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Logistic Regression Models to Predict Wrong-Way Driving Risk at Freeway Off-Ramp Terminals

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LOGISTIC REGRESSION MODELS TO PREDICT WRONG-WAY DRIVING RISK AT FREEWAY OFF-RAMP TERMINALS

ALDOT-WWD Predictive Models

Final Report

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1. INTRODUCTION

Wrong-way driving (WWD) draws a lot of attention, despite being responsible for only a small portion of overall crashes on freeways, primarily due to the high risk of fatalities and/or severe injuries resulting from head-on or opposite-direction sideswipe collisions. In the United States, WWD crashes are responsible for 300 to 400 fatalities per year *(1)*. During the period of 2004–2011, an average of 269 WWD fatal crashes resulted in 359 fatalities annually, which accounts for 1.33 fatalities per WWD fatal crash compared with 1.10 fatalities for all types of fatal crashes *(2)*. Based on the results of a study of WWD crashes in Alabama *(3)*, there were 93 WWD crashes on freeways during 2009–2013, which resulted in 18 fatalities. Despite being only 0.16% of total freeway crashes, WWD crashes were responsible for 3.3% of the overall fatalities on Alabama freeways.

Typically, entering limited access highways via an exit ramp is the primary origin of WWD movements. Although WWD movements sometimes originate from making a U-turn on the mainline and at median crossover, they account for only a small portion of all WWD events. The mechanism of how a driver can make a U-turn on freeways to end up driving the wrong way (WW) was explained in past studies *(4, 5)*. A study in Illinois, for example, showed that only 6.5% of 217 confirmed WWD crashes occurred from WW drivers making a U-turn on the mainline, while the other 93.5% occurred from drivers entering freeways through an exit ramp *(5)*. Therefore, the geometric design characteristics and usage of traffic control devices (TCDs) on exit ramp terminals as well as along ramps are critical in reducing the occurrence of WWD crashes on freeways.

Although impaired driving (i.e., driving under the influence of drugs and/or alcohol) has been identified as one of the major contributing factors to WWD, geometric features and TCDs at the exit ramp terminals can also have a significant impact. While properly designed geometric features can physically obstruct drivers from entering the WW, proper use of WW-related TCDs can also help drivers 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 *(6, 7)*. In this study, these geometric features were selected to be the potential predictors of WWD risk in addition to WW-related TCDs, area type (i.e., urban/rural), and Annual Average Daily Traffic (AADT) on the exit ramp, the entrance ramp, and the crossroad.

This study focuses on developing logistic regression models to predict the risk of WWD at exit ramp terminals of full diamond and partial cloverleaf (parclo) interchanges. Past studies found that parclo interchanges are more susceptible to WWD compared with other interchange types due to the presence of closely spaced parallel entrance and exit ramps (i.e., two-way ramp). On the other hand, diamond interchanges are the most widely used service interchanges (79% of all interchanges fall in this category) in the United States *(8)*. Although they are less susceptible to

WWD events than parclo or trumpet interchanges *(9-12)*, the origins of a major portion of WWD crashes are attributed to the exit ramp terminals of diamond interchanges *(5)*. Therefore, the assessment of WWD risk at exit ramp terminals of diamond and parclo interchanges using mathematical models will greatly benefit the Alabama Department of Transportation (ALDOT) in identifying the high-risk exit ramp terminals for implementing safety countermeasures to deter WWD.

The developed logistic regression models can be used as a network screening tool to rank the exit ramp terminals of parclo and full diamond interchanges from high to low risk of WWD. To verify the model prediction results, 48-hour videos of traffic movements were collected at each of the identified high-risk exit ramp terminals of parclo and full diamond interchanges to collect WWD incident data. Previous studies suggested that WWD crashes are more likely to occur during weekends *(13)*. Thus, the video collection duration was selected to be from Friday to Sunday.

This report summarizes the research activities related to modeling the risk of WWD at the exit ramp terminals of full diamond and parclo interchanges. Section 2 summarizes the findings of previous studies focused on exploring the contributing factors to WWD and predicting the risks of WWD crashes. Section 3 provides a description of crash data used in this study as well as the efforts in collecting geometric design features, TCDs, area types, and AADT data for exit ramp terminals of full diamond and parclo interchanges. Section 4 discusses the method for developing logistic regression models for predicting the risks of WWD at freeway ramp terminals. Section 5 summarizes the results of the developed logistic regression models. Section 6 describes the procedure for conducting network screening using the models developed in this study as well as the results of field verification of the high-risk locations. Important findings and potential recommendations are presented in Section 7.

2. LITERATURE REVIEW

2.1 Contributing Factors to WWD Crashes

Identifying the contributing factors in WWD crashes has been a primary focus of much WWD research for the past several decades. Numerous studies revealed the common factors that contribute to the occurrence of WWD crashes. These studies 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, and severe weather conditions contribute to WWD crashes *(5, 10, 12, 14-18)*. Additionally, a few of these studies identified that some interchange types are more susceptible to cause driver confusion and may contribute to WWD. For instance, Copelan 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 *(14)*. Cooner et al. reported that left-side exit ramps and one-way streets transitioning into freeways are more likely to cause WWD *(15)*. Additionally, previous studies reported that two-quadrant parclo, trumpet, tight diamond, and full diamond interchanges are more susceptible to WWD *(10, 12)*.

2.2 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. For example, Baratian-Ghroghi et al. developed a mathematical model to predict the probability of WWD incidents at an exit ramp terminal of a parclo interchange *(19)*. Pour-Rouholamin and Zhou developed a logistic regression model to study the effect of various geometric design elements on the probability of WW entries at parclo interchanges *(6)*. Sandt et al. identified WWD hotspots by modeling crash risk and analyzing traffic management response times *(20)*. Similar WWD crash risk models were developed for the South Florida area as well *(21)*. Earlier, Rogers et al. 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 *(22)*. These research efforts are briefly discussed in the following paragraphs.

Baratian-Ghorghi et al. *(19)* 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 *(6)* developed a logistic regression model to study the effect of various geometric design elements on the probability of WW entries at parclo interchanges. In this study, 15-year crash data were used to identify exit ramp terminals with a history of WW entry. The geometric design elements of exit ramp terminal with a history of WW entry was compared with those without a history of WW entry. Some geometric design elements were found to have a significant effect on the probability of WW 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. *(20)* reported two approaches to identify WWD hotspots in central Florida. In the first approach, a Poisson regression model was developed 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. *(21)* conducted a similar study for south Florida.

