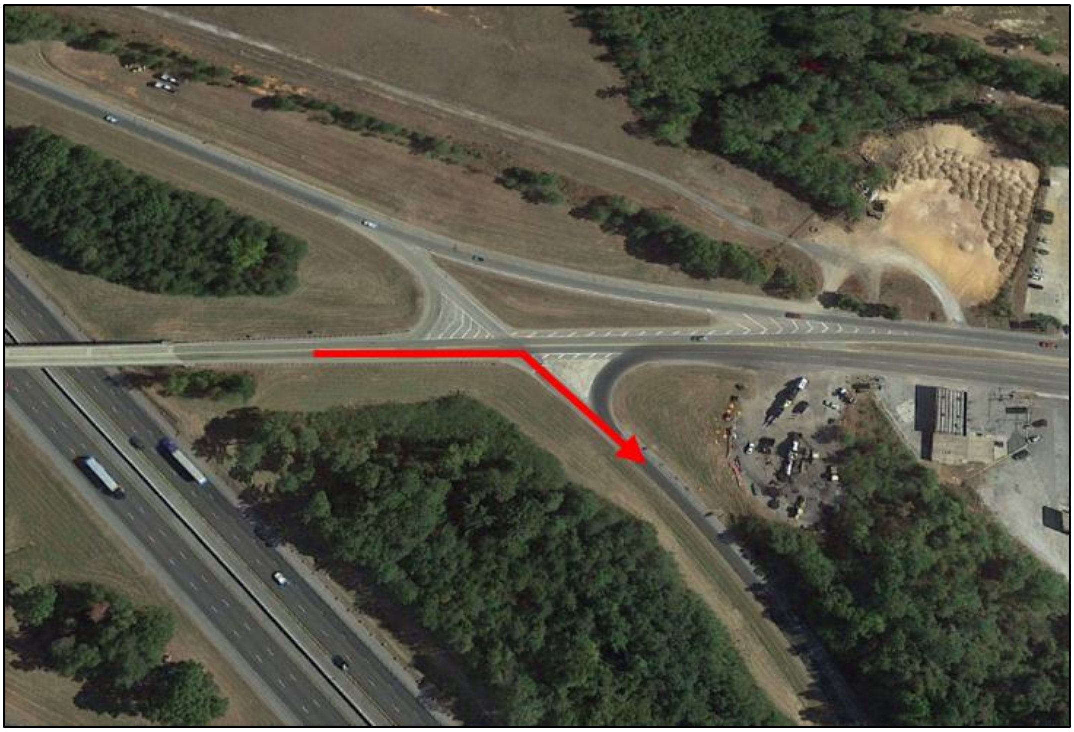
According to the fitted model, the intersection angle, median type on crossroad, tangency of corner radius to crossroad edge, distance of WRONG WAY signs from crossroad, intersection signalization, exit ramp AADT, crossroad AADT, and area type were significantly capable of predicting the probability of WWD at the exit ramp terminals of full diamond interchange. The negative signs before an independent variable such as obtuse angle connection, traffic signal, and exit ramp AADT indicate that they reduce the probability of WWD, and the positive sign indicates that the respective variable is associated with increasing the probability of WWD. Additionally, the OR values, as shown in Table 4.2, explain the extent to which each variable is responsible for increasing or decreasing the probability of WWD entry.

4.1.1.1 Effects of Geometric Design Features on WWD

According to the fitted model, the presence of an obtuse intersection angle reduces the risk of WWD at the exit ramp terminals of full diamond interchanges. The AASHTO Green Book recommended using a right-angle connection between one-way exit ramps of full diamond interchanges and connecting crossroads (AASHTO, 2011). However, the results herein showed that, for a full diamond interchange, obtuse intersection angle is more likely to reduce the probability of WWD entries than a right/acute-angle connection. The reason may be attributed to the fact that wrong-way right-turns are more prevalent at exit ramp terminals of full diamond interchanges, while an obtuse-angle connection makes the wrong-way right-turns difficult. On the contrary, an acute intersection angle makes right-turning maneuvers easy and therefore found to be more prone to WWD (OR=1.32). For a better understanding, a visual representation of potential wrong-way right-turning maneuvers at obtuse and acute angle connection to crossroads are shown in Figure 4.2.



(a) Obtuse angle connection to crossroad



(b) Acute angle connection to crossroad

Figure 4.2 Wrong-way right-turning maneuvers

The odds of WWD slightly increased for a traversable median on the crossroad (OR=1.29). This result clearly supports the Green Book's recommendations for using non-traversable crossroad medians to deter wrong-way left-turning movements (AASHTO, 2011). A non-traversable median provides a physical barrier to the left-turning WWD movements at the exit ramp terminal and reduces the overall likelihood of WWD at an exit ramp terminal.

The Green Book also recommended that the corner radius should not be tangent to the crossroad edge, thus making an angular connection between the left edge of exit ramp and the right edge of crossroad (AASHTO, 2011). Figure 4.3 shows an example of corner radius tangent and non-tangent to the crossroad edge. The results show that the use of corner radius tangent to crossroad edge increases the odds of WWD entry by 3.81 times, which can be attributed to the fact that an angled corner makes wrong-way right-turning maneuvers difficult. Therefore, the result supports the Green Book guidance for using an angled corner to deter right-turning WWD maneuvers from the crossroads.

(a) Corner radius tangent to crossroad edge

(b) Corner radius tangent to crossroad median

Figure 4.3 Examples of corner radius tangency

4.1.1.2 Effects of TCDs on WWD

The MUTCD requires the use of at least one WRONG WAY sign on the exit ramps (FHWA, 2009). However, there is no specific guidance on proper placement of WRONG WAY signs along the length of the exit ramps. The results show that the odds of WWD entry increase by 4.21 times when the distance between the first set of WRONG WAY sign and crossroad is more than 200 feet compared with when the distance is 200 feet or less. This is an interesting result given that placement of WRONG WAY signs varies widely among state and local transportation agencies and there is no specific guideline on the proper location for placing WRONG WAY signs along the exit ramps. Based on the results, the desirable distance of the first set of WRONG WAY sign from a crossroad is 200 feet or less (as shown in Figure 4.4). A more conservative approach may include the use of a second set of WRONG WAY signs close to the freeway and exit ramp connections for drivers who may have missed the first set of WRONG WAY signs. It should be noted that some states (e.g., Illinois) already use two sets of WRONG WAY signs along exit ramps (the first set close to the exit ramp terminal and a second set close to the freeway-ramp diverge area).

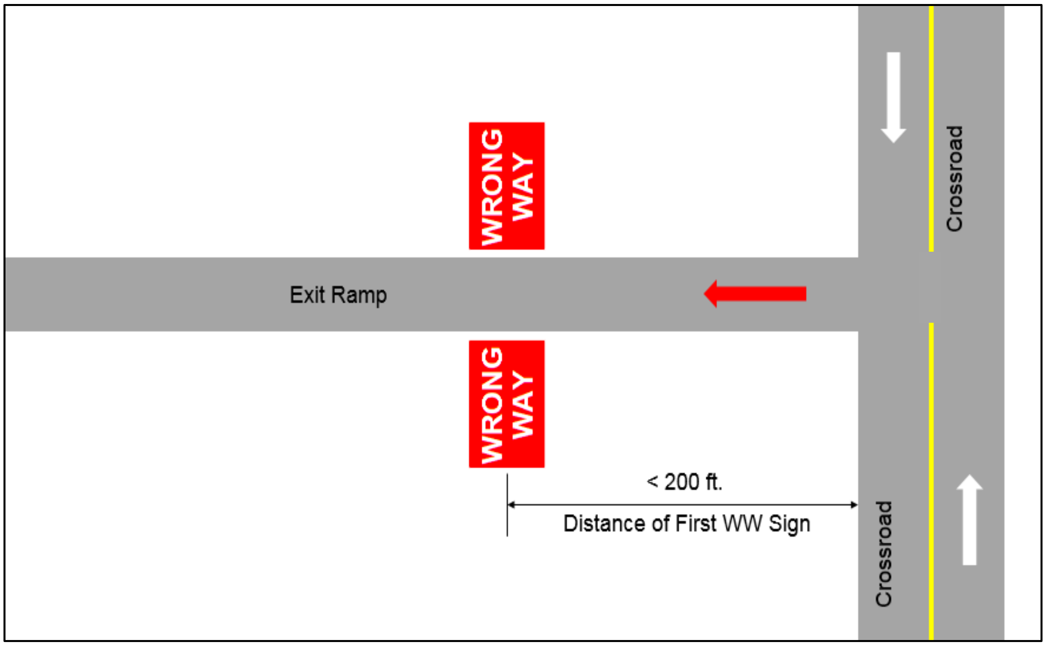


Figure 4.4 Desirable distance of the first set of WRONG WAY sign from the crossroads

Additionally, the fitted model shows that the signalized exit ramp terminals had less risk of WWD entries than unsignalized intersections, which is understandable given the fact that the signalized intersections facilitate more controlled and regulated traffic movements. Based on this finding, the probability of WWD entry should be considered as a supplement to MUTCD traffic signal warrants to justify intersection signalization at the exit ramp terminals.

4.1.1.3 Effects of AADT and Area Type on WWD

The crossroad AADT has a positive impact on the probability of WWD entry at the exit ramp terminals of full diamond interchanges, which means that the higher crossroad AADT increases the probability of WWD entry. This is consistent with a previous study by Sandt et al. (2017) in central Florida. The analysis results also indicate that the exit ramp AADT reduces the chance of WWD entry (OR=0.66). This implies that an increase in exit ramp AADT is associated with the decrease in the chance of WWD entry because the presence of traffic on exit ramps prevent drivers from entering the exit ramp from crossroads. Additionally, the odds of WWD entry for interchanges located in urban areas was found to be 3.80 times higher than in rural areas. Therefore, the interchanges in urban areas should be given higher priority for safety improvements.

4.1.2 Model 2: Exit Ramp Terminals Connected to Two-lane Crossroads

This model only considered the exit ramp terminals of diamond interchanges connected to two-lane crossroads. The sample size consisted of 55 exit ramp terminals with a history of WWD entries and 270 exit ramp terminals with no history of WWD entries. The procedure for developing this model is similar to that of Model 1, except that only a Firth's model was fitted in this case. The results of Model 2 are reported in Table 4.3, including the parameter estimates, standard errors, and OR corresponding to each of the predictor variables. Equation 4.2 depicts the fitted regression equation for Model 2.

Table 4.3 Summary of Firth's logistic regression analysis for Model 2

Independent Variables	Parameter Estimates (β)	S.E.	OR
(Intercept)	-2.275	1.866	-
Intersection Angle			
Right	Reference		
Acute	-0.201	0.520	0.82
Obtuse	-1.247***	0.391	0.29
Is Corner Radius Tangent to Crossroad Edge?			
No	Reference		
Yes	2.904***	0.572	18.25
Distance of First WRONG WAY Sign from Crossroad			
200 feet and less	Reference		
More than 200 feet	1.588***	0.403	4.89
Is the Exit Ramp Terminal Signalized?			
No	Reference		
Yes	-0.249	0.928	0.78
Area Type			
Rural	Reference		
Urban	0.915*	0.493	2.50
log(Exit Ramp AADT)	-0.580*	0.309	0.56
log(Crossroad AADT)	0.239	0.638	1.27
Log-Likelihood	-110.13		
AIC	238.52		
BIC	272.31		

Significance Codes:
***Significant at the 99% confidence interval
**Significant at the 95% confidence interval
*Significant at the 90% confidence interval

Fitted regression equation for Model 2:

$$\boldsymbol{logit}(\boldsymbol{p}) = -2.275 - 0.201(IA_1) - 1.247(IA_2) + 2.904(CR) + 1.588(WWSD) - 0.249(Signalized) + 0.915(AT) - 0.580\, log(exit\ ramp\ AADT) + 0.239\, log(crossroad\ AADT) \quad (4.2)$$

4.1.3 Model 3: Exit Ramp Terminals Connected to Multilane Crossroads

The sample size for predicting WWD entry at exit ramp terminals connected to multilane crossroads consisted of 73 exit ramp terminals with history and 158 exit ramp terminals with no history of WWD entries. A summary of this model is presented in Table 4.4. The fitted logistic regression equation, derived from this model, is shown in Equation 4.3.

Table 4.4 Summary of Firth's logistic regression analysis for Model 3

Independent Variables	Parameter Estimates (β)	S.E.	OR
(Intercept)	-6.478	2.420	-
Intersection Angle			
Right	Reference		
Acute	0.820*	0.459	2.27
Obtuse	-0.072	0.411	0.93
Type of Median on Crossroad			
Non-Traversable	Reference		
Traversable	1.295***	0.393	3.65
Is Corner Radius Tangent to Crossroad Edge?			
No	Reference		
Yes	1.188***	0.467	3.28
Distance of First WRONG WAY Sign from Crossroad			
200 feet and less	Reference		
More than 200 feet	1.485***	0.376	4.41
Is the Exit Ramp Terminal Signalized?			
No	Reference		
Yes	-1.437***	0.523	0.24
Area Type			
Rural	Reference		
Urban	1.951***	0.660	7.04
log(Exit Ramp AADT)	-0.661*	0.342	0.52
log(Crossroad AADT)	1.380**	0.650	3.97
Log-Likelihood	-106.76		
AIC	233.51		
BIC	267.94		

Significance Codes:
***Significant at the 99% confidence interval
**Significant at the 95% confidence interval
*Significant at the 90% confidence interval

Fitted regression equation for Model 3:

$$\boldsymbol{logit}(\boldsymbol{p}) = -6.478 + 0.820(IA_1) - 0.072(IA_2) + 1.295(MC) + 1.188(CR) + 1.485(WWSD) - 1.437(Signalized) + 1.951(AT) - 0.661\log(exit\ ramp\ AADT) + 1.380\log(crossroad\ AADT) \quad (4.3)$$

4.1.4 Comparison between Model 2 and Model 3

A comparison between Model 2 and Model 3 was done to investigate if particular geometric features and/or TCDs are more important for the exit ramp terminals connected to a two-lane crossroad than when they are connected to multilane crossroad. A comparison between Model 2 and Model 3 reveals that the acute angle intersection dramatically increases the risk of WWD when connected to multilane crossroads compared with two-lane crossroads. The crossroad median was not found to be a significant predictor for the two-lane crossroad, although the traversable median increases the odds of WWD entry by 3.65 times at exit ramps connected to multilane crossroads. The non-angular connection increased the odds of WWD by 18.25 times for a two-lane compared with 3.28 times for multilane crossroads. The distance of WRONG WAY signs from a crossroad had similar effects on the probability of WWD at an exit ramp connected to two-lane and multilane crossroads. The signalized intersection of a multilane crossroad and an exit ramp is more effective in reducing the probability of WWD (OR=0.24). While exit ramp AADT had similar effects for two-lane and multilane crossroads, the crossroad AADT was found to be associated with higher chance of WWD for multilane crossroads (OR=3.97). Finally, the multilane crossroad and exit ramp intersections in urban areas had higher odds of WWD (OR=7.04) than two-lane crossroads (OR=2.50). These results can help transportation agencies to identify which parameters should be given more considerations when they select countermeasures at the exit ramp terminals connected to two-lane or multilane crossroads.

4.2 Modeling Results for Parclo Interchange

Before fitting the model for parclo interchange, the potential predictors of WWD risk at parclo interchange were checked for multi-collinearity. The multi-collinearity test shows that none of the independent variables produced VIF of more than 4, as shown in Table 4.5. Therefore, it can be assumed that the independent variables used for modeling the risk of WWD at the exit ramp terminals of parclo interchange are not affected by multi-collinearity phenomenon.

Table 4.5 Test of multi-collinearity among the independent variables for parclo interchange modeling

Variable	**Collinearity Statistics**	
	Tolerance	**VIF**
Intersection Angle	0.82	1.22
Corner Radius from Crossroad	0.62	1.62
Corner Radius to Crossroad	0.62	1.62
Median on Crossroad	0.59	1.69
Median between Entrance and Exit Ramp	0.77	1.30
Width of Median between Entrance and Exit Ramp	0.46	2.20
Channelizing Island	0.87	1.15
Distance to Nearest Access Point	0.70	1.43
Intersection Balance	0.57	1.75
Distance of First WRONG WAY Sign	0.81	1.24
Usage of DO NOT ENTER Sign	0.70	1.43
Presence of “Keep Right” Sign	0.78	1.28
Presence of Wrong-Way Arrow	0.69	1.46
Exit Ramp Signalization	0.35	2.90
Area Type	0.61	1.65
Exit Ramp AADT	0.32	3.13
Entrance Ramp AADT	0.36	2.79
Crossroad AADT	0.29	3.45

The complete data set for parclo interchange consists of the geometric characteristics, wrong-way related TCDs, area type, and AADTs (on the exit ramp, entrance ramp, and the crossroad) at 152 exit ramp terminals. At first, a full model was fitted, which included all the potential predictor variables. The summary of full model is presented in Appendix A, Table A.2. Since some of the variables in the initial full model was not found to be significant in predicting the risk of WWD, backward elimination technique was employed to obtain the final model with variables having a statistically significant impact on the prediction outcome. ANOVA test between full model and final model shows that there is no statistically significant difference between full and final models (χ^2 = 14.33, p = 0.57). Therefore, the final model has the same predictive power as the initial full model, although all the insignificant variables in the full model was excluded to obtain the final model. In statistical modeling, it is desirable to obtain a model with smaller number of independent variables. A summary of the final logistic regression model is shown in Table 4.6, which includes the parameter estimates (with level of significance) along with corresponding standard errors and OR of the predicted variables in the final model.