2.3 Summary of Literature Review

Although 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 developed microscopic models to predict WWD risks at a single intersection based on its geometric design features, usage of TCDs, AADT data, and area types.

3. DATA DESCRIPTION

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 Alabama alone. Therefore, to increase the sample size, WWD crash data from both Alabama and Illinois freeways were collected for a period of five years (2009–2013). Identifying the exit ramp terminals with histories of WW entry is critical to model the risk of WWD. In this study, the entry points of all WWD crashes during the study period was determined through a careful review of crash narratives and the estimation methodology proposed by Zhou et al. *(5)*. These exit ramp terminals were further investigated using Google Earth aerial and street views to collect the geometric design features and TCD usage information. Initially, the 2017 Google Earth imagery was used for data collection. Then, the data were crosschecked with the imagery of crash year or closest year available to verify if improvements were made at the study locations. In case there were any improvements, the data were adjusted to ensure that it portrays the crash year's geometric and signage conditions. As a comparison group, similar information was collected for the exit ramp terminals with no history of WWD during the study period (2009–2013). A comprehensive discussion of the collected data for full diamond and parclo interchanges is presented in the following sections.

3.1 Data Collection for Exit Ramp Terminals of Full Diamond Interchanges

For full diamond interchanges, a total of 128 exit ramp terminals (including 27 confirmed and 101 estimated WW entries) were identified to have at least one WWD crash during the study period. Additionally, there were a total of 428 exit ramp terminals that did not experience any WWD crashes during the same period (2009–2013). Altogether, 556 exit ramp terminals were selected for data collection for the modeling of WWD risks at full diamond interchanges.

The seven geometric design features at full diamond interchanges defined in Figure 1 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. Table 1 presents a descriptive summary of the collected data at the 556 study locations. Based on past studies and existing geometric guidelines, these geometric design features have considerable effect on the possibility of WW entry *(7, 23)*. 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 *(24)*. 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 *(25)*. In this study, the intersection angle is defined as follows: acute – <85 degrees; right – 85 to 95 degrees; and obtuse – >95 degrees.

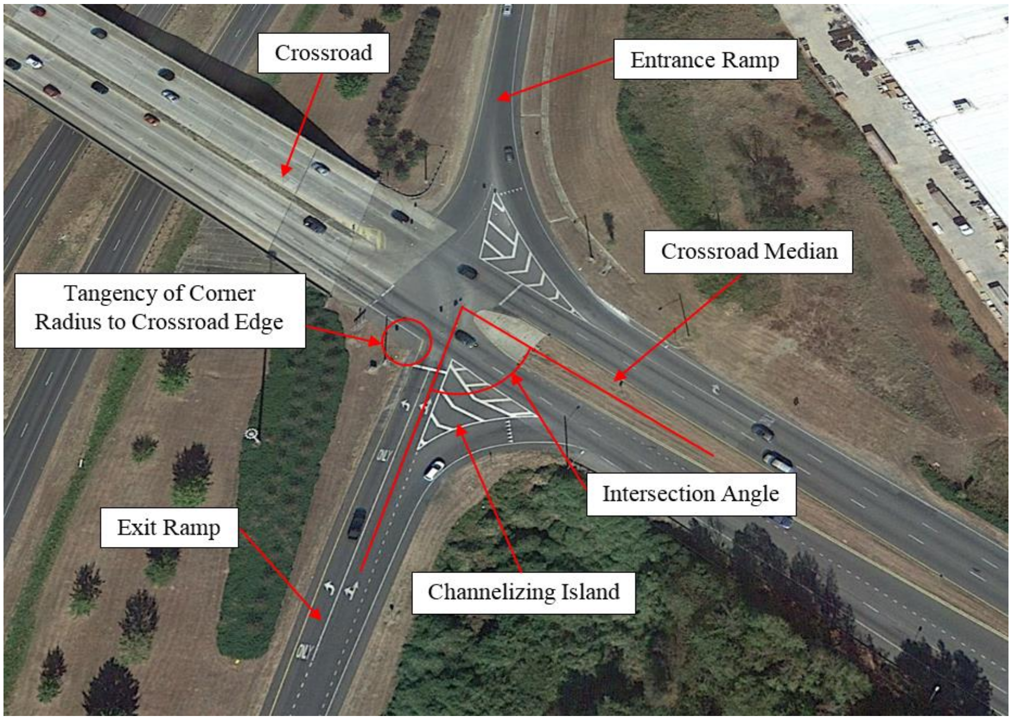

Figure 1. Geometric Design Features of Full Diamond Interchange Exit Ramp Terminals

The type of median on crossroads and channelizing islands on exit ramps are two important design features for deterring WW entries. A non-traversable raised median on the crossroad makes the WW left-turn from a crossroad less likely *(23)*. Similarly, a non-traversable channelizing island reduces WW entries by narrowing the exit ramp throat *(7)*. The presence of access points close to exit ramp terminals increases the chance of WW entries at parclo interchanges *(6)*. The distance of nearest access points from exit ramp terminals was collected with an aim to understand its effect on WW 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 *(23, 26)*. 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.

WW-related signs and intersection signalization at the exit ramp terminals are also critical for reducing WWD. However, the impact of WRONG WAY (WW) signs placement, number of DO NOT ENTER (DNE) signs, and signalization on WWD has not been studied. Hence, the research team collected the distance of WW signs from crossroads, the number and location of DNE signs at the exit ramp, and intersection signalization information to be included in the model to predict the risk of WW entry.

Table 1. Descriptive Summary of Geometric Design Features and TCD Application Practices at Exit Ramp Terminals of Full Diamond Interchanges

Variable	Category	Locations with History of WWD (*n*=128, 23%)		Locations without History of WWD (*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 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%
Number of Lanes on the Crossroad					
	2 or 3 lanes	55	42.97%	270	63.08%
	4 or more lanes	73	57.03%	158	36.92%
Number of Lanes on Exit Ramp					
	One	29	22.66%	53	12.38%
	Two	68	53.13%	313	73.13%
	Three or more	31	24.22%	62	14.49%
Distance of WW sign from Crossroad					
	200 ft. and less	32	25.00%	280	65.42%
	201 to 300 ft.	40	31.25%	70	16.36%
	301 to 400 ft.	19	14.84%	24	5.61%
	401 to 500 ft.	18	14.06%	28	6.54%
	More than 500 ft.	19	14.84%	26	6.07%
Usage of DNE 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%
Signalized/Unsignalized?					
	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%

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 Illinois Department of Transportation (IDOT) traffic count websites.

3.2 Data Collection for the Exit Ramp Terminals of Parclo Interchanges

There were 25 exit ramp terminals (including 9 confirmed and 16 estimated WW entry points) 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 WW-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. A descriptive summary of collected data is presented in Table 2.

Based on the literature review results, the geometric design features having potential effects on the WWD at the parclo interchanges (Figure 2) 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 *(6, 7, 23)*. A brief discussion of these geometric elements is presented below.

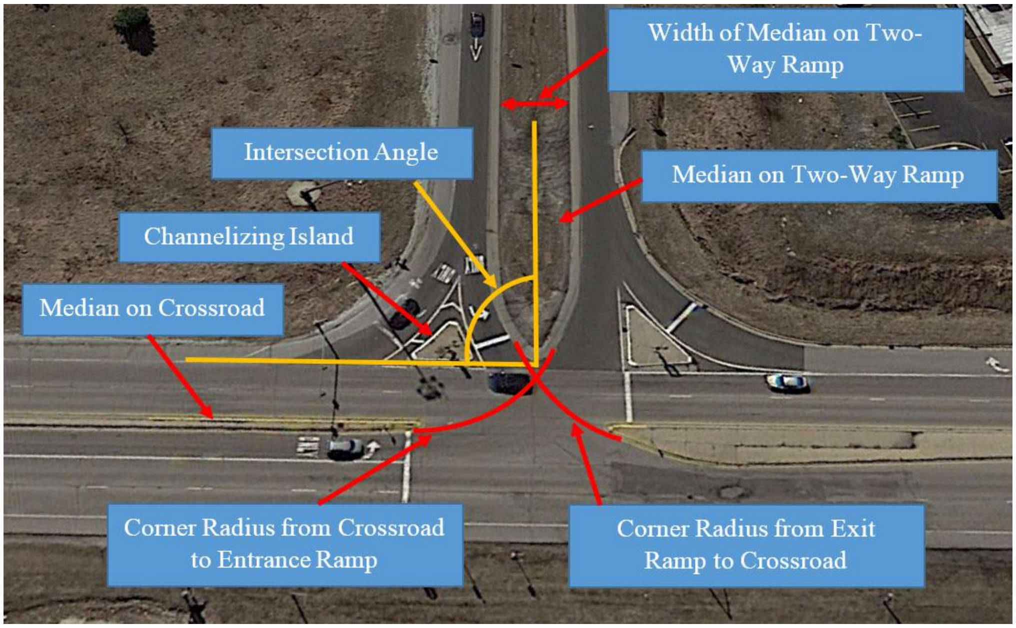

Figure 2. Geometric Design Features at a Parclo Interchange Terminal

1) 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.

2) 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 *(27)*. These suggestions, as presented in the IDOT manual, are based on experiences and engineering judgment. No scientific research was found to support these guidelines.
3) The type of median on crossroads is an important design feature for reducing the probability of WW entries. A non-traversable median on the crossroad works as a physical obstruction to the WW left-turns from the crossroad and makes the exit ramp terminal less susceptible to WW entry *(23)*.
4) Type and width of median between entrance and exit ramp plays an important role in reducing the WWD at the parclo interchange terminals. Non-traversable medians with a minimum width of 50 feet is suggested by the IDOT manual *(27)*.
5) 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 *(7, 26)*.
6) 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 (26). A recent study found that an intersection balance of less than 40% may contribute to a higher likelihood of WWD (6).
7) The presence of access points close to the ramp terminals are likely to cause driver confusion and increase the chance of WW entries at parclo interchanges *(6)*. Zhou et al., 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 *(28)*. Thus, the distance of the nearest access points from the exit ramp terminals, as shown in Figure 3, was collected with an aim to understand their effects on WWD.

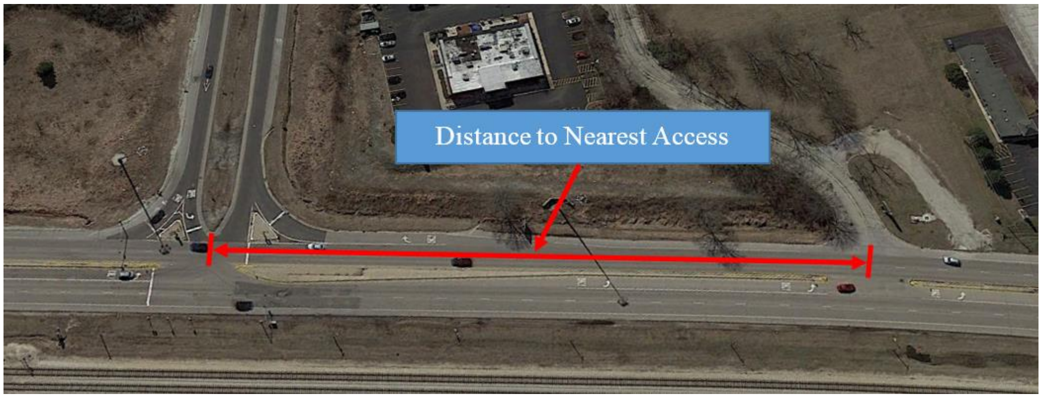

Figure 3. Distance to the Nearest Access Point in the Vicinity of an Interchange Terminal

Table 2. Descriptive Summary of Geometric Design Elements and TCDs at the Parclo Interchange Terminals with and without History of WWD

Variable	**Category**	**Locations with history of WWD (*n*=25, 16.45%)***		**Locations without history of WWD (*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 WW sign from crossroad	200 feet or less	11	44%	58	46%
	More than 200 feet	14	56%	69	54%
DNE 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 WW arrow on the exit ramp	Yes	10	40%	81	64%
	No	15	60%	46	36%
Presence of two sets of WW sign	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%

The Manual on Uniform Traffic Control Devices (MUTCD) suggests that there should be at least one WW sign and one DNE sign along exit ramps to inform drivers about the exit ramp and prevent them from going WW *(29)*. 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. In this study, the distances of the WW signs from the crossroad and placement of DNE signs at the exit ramp throat were collected to understand their effects on the WWD. In addition, the intersection signalization was also analyzed to examine if the signalization at the intersections of two-way ramps can reduce the 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 WW entries. Baratian-Ghorghi et al. *(19)* 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.