The fitted logistic regression model to predict the risk of WWD at the exit ramp terminals of parclo interchange is shown in Equation 4.4. According to the fitted model, the negative sign before a variable indicates that the respective variable is responsible for reducing the probability of WWD, while a positive sign indicates that the respective variable is responsible for increasing the probability of WWD. In that regard, the probability of WWD reduces when the width of median between an entrance and exit ramp is above 30 feet, the distance to the nearest access point is more than 300 feet, the interchange terminal is signalized, and AADT on the exit ramp is high. On the other hand, the probability of WWD increases when the corner radius from crossroad to two-way ramp is more than 60 feet, the median on the crossroad is traversable, the channelizing island on the throat of the exit ramp is not present/traversable, there is no “Keep Right” sign and wrong-way pavement arrow, and the entrance ramp AADT is high.

Table 4.6 Summary of Firth's logistic regression analysis for parclo interchange

Independent Variables	Parameter Estimates (β)	S.E.	OR
(Intercept)	-6.496	1.863	-
Corner Radius from Crossroad			
60 feet or less	Reference		
More than 60 feet	0.898**	0.450	2.45
Median on Crossroad			
Non-Traversable	Reference		
Traversable	0.747**	0.356	2.11
Width of Median Between Exit and Entrance Ramp			
30 feet or less	Reference		
More than 30 feet	-0.673*	0.359	0.51
Channelizing Island on Exit Ramp Throat			
Non-Traversable	Reference		
No Channelization	0.163	0.669	1.18
Traversable	1.437***	0.476	4.21
Distance to Nearest Access Point			
300 feet or less	Reference		
More than 300 feet	-0.442*	0.259	0.64
"Keep Right" Sign			
Present	Reference		
Not Present	0.539*	0.302	1.71
Wrong-Way Arrow			
Present	Reference		
Not Present	0.894**	0.333	2.44
Signalized?			
No	Reference		
Yes	-1.645***	0.531	0.19
log(exit ramp AADT)	-0.575*	0.295	0.56
log(entrance ramp AADT)	1.789***	0.750	5.98
Log-Likelihood	-55.76		
AIC	135.52		
BIC	171.81		

Significance Codes:
***Significant at the 99% confidence interval
**Significant at the 95% confidence interval
*Significant at the 90% confidence interval

It should be noted that some of the variables were not included in the final model because they were not found to be statistically significant in predicting WWD risk at the exit ramp terminals of parclo interchanges. Statistically insignificant variables include intersection angle, corner radius from two-way ramp to crossroad, type of median between entrance and exit ramps, intersection balance, usage of DO NOT ENTER signs, distance of the first set of WRONG WAY sign, presence of two sets of WRONG WAY signs, and area type along the exit ramp. Although some recent studies found that the intersection balance may have an impact on WWD incidents at the exit ramp terminals of parclo interchange (Pour-Rouholamin and Zhou, 2016; Wang and Zhou, 2018), this variable was not found to be significant predictor based on the data used in this study.

Fitted logistic regression model for parclo interchange:

$$\begin{aligned}\mathbf{logit}(\boldsymbol{p}) = &-6.496 + 0.898(CR) + 0.747(MC) - 0.673(MW) + 0.163(CI_1) + 1.437(CI_2) \\ &- 0.442(DAP) + 0.539(KRS) + 0.894(WWA) - 1.645(Signalized) \\ &- 0.575\, log(exit\ ramp\ AADT) + 1.789\, log(entrance\ ramp\ AADT) \qquad (4.4)\end{aligned}$$

Where,

$$CR = \begin{cases} 1, & if\ the\ corner\ radius\ from\ crossroad\ is\ more\ than\ 60\ feet \\ 0, & otherwise \end{cases}$$

$$MC = \begin{cases} 1, & if\ the\ median\ on\ the\ crossroad\ is\ traversable \\ 0, & otherwise \end{cases}$$

$$MW = \begin{cases} 1, & if\ the\ width\ of\ median\ between\ on\ and\ off\ ramp\ is\ more\ than\ 30\ feet \\ 0, & otherwise \end{cases}$$

$$CI_1 = \begin{cases} 1, & if\ there\ is\ no\ channelization\ on\ the\ throat\ of\ exit\ ramp \\ 0, & otherwise \end{cases}$$

$$CI_2 = \begin{cases} 1, & if\ the\ channelization\ on\ the\ throat\ of\ exit\ ramp\ is\ traversable \\ 0, & otherwise \end{cases}$$

$$DAP = \begin{cases} 1, & if\ the\ distance\ to\ nearest\ access\ point\ is\ more\ than\ 300\ feet \\ 0, & otherwise \end{cases}$$

$$KRS = \begin{cases} 1, & if\ there\ is\ no\ KEEP\ RIGHT\ sign\ on\ the\ median\ between\ on\ and\ off\ ramp \\ 0, & otherwise \end{cases}$$

$$WWA = \begin{cases} 1, & if\ there\ is\ no\ WW\ pavement\ arrow\ on\ the\ exit\ ramp \\ 0, & otherwise \end{cases}$$

$$Signalized = \begin{cases} 1, & if\ the\ exit\ ramp\ terminal\ is\ signalized \\ 0, & otherwise \end{cases}$$

$log(exit\ ramp\ AADT) = Logarithmic\ value\ of\ exit\ ramp\ AADT$

$\log(entrance\ ramp\ AADT) = Logarithmic\ value\ of\ entrance\ ramp\ AADT$

4.2.1 Effects of Geometric Design Features on WWD

The probability of WWD increased by 2.45 times when the corner radius from crossroad to entrance ramp is above 60 feet. Typically, a sharp corner radius is expected to ensure that the left-turning wrong-way maneuvers from the crossroad to exit ramp is not easy for drivers. The IDOT design manual suggests that the corner radius from a crossroad to two-way ramp should not be more than 80 feet (IDOT, 2010). Based on the findings of this study, it can be recommended that, in general, the 60 feet corner radius has the best potential to reduce the chances of WWD entry. However, the number of lanes on the crossroad and the exit ramp may significantly affect this corner radius. Intersection balance will also affect the corner radius. Therefore, engineering judgment should be employed to decide the corner radius at the interchange terminals with multiple lanes on the crossroad and on the exit ramp.

A traversable median on the crossroad was found to increase the chances of WWD by 2.11 times compared with a non-traversable median. Pour-Rouholamin and Zhou (2016a) found similar results when predicting the effect of geometric design elements on the probability of WWD entries. In addition, the existing guidelines stressed on providing a non-traversable median on the crossroad to physically obstruct the left-turning wrong-way maneuvers from the crossroad (AASHTO, 2011; Zhou and Pour-Rouholamin, 2014). Therefore, this study further corroborates the importance of a non-traversable crossroad median in mitigating the WWD problem at exit ramp terminals.

There is lack of guidance concerning the appropriate median width between two-way ramps. A minimum width of 50 feet is recommended in the IDOT manual (IDOT, 2010). Pour-Rouholamin and Zhou (2016a) reported that this width can be reduced to a minimum of 30 to 40 feet. In this study, the chances of WWD was found to decrease whenever the width was above 30 feet. Therefore, the minimum standard width of median between two-way ramps should be at least 30 feet to ensure that this design element does not contribute to increased chance of WWD at the exit ramp terminals of parclo interchange.

Non-traversable channelizing island is recommended in the available guidelines to reduce the width of exit ramp throat, thus keeping less traversable pavement width for wrong-way drivers (Zhou and Pour-Rouholamin, 2014). In this study, the non-traversable channelizing island was found to be associated with a lower chance of WWD compared with no or traversable channelizing island. However, interestingly, the chance of WWD entries is more for a traversable channelizing island (OR = 4.21) compared with no channelizing island (OR = 1.18). This can be attributed to the fact that an exit ramp with a traversable channelizing island typically has a wider throat than that of having no channelizing island. This wider throat provides an extra traversable area to wrong-way drivers, which may make exit ramps with traversable channelizing islands more susceptible to WWD compared to that without any channelization.

The presence of access points/driveways close to interchange terminals can contribute to additional driver confusion and increase the probability of WWD entries. Zhou et al. (2008) recommended that the minimum distance of access points/driveways should be at least 600 feet from an exit ramp terminal. This study also corroborates that the presence of access points within close proximity is associated with more chance of driver confusion and resulting WWD movements. To be more specific, this study found that the exit ramp terminals with access points within 300 feet have higher chance of WWD entries compared to those without any access points within 300 feet.