4. DEVELOPMENT OF LOGISTIC REGRESSION MODELS

The response variable in this study is dichotomous in nature (i.e., exit ramp terminals with or without a history of WW entries). Binary logistic regression is a classic statistical technique to handle such problems with a dichotomous dependent variable. Moreover, many previous studies used this technique to study the probability of traffic crashes and the effects of different variables on certain types of crashes *(30-35)*. While standard binary logistic regression, which is based on maximum likelihood method, works well for a large and balanced sample size, it may produce biased outcome and convergent failures when applied to rare event crash data *(36-39)*. Therefore, standard binary logistic regression models may not be suitable for analyzing WWD events due to their rareness. To overcome these limitations, this study used Firth's penalized likelihood logistic regression method, which minimizes the biased probability and convergent failures resulting from the maximum likelihood estimate of rare event data.

To develop the model, the response variables were assigned a binary indicator that had a value of 0 if there was no history of WW entry at an exit ramp terminal and 1 otherwise. Because most of the locations in this study have only one WWD event, a binary response variable is a logical approach in this case. The categorical explanatory 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 indicator (0 or 1), which can cause skewness to the model. Therefore, the AADT values were transformed to a logarithmic scale to reduce the skewness. The "logistf" package in "R-project" was used to carry out the modeling approach *(39)*. The fitted logistic regression model can be expressed as shown in Equation 1.

$$logit(p) = \ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_n X_n \qquad \textbf{\textit{(1)}}$$

where p is the probability of WW entry at an exit ramp terminal, X_1, X_2, X_3………X_n are the explanatory variables, β_0 is the intercept, and β_1, β_2, β_3, …………β_n are the regression coefficients.

After preparing the data set, a full logistic regression model was developed, which included all the explanatory variables in the primary data set. However, not all the variables in this primary data set are statistically significant in predicting the probability of WW entry. Therefore, at the next step, the backward elimination technique was employed to achieve the most parsimonious logistic model and to discover the subset of variables that are most suitable in predicting the probability of WW entry. The backward elimination technique uses the Akaike information criteria (AIC), which can be calculated using Equation 2, to decide the most parsimonious model. Typically, the most parsimonious and best-fitted model is the one that produces the lowest AIC.

$$AIC = 2k - L_\beta \qquad \textbf{\textit{(2)}}$$

where k is the number of explanatory variables, and L_β is the maximum log-likelihood of the model.

The odds ratio (OR) was computed for the explanatory variables included in the final models. By definition, the OR of a certain variable expresses the change in the probability of WW 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 WW entry, and a value of less than 1 indicates the decreased probability when compared with the reference group.

5. LOGISTIC REGRESSION MODELING RESULTS

5.1 Modeling Results for Full Diamond Interchange

The final data set for modeling consisted of 128 exit ramp terminals with history of WW entries and 428 exit ramp terminals with no history of WW entries. A base model was developed 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 developed for the exit ramp terminals connected to two-lane and multilane crossroads, respectively. This was done to investigate if a particular geometric feature or a TCD is more important for the exit ramp terminals connected to a two-lane crossroad than a multilane crossroad. Therefore, a total of three models were developed: 1) Model 1 – base model to predict WW entry regardless of the number of lanes on the crossroad; 2) Model 2 – a model to predict WW entry at the exit ramp terminal connected to a two-lane crossroad; and 3) Model 3 – a model to predict WW entry at the exit ramp terminal connected to a multilane crossroad.

5.1.1 Model 1: Base Model for Predicting WW Entry

The aim of the base model was to predict the probability of WW entries regardless of the number of lane(s) on the connecting crossroad. First, a full model was developed, including all the explanatory variables. However, not all of the variables were statistically significant. Therefore, a backward elimination technique was employed to achieve a reduced final model, which only considers a subset of explanatory variables in the data set and minimizes the AIC value. A Chi-square test between the null model and the final model indicated that the deviance of the final model is significantly lower (p<0.001) than the null model.

The summary of final base model is presented in Table 3. The fitted logistic regression model is shown in Equation 3. In the fitted model, p is the probability of WW entry at exit ramp terminals of a full diamond interchange.

$$\boldsymbol{logit}(\boldsymbol{p}) = \boldsymbol{ln}\left(\frac{\boldsymbol{p}}{\boldsymbol{1-p}}\right) = -4.799 + 0.257(X_{IA1}) - 0.644(X_{IA2}) + 0.233(X_{MC}) + 1.309(X_{CR}) + 1.313(X_{WWSD1}) + 1.634(X_{WWSD2}) + 1.448(X_{WWSD3}) + 1.576(X_{WWSD4}) - 0.305(X_{Signal}) - 0.410(X_{\log(exit\ ramp\ AADT)}) + 0.832(X_{\log(crossroad\ AADT)}) + 1.361(X_{AT}) \qquad \textbf{(3)}$$

where

$$X_{IA1} = \begin{cases} 1, & if\ intersection\ angle\ is\ acute \\ 0, & otherwise \end{cases}$$

$$X_{IA2} = \begin{cases} 1, & if\ intersection\ angle\ is\ obtuse \\ 0, & otherwise \end{cases}$$

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

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

$$X_{WWSD1} = \begin{cases} 1, & if\ the\ distance\ of\ WW\ sign\ from\ crossroad\ is\ between\ 201\ ft\ to\ 300\ ft \\ 0, & otherwise \end{cases}$$

$$X_{WWSD2} = \begin{cases} 1, & if\ the\ distance\ of\ WW\ sign\ from\ crossroad\ is\ between\ 301\ ft\ to\ 400\ ft \\ 0, & otherwise \end{cases}$$

$$X_{WWSD3} = \begin{cases} 1, & if\ the\ distance\ of\ WW\ sign\ from\ crossroad\ is\ between\ 401\ ft\ to\ 500\ ft \\ 0, & otherwise \end{cases}$$

$$X_{WWSD4} = \begin{cases} 1, & if\ the\ distance\ of\ WW\ sign\ from\ crossroad\ is\ more\ than\ 500\ ft \\ 0, & otherwise \end{cases}$$

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

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

$$X_{\log(crossroad\ AADT)} = Logarithmic\ value\ of\ crossroad\ AADT$$

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

Table 3. Summary of Firth's Logistic Regression for the Base Model (Model 1)

Variables	Category	Parameter Estimates	Estimated Std. Error	Chi-Square Statistics	OR
Intercept		-4.799	1.381	13.144	
Intersection Angle					
	Right	Reference			
	Acute	0.257	0.320	0.659	1.293
	Obtuse	-0.644	0.268	5.823	0.525
Median on Crossroad					
	Non-traversable	Reference			
	Traversable	0.233	0.304	0.597	1.262
Is Corner Radius Tangent to Crossroad Edge?					
	No	Reference			
	Yes	1.309	0.303	20.373	3.702
Distance of WW Sign from Crossroad					
	200 ft. and less	Reference			
	201 to 300 ft.	1.313	0.307	18.600	3.717
	301 to 400 ft.	1.634	0.388	17.592	5.124
	401 to 500 ft.	1.448	0.394	13.344	4.255
	More than 500 ft.	1.576	0.403	15.325	4.836
Signalized/Unsignalized?					
	Unsignalized	Reference			
	Signalized	-0.305	0.372	0.687	0.737
log(Exit Ramp AADT)		-0.410	0.400	1.066	0.664
log(Crossroad AADT)		0.832	0.435	3.883	2.298
Area Type					
	Rural	Reference			
	Urban	1.361	0.357	15.022	3.900

Equation 3 indicates that the intersection angle, median type on crossroad, tangency of corner radius to crossroad edge, distance of WW signs from crossroad, intersection signalization, exit ramp AADT, crossroad AADT, and area type were significantly capable of predicting the probability of WW entry. Other explanatory variables (e.g., distance to the nearest access point, channelizing island, and usage of DNE sign) were not statistically significant and thus excluded from the final model. In Equation 3, the negative signs before the independent variables such as obtuse angle connection, traffic signal, and exit ramp AADT indicate that they reduce the chances of WW entry, and the positive sign indicates that they increase the chances of WW entry. Additionally, the OR values in Table 3 explain the extent to which each parameter is responsible for increasing or decreasing the chances of WW entry.

5.1.1.1 Effects of Geometric Design Features on WWD

According to the developed model, the presence of an obtuse intersection angle reduces the risk of WWD at full diamond interchanges. The *AASHTO Green Book (23)* recommended using a right-angle connection between one-way exit ramps of full diamond interchanges and crossroads. However, the results herein showed that, for a full diamond interchange, obtuse intersection angle is more likely to reduce the probability of WW entries than a right/acute-angle connection. The reason may be attributed to the fact that WW right-turns are more prevalent at exit ramp terminals of full diamond interchanges, while an obtuse-angle connection makes the WW right-turns difficult. On the contrary, the acute angle makes right-turning maneuvers easy and therefore found to be more prone to WWD (OR=1.293). For a better understanding, a visual representation of potential WW right-turning maneuvers at an obtuse and acute angle intersection are shown in Figure 4.

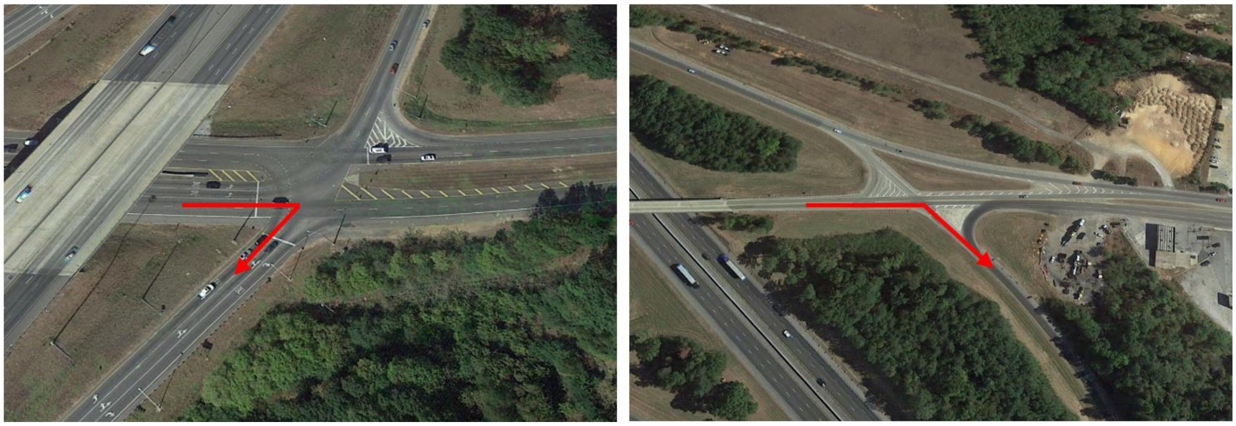

Figure 4. WW Right-Turning Maneuvers for Obtuse Angle (Left) and Acute Angle (Right) Connection to Crossroads

The odds of WW entry slightly increased for a traversable median on the crossroad (OR=1.262). This result clearly supports the *Green Book*’s recommendations for using non-traversable crossroad medians to deter WW left-turning movements *(23)*.

The *Green Book (23)* also recommended that the corner radius should not be tangent to the crossroad edge, thus making the connection between the left edge of exit ramp and the right edge of crossroad angular. Refer to Figure 5 for 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 WW entry by 3.7 times, which can be attributed to the fact that an angled corner makes WW right-turning maneuvers difficult. Therefore, the result supports the *Green Book* guidance for using an angled corner to deter right-turning WW entry from crossroads.

Figure 5. Examples: Left – Corner Radius Tangent to Crossroad Edge; Right – Corner Radius Tangent to Crossroad Median

5.1.1.2 Effects of TCDs on WWD

MUTCD *(29)* requires the use of at least one WW sign on exit ramps. However, there is no specific guidance on proper placement of WW signs along these ramps. The results show that the odds of WW entry increase by three to five times when the distance between the first WW sign and crossroad is more than 200 ft. compared with when the distance is 200 ft. or less. This is an interesting result given that placement of WW signs varies widely among state and local transportation agencies and there is no guideline on the proper location for placing WW signs on exit ramps. Based on the results, the desirable distance of the first WW sign from a crossroad is 200 ft. or less. A more conservative approach may include the use of a second set of WW signs close to the freeway and exit ramp connections for drivers who miss the first WW sign. It should be noted that some states already used two sets of WW signs along exit ramps (the first set close to the exit ramp terminal and a second set farther away).