4.2.2 Effects of TCDs on WWD

The MUTCD requires at least one WRONG WAY and one DO NOT ENTER sign at the exit ramps (FHWA, 2009). However, the effectiveness of wrong-way related TCDs also depends on their placement at the exit ramp terminals. In this study, the absence of KEEP RIGHT signs (on the median between two-way ramps) and wrong-way pavement arrows were found to increase the probability of WWD by 1.71 and 2.44 times, respectively. Additionally, the signalized exit ramp terminals were found to have significantly lower risk of WWD (OR = 0.19) compared to unsignalized exit ramp terminals. Interestingly the distance of first set of WRONG WAY sign was not found to be a significant variable in predicting the probability of WWD entry at the exit ramp terminals of parclo interchange, although it was significant in predicting the risk of WWD entry at the exit ramp terminals of full diamond interchange.

4.2.3 Effects of AADT on WWD

In this study, the locations with higher AADT volumes on exit ramps were found to have lower risks of WWD (OR = 0.56). On the other hand, locations with higher AADT volumes on entrance ramps were found to have higher risks of WWD (OR = 5.98), which can be attributed to the fact that the higher entrance ramp AADT means a higher number of potential wrong-way drivers. Locations with low exit ramp AADT and high entrance ramp AADT (especially high left-turn onto the entrance ramps) are likely to have more left-turn volume toward the entrance ramp and less stopped vehicles at the exit ramp. Such locations are likely to be more prone to WWD. On the contrary, the locations with more vehicles on the exit ramp helps the drivers on the crossroad to recognize the exit ramp due to the oncoming traffic, which results in lower chance of WWD movements.

5 Evaluation of the Models Performance Using Case Studies in Alabama

Evaluation of the models' performance consisted of conducting network screening for the exit ramp terminals along Alabama freeways using the fitted models to identify locations with high-predicted risk of WWD and observing WWD incidents by monitoring the top ten high-risk locations using video cameras. It was assumed that the fitted models could be considered successful if one or more of top ten high-risk locations experience one or more WWD incidents during the 48-hours of video monitoring. This assumption seems reasonable as the WWD events are typically rare. However, given the availability of time and resources, the duration of video monitoring can be increased to observe WWD incidents over a longer period. The following sections are dedicated to the discussion of findings from network screening and video data collection.

5.1 Findings from Network Screening and Video Monitoring

As mentioned earlier in Section 3.3.1, the first step in network screening was collecting required data. After developing the models, it was possible to determine the data elements required for the network screening. Table 5.1 shows the required data elements for the network screening of full diamond and parclo exit ramp terminals along with their sources. It should be noted here that the sources of required data elements are easily accessible to the public, which indicates that the network screening using the fitted models is easy and less time consuming (since it does not include the administrative processing time for requesting data that is not publicly available).

Table 5.1 Data elements needed for network screening

Category	Required Data		Data Source
	Full Diamond	Parclo	
Geometric Design Elements	-Intersection angle -Type of median on crossroad -Tangency of radius to crossroad edge	-Corner radius from crossroad -Type of median on crossroad -Width of median between exit and entrance ramps -Type of channelizing island -Distance to nearest access point	Google Earth Aerial Imagery
TCDs	-Distance of WRONG WAY sign from the crossroad -Intersection signalization	-Presence/absence of "Keep Right" sign -Presence/absence of wrong-way pavement arrow -Intersection signalization	Google Earth Aerial and Street View
AADT	-Exit ramp AADT -Crossroad AADT	-Exit ramp AADT -Entrance ramp AADT	ALDOT Traffic Count Website
Area Type	-Urban/rural		Census Urban Area Map

In the second step, predicting the risk of WWD at individual exit ramp terminals was carried out by using the automated excel spreadsheets (as shown in Appendix B) that was developed based on Equations 4.1 and 4.4. Then the predicted WWD risk was sorted from high to low to determine the top ten high-risk locations. The top ten high-risk exit ramp terminals identified by network screening and the findings from video monitoring of those locations are discussed in the following sections.

5.1.2 Top Ten High-Risk Exit Ramp Terminals of Full Diamond Interchanges

Table 5.2 shows that six of the ten locations identified by the model had a WWD crash history. It indicated that the model can successfully identify locations with a crash history. To evaluate the model prediction results, WWD incident was also collected using video cameras. It was found that two locations experienced one WWD incident each (Table 5.2) during the data collection period. Due to the rare nature of WWD incidents, one incident over 48 hours is considered high for an intersection. To further evaluate the fitted models for full diamond interchanges, the author recommends to collect WWD incident data for a longer duration (for a whole week/month if possible) to confirm if there are recurring WWD incidents.

Based on the engineering judgements, it can be stated that the full diamond interchange model (Equation 4.1) are capable of successfully identifying the high and low risk locations. Because the locations with high predicted risk seems to have some poor designs such as traversable median on the crossroad, acute intersection angle, corner radius tangent to crossroad edge, first WRONG WAY sign far away from the exit ramp, low exit ramp AADT, and high crossroad AADT. On the contrary, a visual inspection of low-risk locations provides evidence that those locations have good design features and likely to be less susceptible to WWD. Some examples of low and high-risk full diamond exit ramp terminals are presented in Appendix C, Figures C.1 to C.2.

Table 5.2 Results of video analysis for exit ramp terminals of full diamond interchanges

Ranking	Locations	Was there any WWD Crash in the Past?	Probability of WWD Entry	Number of WWD Entries*
1	I-20 Exit 156 WB	Yes	84%	0
2	I-59 Exit 132 SB	Yes	84%	0
3	I-20 Exit 191 EB	Yes	82%	0
4	I-65 Exit 170 SB	No	77%	1 (daytime)
5	I-65 Exit 310 SB	No	74%	0
6	I-65 Exit 170 NB	No	73%	0
7	I-565 Exit 3 EB	Yes	73%	0
8	I-459 Exit 31 NB	Yes	73%	0
9	I-65 Exit 15 SB	No	71%	1 (daytime)
10	I-10 Exit 13 EB	Yes	70%	0

**Wrong-way drivers travelled at least some distance along the exit ramp.*

5.1.3 Top Ten High-Risk Exit Ramp Terminals of Parclo Interchanges

Table 5.3 lists the top ten locations and their predicted probability of WWD, along with crash history and the number of WWD incidents during 48 hours of a typical weekend. It showed that five of the ten locations had WWD crashes in the past between 2009-2013. WWD incidents was observed by collecting 48-hour videos of traffic movements at each of the ten high-risk exit ramp terminals. After analyzing the videos, two out of the ten locations were found to have more than ten WWD incidents over a 48-hour period. The location with the highest probability (Rank #1: I-65 Exit 284 SB) experienced 17 WWD entries. In addition, another two locations were found to have one WWD movement in a 48-hour period. The occurrences of WWD incidents at high-risk locations indicate that the fitted model is capable of identifying high-risk exit ramp terminals of parclo interchanges. A visual inspection, based on engineering judgements, of the locations with high and low predicted WWD risk also supports that the model is capable of predicting the risk of

WWD, as the high-risk locations seem to have poor design features while the low-risk locations typically have good design features that reduce driver confusions and resulting WWD movements. Some examples of high and low risk locations are presented in Appendix C Figures C.3 to C.5.

Table 5.3 Results of video analysis for the exit ramp terminals of parclo interchanges

Ranking	Locations	Was there any WWD Crash in the Past?	Probability of WWD Entry	Number of WWD Entries*
1	I-65 Exit 284 SB	Yes	79%	17 (Daytime – 9; Nighttime – 8)
2	I-65 Exit 284 NB	Yes	70%	0
3	I-85 Exit 60 NB	No	61%	0
4	I-65 Exit 208 SB	Yes	61%	10 (Daytime – 1; Nighttime – 9)
5	I-65 Exit 22 NB	No	57%	0
6	I-65 Exit 208 NB	Yes	51%	1 (Nighttime)
7	US 280 AL-38 Exit	No	46%	0
8	I-10 Exit 44 WB	No	38%	1 (Daytime)
9	I-65 Exit 247 SB	Yes	37%	0
10	I-65 Exit 247 NB	No	33%	0

**Wrong-way drivers travelled at least some distance along the exit ramp.*

The WWD incident analysis also revealed that all WWD entries at the parclo interchange terminals were found to be the left-turn movements from the crossroad. Thus, it is evident that the left-turns from the crossroad to the two-way ramp are the most dangerous maneuvers in terms of WWD at the exit ramp terminals of parclo interchange. Therefore, more emphasis should be given to the geometric design features to physically obstruct drivers from making wrong-way left-turns from the crossroad. Additionally, the wrong-way related TCDs should be placed targeting left-turning traffic from the crossroad.

It should be noted that no WWD incidents were observed during the 48 hours at I-65 Exit 284 NB, which is ranked #2 according to the model prediction. One reason for this is that there is a low left-turn volume to the entrance ramp and a comparatively high AADT volume on the exit ramp at this location. The existing morning and afternoon (inside parentheses) peak hour traffic volumes at this location is shown in Figure 5.1, which indicates that the left-turn volumes to entrance ramps are high for the SB ramp compared with that of the NB ramp. While the fitted model includes the AADT on the entrance ramp as a high impact predictor (OR=6.619), the actual WWD risk depends on the percentage of left-turns from the crossroad to the entrance ramp. All of the WWD incidents observed in the field study are caused by left-turning drivers from the crossroad, which further supports this statement.

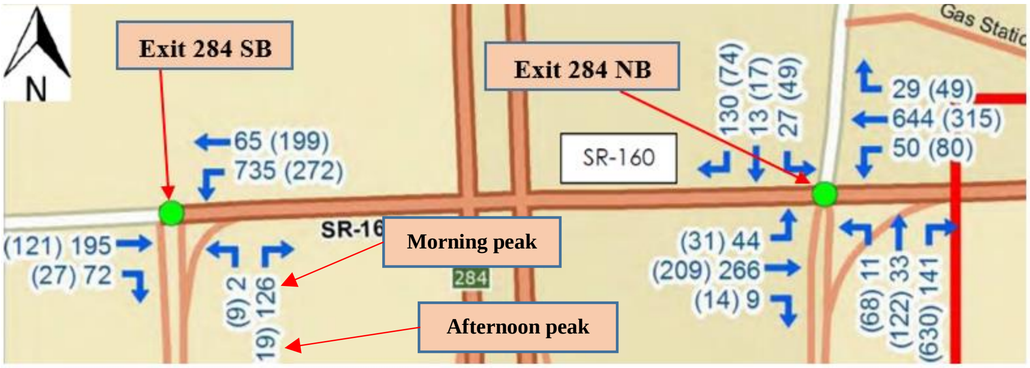


Figure 5.1 Existing afternoon and morning peak hour traffic volumes

6 Conclusions and Recommendations

The exit ramp terminals are the most common points of origin for most WWD incidents and resulting crashes on freeways. Therefore, it is critical to adopt a proactive approach to identify the exit ramp terminals with high risk of WWD and implement countermeasures to deter their occurrences before a crash happens. The most challenging parts in adopting such a proactive approach, commonly known as a systemic safety approach, are identifying high-risk ramp terminals without crash history. This dissertation focused on calibrating logistic regression models to predict the risk of WWD at the exit ramp terminals of full diamond and parclo interchange. These models may enable transportation agencies to identify the exit ramp terminals with higher risk of WWD based on the predicted risk. Eventually the transportation agencies will be able to adopt a systemic safety approach to mitigate WWD on freeways within their jurisdiction and proactively treat the high-risk exit ramp terminals to reduce risk of WWD.

In this study, the crash risk prediction models have been calibrated for two interchange types, namely full diamond and parclo interchange. According to the results, certain geometric features and TCDs, traffic volume, and area type are found to be statistically significant in predicting the risk of WWD at the exit ramp terminals. To be more specific, the geometric features such as intersection angle, type of median on crossroad, and tangency of corner radius were found to be significant predictor of WWD risk at the exit ramp terminals of full diamond interchange. For parclo interchange, the geometric features such as corner radius from crossroad, type of median on crossroad, width of median between exit and entrance ramp, channelizing island on exit ramp throat, and distance to nearest access point were significant predictor of WWD risk. Regarding TCDs, distance of first WRONG WAY sign from crossroad was significant for full diamond interchange, presence of “Keep Right” sign and wrong-way pavement arrow was significant for parclo interchange, and intersection signalization was significant for both full diamond and parclo interchange. Regarding traffic volume, crossroad and exit ramp AADT was significant predictor for full diamond interchange, while exit and entrance ramp AADT was significant predictor for parclo interchange. Area type was only found to be significant predictor of WWD risk at the exit ramp terminals of full diamond interchange.

Using the fitted model, network screening case studies were conducted for the exit ramp terminals of full diamond and parclo interchanges along Alabama freeways. According to the network screening results, six out of the top ten high-risk exit ramp terminals of full diamond interchange in Alabama have experienced WWD crashes between 2009-2013. It indicates that the model can successfully identify the high-risk exit ramp terminals of full diamond interchanges. To evaluate the model performance, WWD incident data was collected over a 48-hours weekend period at each of the top ten high-risk exit ramp terminals. Only two of top ten high-risk exit ramp terminals found to have one WWD incident each during the 48-hours weekend period. Since the WWD movements are known to be rare events, the author recommends collecting WWD incident data for a longer duration (possibly for multiple weekends/one entire week/one entire month) to confirm if there are recurring WWD incidents and to evaluate the model performance more precisely.

According to the network screening results for parclo interchange, five out of the top ten high-risk exit ramp terminals along freeways in Alabama experienced WWD crashes between 2009-2013. Further, the model prediction results were verified by WWD crash and incident data.

The traffic movement data at the top ten high-risk locations revealed that two locations experienced ten or more WWD incidents and an additional two locations experience one WWD incidents each over a 48-hour period of a typical weekend. Therefore, the model for predicting the risk of WWD at the exit ramp terminals of parclo interchange was successful in identifying the high-risk exit ramp terminals along freeways in Alabama.

Overall, the fitted model was considered to be successful in identifying the high-risk exit ramp terminals of full diamond and parclo interchanges. Therefore, application of these models to adopt a systemic approach is likely to be successful. More specifically, the fitted models will be helpful to conduct Step 3 (i.e., identify high-risk locations) and the video data collection for observing WWD incidents will be helpful to conduct Step 4 (i.e., verify high-risk locations) of the systemic approach. Based on the calibrated crash risk models, a list of recommendation for full diamond and parclo interchange are discussed in the following sections.

6.1 Recommendations for Full Diamond Interchange

Although full diamond interchanges are less susceptible to WWD compared with parclo interchanges, the initial entry points of a large portion of WWD crashes are found to be attributed to the exit ramp terminals of diamond interchanges because they are the most common type of interchanges in the United States. The results of the data analysis identified specific geometric characteristics and TCDs that contribute to the probability of WWD crashes at this type of interchange. Based on these results, a list of general countermeasures for reducing the risk of WWD are recommended as follows:

1) Although a right-angle connection is recommended by the AASHTO *Green Book* (2011) for connecting exit ramps to crossroads, the results show that an obtuse-angle connection can lower the risk of WWD, as it makes the wrong-way right-turning maneuver difficult.

Therefore, the connection between crossroads and exit ramps of full diamond interchanges is recommended to be an obtuse angle for reducing WWD.

2) The *Green Book* (2011) recommends using a non-traversable median on the crossroad and angular connection between the left edge of exit ramp and right edge of crossroad to deter WWD entry. The data analysis results of this study support these recommendations and guidelines in the *Green Book*.
3) An obtuse-angle intersection and an angular connection between the left edge of an exit ramp and right edge of a crossroad makes the right-turning wrong-way maneuver difficult, while a non-traversable crossroad median makes the left-turning wrong-way maneuver less likely. Therefore, a combination of these geometric features is likely to ensure the least possibility of WWD entry.
4) Although the MUTCD (FHWA, 2009) recommends using at least one WRONG WAY sign on exit ramps, the placement of this sign along the exit ramp is not specified. This study results suggest that the first WRONG WAY sign should be located within 200 feet from the crossroads, so that these signs are clearly visible to motorists on the crossroad.
5) Signalized exit ramp terminals have lower chance of WWD entry, as they provide more regulated traffic flow. Therefore, the probability of WWD entry can be considered as a supplement to the MUTCD traffic signal warrants to justify the application of signals at the exit ramp terminals. However, further research is necessary to establish proper guidance for incorporating the probability of WWD entry as a supplement to the MUTCD traffic signal warrants.

6) The results showed that the locations with low exit ramp AADT and high crossroad AADT are more prone to WWD entries. Therefore, such locations should be given higher priority for implementing safety countermeasures.
7) The interchanges in urban areas should be given higher priority for implementing safety countermeasures.

6.2 Recommendations for Parclo Interchange

The logistic regression models fitted in this study can be used to identify the parclo interchange terminals with a high-risk for WWD and prioritize locations for implementing countermeasures to deter WWD incidents. Based on the results obtained from the logistic regression model, a list of recommendations for reducing the risk of WWD at the exit ramp terminals of parclo interchange are summarized, as follows:

1) The corner radius from crossroad to the entrance ramp should be a maximum of 60 feet whenever possible. Such a short turning radius makes the wrong-way left-turning movement from the crossroad to exit ramp difficult and helps in reducing WWD. At locations with multiple lanes on the exit ramp and the crossroad, it may not be feasible to provide a corner radius of 60 feet or less. In such cases, the corner radius should be designed to make the wrong-way left-turning movement from the crossroad to exit ramp difficult.
2) A non-traversable median is recommended to obstruct left-turning vehicles from going wrong-way to the exit ramps. Non-traversable median should be extended within an intersection functional area to ensure that the wrong-way left-turning movements from the crossroad to exit ramp is not an easy maneuver.
3) The median between two-way ramps should be at least 30 feet wide to reduce the risk of WWD. In addition, the raised median barrier between two-way ramps should be sufficiently behind

the stop bar on the exit ramp so that it does not obstruct the view of the entrance ramp for drivers who intend to turn left from a crossroad and go to an entrance ramp.