Additionally, the developed model shows that the signalized exit ramp terminals had less WW 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 WW entry should be considered as a supplement to MUTCD traffic signal warrants to justify intersection signalization at exit ramp terminals.

5.1.1.3 Effects of AADT on WWD

The crossroad AADT has a positive impact on the probability of WW entry at the exit ramp terminals of full diamond interchanges, which means that the higher crossroad AADT increases the chance of WW entry. This is consistent with a previous study by Sandt et al. in central Florida *(20)*. The analysis results also indicate that the exit ramp AADT reduces the chance of WW entry

(OR=0.737). This implies that an increase in exit ramp AADT is associated with the decrease in the chance of WW entry because the presence of traffic on exit ramps prevent drivers from entering the exit ramp from crossroads. Additionally, the odds of WW entry for interchanges located in urban areas was found to be 3.9 times higher than in rural areas. Therefore, the interchanges in urban areas should be given higher priority for improvements.

5.1.2 Model 2: For Predicting WW Entry at the 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 WW entries and 270 exit ramp terminals with no history of WW entry. The procedure for developing this model is similar to that of Model 1. A Chi-square test between the null and final models indicated that the deviance of the final model is statistically significantly lower (p<0.001) than the null model. The fitted logistic regression equation is shown in Equation 4. A summary of this model is presented in Table 4.

$$\boldsymbol{logit}(\boldsymbol{p}) = \boldsymbol{ln}\left(\frac{\boldsymbol{p}}{\boldsymbol{1-p}}\right) = -2.364 - 0.264(X_{IA1}) - 1.145(X_{IA2}) + 2.181(X_{CR}) + 1.153(X_{WWSD1}) + 1.460(X_{WWSD2}) + 1.285(X_{WWSD3}) + 1.374(X_{WWSD4}) - 0.251(X_{Signal}) - 0.597(X_{\log(exit\ ramp\ AADT)}) + 0.250(X_{\log(crossroad\ AADT)}) + 1.023(X_{AT}) \tag{4}$$

Table 4. Summary of Firth's Logistic Regression Model for Exit Ramp Terminals Connected to Two-Lane Crossroads (Model 2)

Variables	Category	Parameter Estimates	Estimated Std. Error	Chi-Square Statistics	OR
Intercept		-2.364	1.835	1.759	
Intersection Angle					
	Right	Reference			
	Acute	-0.264	0.507	0.284	0.768
	Obtuse	-1.145	0.387	9.069	0.318
Is Corner Radius Tangent to Crossroad Edge?					
	No	Reference			
	Yes	2.181	0.461	29.802	8.855
Distance of WW Sign from Crossroad					
	200 ft. and less	Reference			
	201 to 300 ft.	1.153	0.499	5.152	3.168
	301 to 400 ft.	1.460	0.615	5.429	4.306
	401 to 500 ft.	1.285	0.509	6.409	3.615
	More than 500 ft.	1.374	0.509	7.328	3.951
Signalized/Unsignalized?					
	Unsignalized	Reference			
	Signalized	-0.251	0.879	0.087	0.778
log(Exit Ramp AADT)		-0.597	0.604	0.983	0.550
log(Crossroad AADT)		0.250	0.621	0.167	1.284
Area Type					
	Rural	Reference			
	Urban	1.023	0.499	4.185	2.782

5.1.3 Model 3: For Predicting WW Entry at the Exit Ramp Terminals Connected to Multilane Crossroads

The sample size for predicting WW 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 WW entries. A Chi-square test between the null and final models indicated that the deviance of the final model is statistically significantly lower (p<0.001) than the null model. A summary of this model is presented in Table 5. The fitted logistic regression equation, derived from this model, is shown in Equation 5.

$$\boldsymbol{logit(p)} = \boldsymbol{ln}\left(\frac{\boldsymbol{p}}{\boldsymbol{1-p}}\right) = -6.626 + 0.864(X_{IA1}) - 0.036(X_{IA2}) + 1.292(X_{MC}) + 1.162(X_{CR}) + 1.429(X_{WWSD1}) + 1.734(X_{WWSD2}) + 1.270(X_{WWSD3}) + 1.427(X_{WWSD4}) - 1.450(X_{Signal}) - 0.560(X_{\log(exit\ ramp\ AADT)}) + 1.365(X_{\log(crossroad\ AADT)}) + 1.899(X_{AT}) \qquad \textit{(5)}$$

Table 5. Summary of Firth's Logistic Regression Model for Exit Ramp Terminals Connected to Multilane Crossroads (Model 3)

Variables	Category	Parameter Estimates	Estimated Std. Error	Chi-Square Statistics	OR
Intercept		-6.626	1.381	13.144	
Intersection Angle					
	Right	Reference			
	Acute	0.864	0.320	0.659	2.373
	Obtuse	-0.036	0.268	5.823	0.965
Median on Crossroad					
	Non-traversable	Reference			
	Traversable	1.292	0.304	0.597	3.640
Is Corner Radius Tangent to Crossroad Edge?					
	No	Reference			
	Yes	1.162	0.303	20.373	3.196
Distance of WW Sign from Crossroad					
	200 ft. and less	Reference			
	201 to 300 ft.	1.429	0.307	18.600	4.175
	301 to 400 ft.	1.734	0.388	17.592	5.663
	401 to 500 ft.	1.270	0.394	13.344	3.561
	More than 500 ft.	1.427	0.403	15.325	4.166
Signalized/Unsignalized?					
	Unsignalized	Reference			
	Signalized	-1.450	0.372	0.687	0.235
log(Exit Ramp AADT)		-0.560	0.400	1.066	0.571
log(Crossroad AADT)		1.365	0.435	3.883	3.916
Area Type					
	Rural	Reference			
	Urban	1.899	0.357	15.022	6.679

5.1.4 Comparison between Model 2 and Model 3

The results of Models 2 and 3 can be interpreted in a similar way to those of Model 1. However, it was worth comparing the results of Models 2 and 3 to investigate if a particular geometric feature or TCD is more important for the exit ramp terminal connected to a two-lane crossroad than when they meet a 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 WW entry by 3.64 times at exit ramps connected to multilane crossroads. The non-angular connection increased the odds of WWD by 8.85 times for a two-lane compared with 3.20 times for multilane crossroads. The distance of WW 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 chance of WWD (OR=0.235). 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=3.916). Finally, the multilane crossroad and exit ramp intersection in urban areas had higher odds of WWD (OR=6.679) than two-lane crossroads. 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.