4) The traversable width of an exit ramp throat should be reduced by constructing non-traversable channelizing islands.
5) If possible, no access point should be allowed within 300 feet from exit ramps. Access points within close proximity of exit ramps cause additional driver confusions and increase the chance of WWD movements.
6) Although the distance of first set of WRONG WAY sign was not found to be a significant variable in predicting the probability of WWD entry at the exit ramp terminals of parclo interchange, it is recommended that the first set of WRONG WAY sign should be placed within 200 feet from the crossroad. This recommendation is based on the findings of full diamond interchange models.
7) “Keep Right” signs should be placed at the nose of median between entrance and exit ramp.
8) Wrong-way pavement arrows should be installed on the exit ramp pavement and maintain high visibility during both day and night.
9) Ramp terminals with low exit ramp AADT and high entrance ramp AADT (especially where a major portion of entrance ramp AADT are left-turning drivers from the crossroad) are found to increase WWD movements. Therefore, such locations should be prioritized to treat with WWD safety countermeasures

7 Limitations and Future Study

The research team will continue to use the models to identify exit ramp terminals (particularly of parclo interchanges) with high risk of WWD in several states across the country. After identifying the high-risk exit ramp terminals, WWD incidents data will be collected to evaluate the performance of the models more precisely. Based on the lessons learned from applying the models in the context different states, the current models can be improved by including more variables to achieve better results. Finally, a “one-stop” planning tool can be developed to help the transportation agencies in identifying high-risk exit ramp terminals, initial selection of safety countermeasures to reduce WWD risk, and finalize the countermeasures for implementation based on their safety benefits and costs.

The main purpose for the fitted models is to identify high-risk locations for engineering improvements. Other factors may also affect WWD crashes, such as left-turn volumes onto the entrance ramps, street lighting, and number of alcohol sales near interchanges. Therefore, WWD incident and crash data should be collected and analyzed to supplement the model prediction results to prioritize the exit ramp terminals for safety improvements.

Due to the time, budget, and sample size restrictions, this study only fitted models to predict the risk of WWD at the exit ramp terminals of full diamond and parclo interchange. Future studies should expand the scope and consider developing models for other interchange types such as half-diamond, compressed diamond, diverging diamond, trumpet, and full cloverleaf interchange. To develop models for these less common interchange types, the data from only two states may not be enough. It may be necessary to include data from more states to get sufficient sample size to develop the logistic regression models.

The development of models solely depended on the WWD crash data. Because most of the locations in this study have only one WWD crash over the study period, logistic regression models to predict the risk of WWD was an appropriate approach. However, in the future, the researchers can collect WWD incidents using video cameras to include the number of incidents by locations in to the models to predict the expected number of incidents over a certain period instead of predicting the probability of WWD entry.

The model fitted in this study can only be applied to freeway exit ramp terminals. Past studies indicated that a significant portion of WWD incidents and crashes on divided highways originates at unsignalized intersections on divided highways. The research team conducted several case studies in an attempt to understand the characteristics of WWD crashes that originate at the intersections of divided highways. The results of the case studies indicated that locations with WWD crash histories have some common geometric design characteristics. Therefore, WWD crash-risk prediction models can be developed to identify high-risk intersections of multi-lane divided highways.

ALDOT is currently implementing low-cost countermeasures at two of the high-risk parclo exit ramp terminals that was identified by the fitted model and confirmed by the video data of having more than ten WWD incidents over 48-hours of weekend period. Future study can coordinate with ALDOT to study the countermeasure selection and implementation process as well as evaluate the impacts of those countermeasures in reducing WWD incidents. Such a study will help in completing the Steps 5 to 7 of the proposed systemic safety approach. As a reminder, the Steps 5 to 7 of the proposed systemic approach are selecting, implementing, and evaluating potential countermeasures, respectively.

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Appendix A: Summary of Full Models

Table A.1 Summary of full model for full diamond interchange

Independent Variables	β	S.E.	OR
(Intercept)	-5.524	1.573	-
Intersection Angle			
Right	Reference		
Acute	0.283*	0.159	1.33
Obtuse	-0.649**	0.269	0.52
Type of Median on Crossroad			
Non-Traversable	Reference		
Traversable	0.285*	0.150	1.33
Channelizing Island			
Non-Traversable	Reference		
Traversable	0.092	0.303	1.10
Distance to Nearest Access Point			
200 feet and less	Reference		
201 to 400 feet	0.334	0.421	1.40
401 to 600 feet	0.503	0.447	1.65
601 to 800 feet	-0.008	0.497	0.99
More than 200 feet	0.602	0.444	1.83
Is Corner Radius Tangent to Crossroad Edge?			
No	Reference		

Yes	1.294***	0.301	3.65
Distance of First WRONG WAY Sign from Crossroad			
200 feet and less	Reference		
More than 200 feet	1.368***	0.255	3.93
Usage of DO NOT ENTER Sign			
One (right/left side of exit ramp)	Reference		
Two (channelizing island and right/left side of exit ramp)	0.488	0.506	1.63
Two (both side of exit ramp)	0.266	0.466	1.30
Three (channelizing island and both side of exit ramp)	0.496	0.575	1.64
Is the Exit Ramp Terminal Signalized?			
No	Reference		
Yes	-0.380*	0.186	0.68
Area Type			
Rural	Reference		
Urban	1.288***	0.353	3.63
log(Exit Ramp AADT)	-0.345*	0.233	0.71
log(Crossroad AADT)	0.813**	0.430	2.25

Significance Codes:

***Significant at the 99% confidence interval

**Significant at the 95% confidence interval

*Significant at the 90% confidence interval

Table A.2 Summary of full model for parclo interchange

Independent Variables	β	S.E.	OR
(Intercept)	-7.370	2.012	-
Intersection Angle			
Right	Reference		
Acute	-1.216	0.908	0.30
Obtuse	0.720	0.722	2.05
Corner Radius from Crossroad			
60 feet or less	Reference		
More than 60 feet	0.915**	0.392	2.50
Corner Radius to Crossroad			
80 feet or less	Reference		
81 to 100 feet	0.965	0.833	2.62
101 to 120 feet	0.835	1.026	2.30
More than 120 feet	0.674	1.159	1.96
Median on Crossroad			
Non-Traversable	Reference		
Traversable	0.752**	0.310	2.12
Median Between Exit and Entrance Ramp			
Non-Traversable	Reference		
Traversable	-3.579	2.431	0.03
Width of Median Between Exit and Entrance Ramp			
30 feet or less	Reference		
More than 30 feet	-0.678*	0.313	0.51

Channelizing Island			
Non-Traversable	Reference		
No Channelization	0.211	0.915	1.23
Traversable	1.412***	0.579	4.10
Distance to Nearest Access Point			
300 feet or less	Reference		
More than 300 feet	-0.432*	0.332	0.65
Intersection Balance			
31% to 40%	Reference		
41% to 50%	-0.886	0.728	0.41
51% to 60%	-0.799	0.849	0.45
More than 60%	-1.421	1.186	0.24
Distance to First WRONG WAY Sign			
200 feet or less	Reference		
More than 200 feet	0.075	0.592	1.08
Usage of DO NOT ENTER Sign			
One (right/left side of exit ramp)	Reference		
Two (channelizing island and right/left side of exit ramp)	1.243	0.803	3.47
Two (both side of exit ramp)	1.167	0.872	3.21
Three (channelizing island and both side of exit ramp)	0.261	0.995	1.30
"Keep Right" Sign			
Present	Reference		
Not Present	0.533*	0.366	1.70
Wrong-Way Arrow			

Present	Reference		
Not Present	0.872**	0.403	2.39
Signalized			
No	Reference		
Yes	-1.693***	0.439	0.18
Area Type			
Rural	Reference		
Urban			1.00
log(exit ramp AADT)	-0.556*	0.329	0.57
log(entrance ramp AADT)	1.939***	0.554	6.95
log(crossroad AADT)	1.029	1.516	2.80