5.2 Modeling Results for Parclo Interchange

The complete data set for parclo interchange consists of the geometric characteristics, WW-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 developed, which included all the potential predictor variables, as shown in Table 1. After that, backward elimination technique was employed to identify the variables having statistically a significant impact on the prediction outcome. The backward elimination technique also ensures that the final model is most parsimonious and efficient. A summary of the final logistic regression model is shown in Table 6.

The mathematical expression of the developed model is shown in Equation 6. In this equation, the negative sign before a variable indicates that the respective variable is responsible for reducing the chances of WWD, while the positive sign indicates that the respective variable is responsible for increasing the chances. In that regard, the chances 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 chances 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, the distance of the first WW sign from a crossroad is above 200 feet, there is no KEEP RIGHT sign and WW pavement arrow, and the entrance ramp AADT is high. It should be noted that some of the variables were not included in the final model because they are not statistically significant. These variables include intersection angle, corner radius from two-way ramp to crossroad, type of median between entrance and exit ramps, intersection balance, DNE signs, and presence of two sets of WW signs along the exit ramp. However, some recent studies found that the intersection balance may have an impact on WWD incidents at parclo interchange terminals *(6, 41)*.

$$\begin{aligned}\textbf{logit}(\mathbf{p}) = {} & -6.334 + 0.982(\mathrm{X_{CR1}}) + 0.552(\mathrm{X_{CR2}}) + 0.474(\mathrm{X_{CR3}}) + 0.616(\mathrm{X_{MC}}) - 0.704(\mathrm{X_{MW1}}) \\ & - 0.785(\mathrm{X_{MW2}}) + 0.214(\mathrm{X_{CI1}}) + 1.384(\mathrm{X_{CI2}}) - 0.978(\mathrm{X_{DAP1}}) - 0.106(\mathrm{X_{DAP2}}) \\ & - 0.372(\mathrm{X_{DAP3}}) + 0.062(\mathrm{X_{WWSD}}) + 0.548(\mathrm{X_{KRS}}) + 0.875(\mathrm{X_{WWPA}}) - 1.521\left(\mathrm{X_{Signal}}\right) \\ & - 0.507\left(\mathrm{X_{log(exit\ ramp\ AADT)}}\right) + 1.890\left(\mathrm{X_{log(entrance\ ramp\ AADT)}}\right) \qquad \textbf{\textit{(6)}}\end{aligned}$$

where,

$$X_{CR1} = \begin{cases} 1, & if\ the\ corner\ radius\ from\ crossroad\ is\ between\ 61\ to\ 80\ feet \\ 0, & otherwise \end{cases}$$

$$X_{CR2} = \begin{cases} 1, & if\ the\ corner\ radius\ from\ crossroad\ is\ between\ 81\ to\ 100\ feet \\ 0, & otherwise \end{cases}$$

$$X_{CR3} = \begin{cases} 1, & if\ the\ corner\ radius\ from\ crossroad\ is\ more\ than\ 100\ feet \\ 0, & otherwise \end{cases}$$

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

$$X_{MW1} = \begin{cases} 1, & if\ the\ width\ of\ median\ between\ on\ and\ off\ ramp\ is\ between\ 31\ to\ 50\ feet \\ 0, & otherwise \end{cases}$$

$$X_{MW2} = \begin{cases} 1, & if\ the\ width\ of\ median\ between\ on\ and\ off\ ramp\ is\ more\ than\ 50\ feet \\ 0, & otherwise \end{cases}$$

$$X_{CI1} = \begin{cases} 1, & if\ there\ is\ no\ channelization\ on\ the\ throat\ of\ exit\ ramp \\ 0, & otherwise \end{cases}$$

$$X_{CI2} = \begin{cases} 1, & if\ the\ channelization\ on\ the\ throat\ of\ exit\ ramp\ is\ traversable \\ 0, & otherwise \end{cases}$$

$$X_{DAP1} = \begin{cases} 1, & if\ the\ distance\ to\ nearest\ access\ point\ is\ between\ 301\ to\ 600\ feet \\ 0, & otherwise \end{cases}$$

$$X_{DAP2} = \begin{cases} 1, & if\ the\ distance\ to\ nearest\ access\ point\ is\ between\ 601\ to\ 900\ feet \\ 0, & otherwise \end{cases}$$

$$X_{DAP3} = \begin{cases} 1, & if\ the\ distance\ to\ nearest\ access\ point\ is\ more\ than\ 900\ feet \\ 0, & otherwise \end{cases}$$

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

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

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

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

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

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

5.2.1 Effects of Geometric Design Features on WWD

The chances of WWD increased by 1.61 to 2.67 times when the corner radius from crossroad to two-ramp is above 60 feet. Typically, a sharp corner radius is expected to ensure that the left-turning WW 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 *(27)*. 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. 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 in the crossroad and exit ramp.

A traversable median on the crossroad was found to increase the chances of WWD by 1.85 times compared with a non-traversable median. Pour-Rouholamin and Zhou *(6)* found similar results when predicting the effect of geometric design elements on the probability of WW entries. In addition, the existing guidelines stressed on providing a non-traversable median on the crossroad to physically obstruct the left-turning WW maneuvers from the crossroad *(7, 23)*. 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 in regard to the appropriate median width between two-way ramps. A minimum width of 50 feet is recommended in the IDOT manual *(27)*. Pour-Rouholamin and Zhou *(6)* 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.

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 WW drivers *(7)*. 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 WW entries is more for a traversable channelizing island (OR = 3.99) compared with no channelizing island (OR = 1.24). 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 WW drivers, which may make exit ramps with traversable channelizing islands more susceptible to WWD.

The presence of access points/driveways close to interchange terminals can contribute to additional driver confusion and increase the chance of WW entries. In this study, access points within 300 feet were found to be associated with higher chance of WW entries.