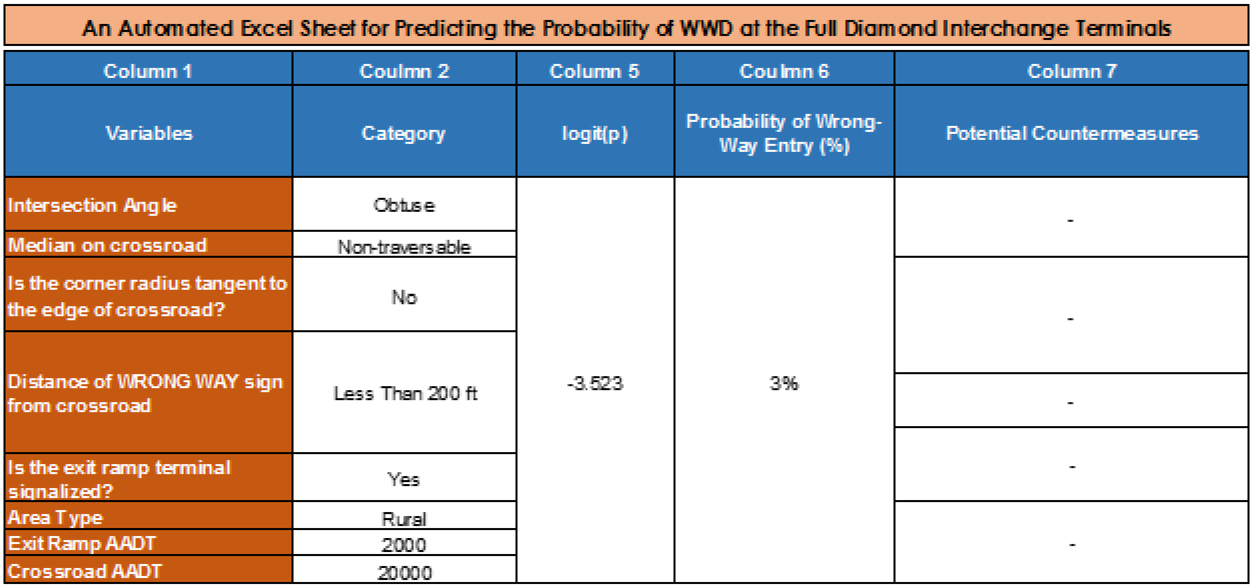
Significance Codes:

***Significant at the 99% confidence interval

**Significant at the 95% confidence interval

*Significant at the 90% confidence interval

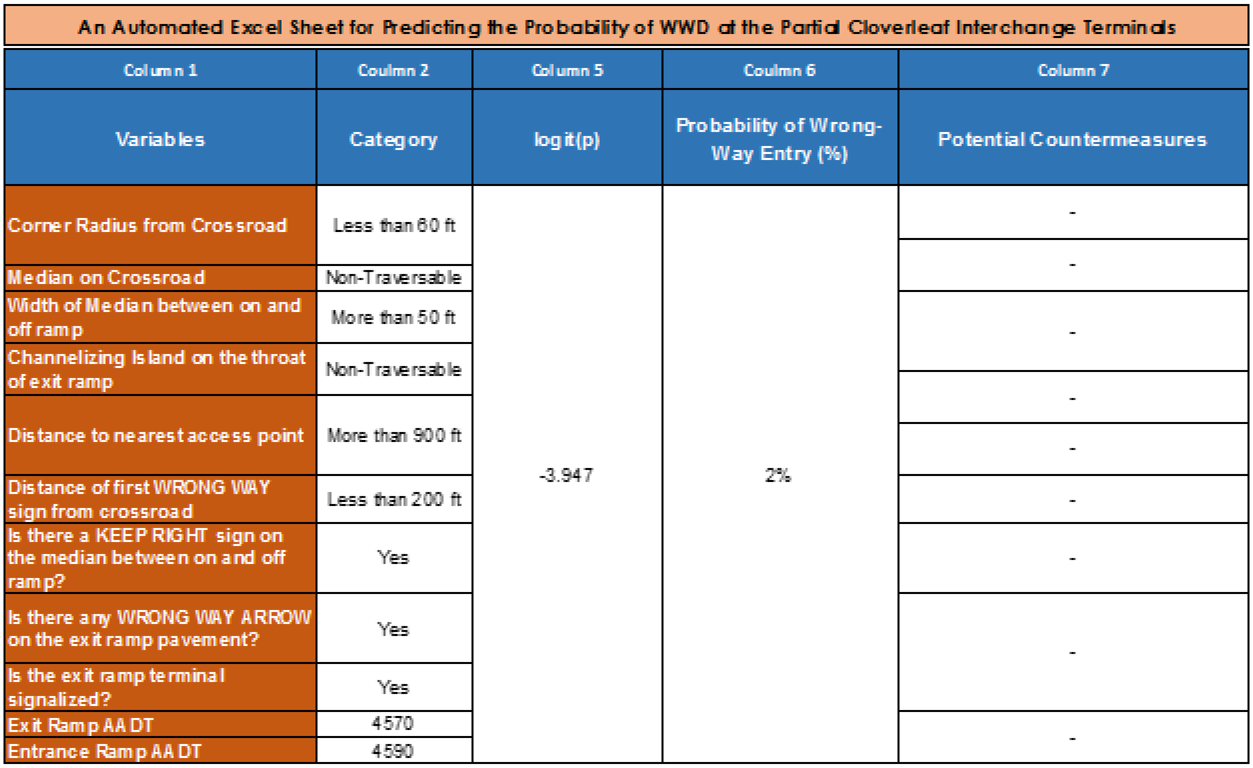
Appendix B: Screenshots of Excel Spreadsheets for Predicting Risk of WWD



An Automated Excel Sheet for Predicting the Probability of WWD at the Full Diamond Interchange Terminals

Column 1	Coulmn 2	Column 5	Coulmn 6	Column 7
Variables	Category	logit(p)	Probability of Wrong-Way Entry (%)	Potential Countermeasures
Intersection Angle	Obtuse	-3.523	3%	-
Median on crossroad	Non-traversable			
Is the corner radius tangent to the edge of crossroad?	No			-
Distance of WRONG WAY sign from crossroad	Less Than 200 ft			-
Is the exit ramp terminal signalized?	Yes			-
Area Type	Rural			-
Exit Ramp AADT	2000			
Crossroad AADT	20000			

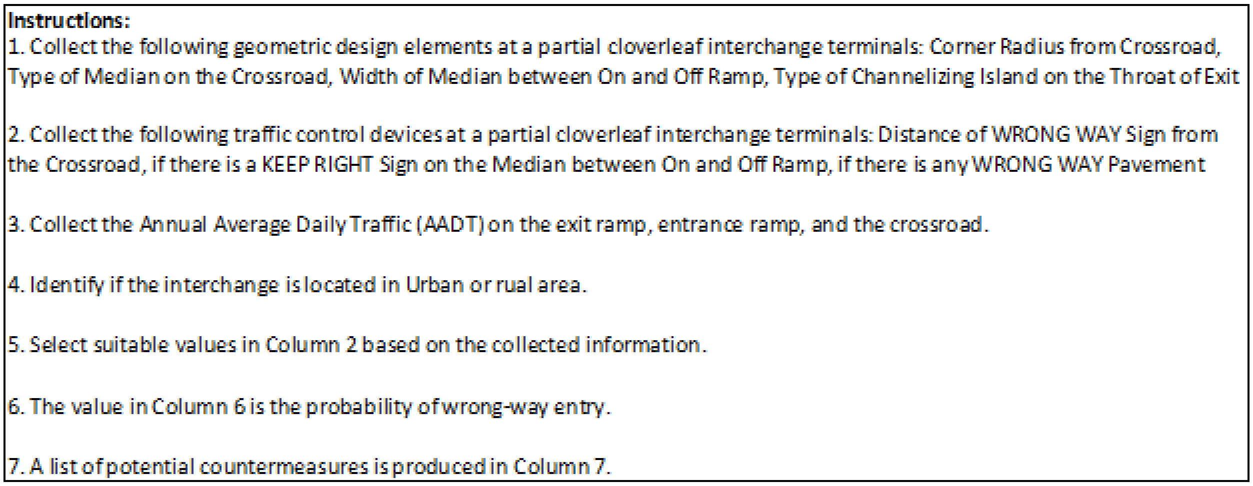
Figure B.1 Excel spreadsheet for full diamond interchange



An Automated Excel Sheet for Predicting the Probability of WWD at the Partial Cloverleaf Interchange Terminals

Column 1	Coulmn 2	Column 5	Coulmn 6	Column 7
Variables	Category	logit(p)	Probability of Wrong-Way Entry (%)	Potential Countermeasures
Corner Radius from Crossroad	Less than 60 ft	-3.947	2%	-
Median on Crossroad	Non-Traversable			-
Width of Median between on and off ramp	More than 50 ft			-
Channelizing Island on the throat of exit ramp	Non-Traversable			-
Distance to nearest access point	More than 900 ft			-
Distance of first WRONG WAY sign from crossroad	Less than 200 ft			-
Is there a KEEP RIGHT sign on the median between on and off ramp?	Yes			-
Is there any WRONG WAY ARROW on the exit ramp pavement?	Yes			-
Is the exit ramp terminal signalized?	Yes			
Exit Ramp AADT	4570			-
Entrance Ramp AADT	4590			

Figure B.2 Excel spreadsheet for parclo interchange



Instructions:

1. Collect the following geometric design elements at a partial cloverleaf interchange terminals: Corner Radius from Crossroad, Type of Median on the Crossroad, Width of Median between On and Off Ramp, Type of Channelizing Island on the Throat of Exit

2. Collect the following traffic control devices at a partial cloverleaf interchange terminals: Distance of WRONG WAY Sign from the Crossroad, if there is a KEEP RIGHT Sign on the Median between On and Off Ramp, if there is any WRONG WAY Pavement

3. Collect the Annual Average Daily Traffic (AADT) on the exit ramp, entrance ramp, and the crossroad.

4. Identify if the interchange is located in Urban or rual area.

5. Select suitable values in Column 2 based on the collected information.

6. The value in Column 6 is the probability of wrong-way entry.

7. A list of potential countermeasures is produced in Column 7.

Figure B.3 Instructions for using excel spreadsheet shown in figures B.1 and B.2

Appendix C: High and Low-Risk Design Examples

Figure C.1 High-risk exit ramp terminal of full diamond interchange

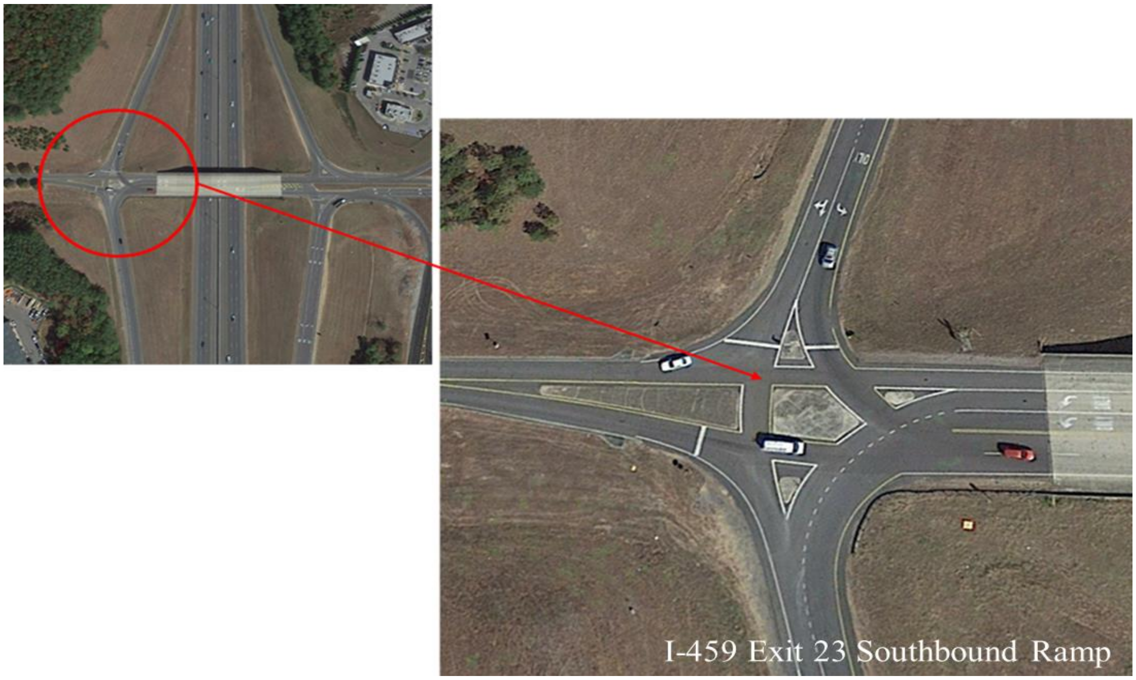


Figure C.2 Low-risk exit ramp terminal of full diamond interchange

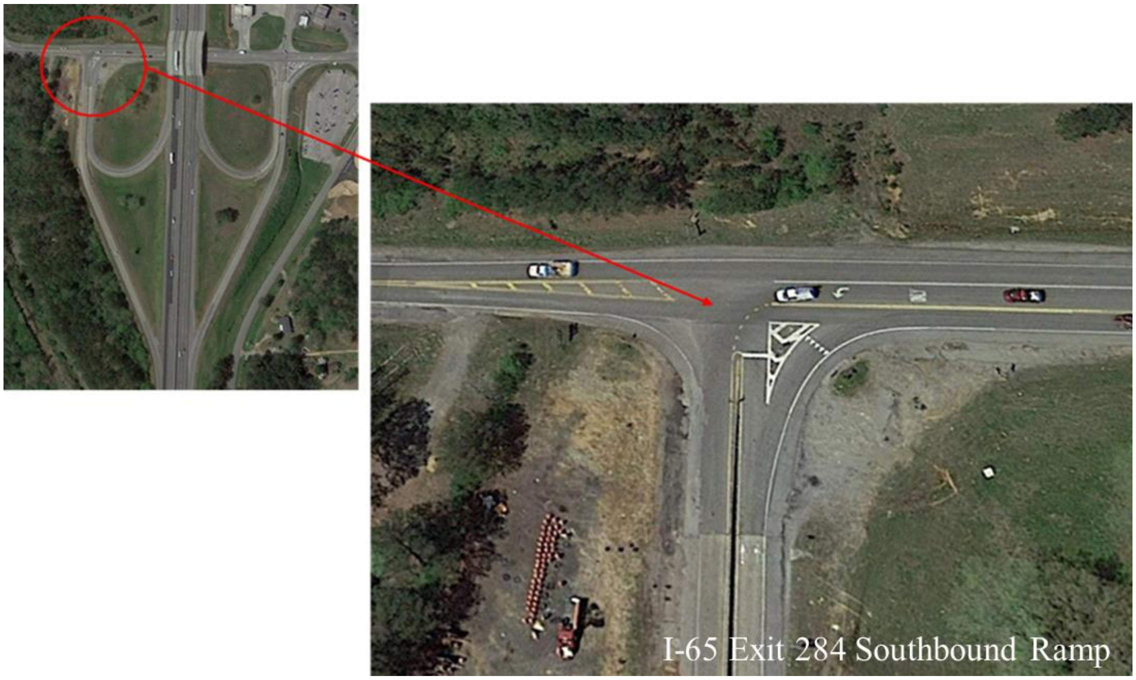


Figure C.3 High-risk exit ramp terminal of parclo interchange

Figure C.4 High-risk exit ramp terminal of parclo interchange

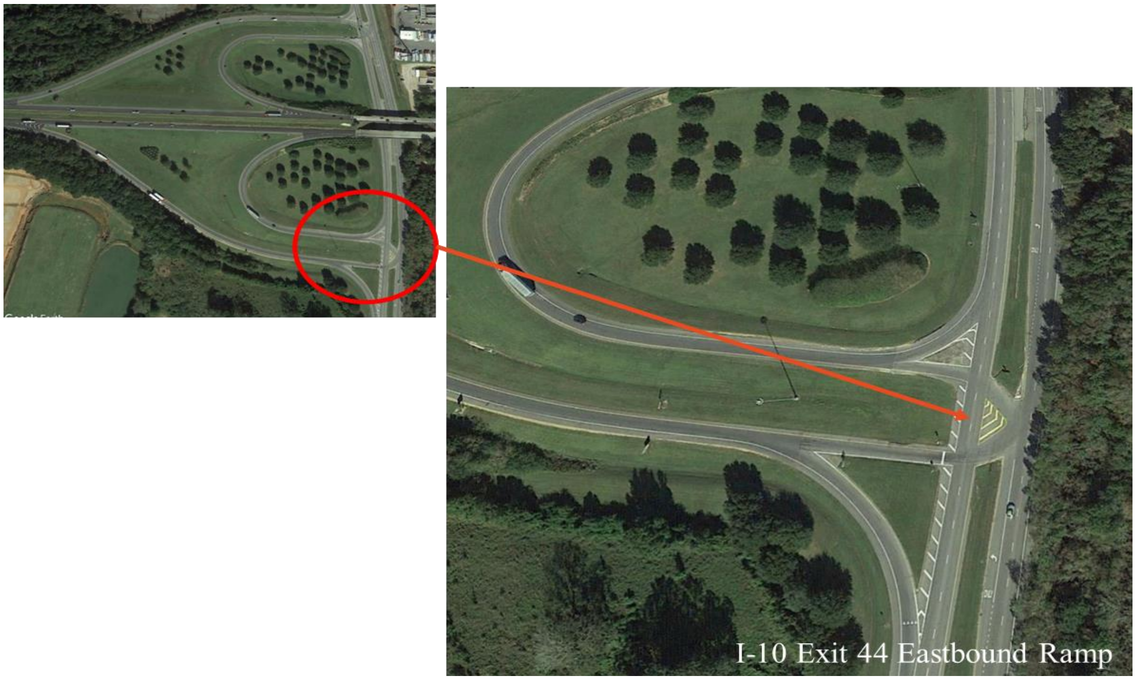


Figure C.5 Low-risk exit ramp terminal of parclo interchange