Table 6. Summary of Firth's Penalized Likelihood Logistic Regression Model for Parclo Interchange

Variables	Category	Parameter Estimates	Estimated Std. Error	Chi-Square Statistics	OR
Intercept		-6.334	2.672	6.797	-
Corner Radius from Crossroad					
	60 feet or less	Reference			-
	61 to 80 feet	0.982	0.782	1.723	2.670
	81 to 100 feet	0.552	0.855	0.425	1.737
	More than 100 feet	0.474	1.081	0.204	1.606
Median on Crossroad					
	Non-Traversable	Reference			-
	Traversable	0.616	0.605	1.082	1.852
Width of Median Between exit and Entrance Ramps					
	30 feet or less	Reference			-
	31 to 50 feet	-0.704	0.632	1.309	0.495
	More than 50 feet	-0.785	0.947	0.779	0.456
Channelizing Island					
	Non-Traversable	Reference			-
	None	0.214	0.935	0.059	1.239
	Traversable	1.384	0.828	3.095	3.991
Distance to Nearest Access Point					
	300 feet or less	Reference			-
	301 to 600 feet	-0.978	0.912	1.206	0.376
	601 to 900 feet	-0.106	0.839	0.017	0.899
	More than 900 feet	-0.372	0.846	0.202	0.689
Distance of First WW Sign from Crossroad					
	200 feet or less	Reference			-
	More than 200 feet	0.062	0.519	0.014	1.064
KEEP RIGHT Sign					
	Yes	Reference			-
	No	0.548	0.516	1.142	1.730
WW Pavement Arrow					
	Yes	Reference			-
	No	0.875	0.569	2.354	2.399
Signal					
	No	Reference			-
	Yes	-1.521	0.748	4.577	0.218
log(exit ramp AADT)		-0.507	0.638	0.648	0.602
log(entrance ramp AADT)		1.890	0.763	7.167	6.619

5.2.2 Effects of TCDs on WWD

MUTCD *(29)* requires at least one WW and one DNE sign at exit ramps. However, the effectiveness of WW-related TCDs also depends on their placement at the exit ramp terminals. In this study, the presence of the first WW sign within 200 feet was found to be associated with a lower chance of WWD. In addition, the absence of KEEP RIGHT signs (on the median between two-way ramps) and WW pavement arrows were found to increase the chance of WWD by 1.73 and 2.40 times, respectively. Similarly, the signalized interchange terminals were found to have significantly lower risk of WWD (OR = 0.218).

5.2.3 Effects of AADT on WWD

In this study, locations with higher AADT volumes on exit ramps were found to have lower risks of WWD (OR = 0.602). On the other hand, locations with higher AADT volumes on entrance ramps were found to have higher risks of WWD (OR = 6.619), which can be attributed to the fact that the higher entrance ramp AADT means a higher number of potential WW 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.

6. NETWORK SCREENING AND MODEL VERIFICATION

6.1 Network Screening

A three-step network screening approach (Figure 6) was developed in this study. The first step involves collecting data for all the exit ramp terminals of full diamond and parclo interchanges in Alabama. Table 7 lists the data required for network screening and the data sources.

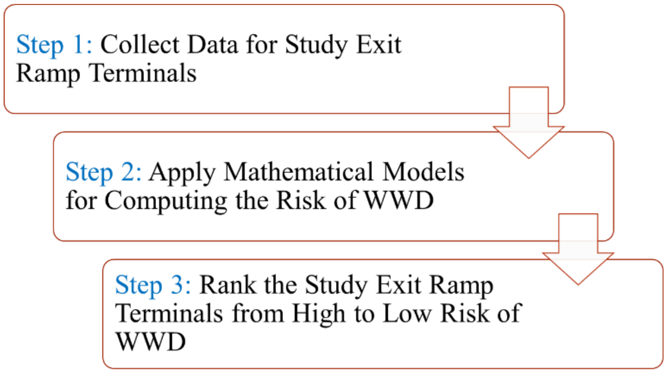

Figure 6. Steps Involved in Network Screening for WWD

Table 7. 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	-Distance of WRONG WAY sign from the crossroad -Presence/absence of KEEP RIGHT sign -Presence/absence of WW 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	-Urban/rural	Census Urban Area Map

The second step involves applying mathematical models to predict the risk of WWD. Equations 3 and 5 can be applied to predict the probability of WWD at full diamond and parclo interchanges, respectively. In these equations, one should solve for p to compute the probability of WWD at a certain exit ramp terminal. For convenience, the research team integrated these mathematical models into automated Excel spreadsheets. These Excel spreadsheets will enable the ALDOT personnel to compute the probability of WWD at the exit ramp terminals by simply inputting the AADT volumes and geometric design features and TCDs from the drop-down selection list. In addition to predicting the probability of WWD, the Excel spreadsheets readily provide 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 A.

After computing the probability of WWD at individual locations, in the third step, all the exit ramp terminals of the same interchange type were sorted in descending order, i.e., from high to low risk of WWD. According to the network screening results in Alabama, the top ten high-risk locations for full diamond and parclo interchanges are listed in Tables 8 and 9, respectively.

6.2 Model Verification

To verify the models, the top ten high-risk exit ramp terminals identified by the model were monitored using video cameras for 48 hours during typical weekends (i.e., not affected by any special events/construction/sever weather). The research team visited these high-risk locations and set up cameras to collect videos of traffic movements. For each location, 48-hour video was recorded from Friday, 5:00 p.m. to Sunday, 5:00 p.m. Later, the research members watched the videos and recorded WWD incidents (if there were any). The results of video analysis are discussed in the following sections.

6.2.1 Model Verification Results for Full Diamond Interchanges

Table 8 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 further verify the model prediction results, WWD incident data were collected using cameras. It was found that two locations experienced at least one WWD incident (Table 8). Due to the randomness of WWD incidents, one incident over 48 hours is considered high for an intersection. To further verify the developed models for full diamond interchanges, the researchers recommended to collect more WWD incident data for a longer duration (for a whole week/month if possible) to confirm if there are recurring WWD incidents.

Table 8. Results of Video Analysis for Exit Ramp Terminals of Full Diamond Interchanges

Ranking	Locations	Was there any WWD Crash in the Past?	Probability of WW Entry	Number of WW 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.*

6.2.2 Model Verification Results for Parclo Interchange

Table 9 lists the top ten locations and their predicted probability of WWD, along with 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. To further verify the model prediction results, the research team collected 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 WW entries. In addition, another two locations were found to have one WWD movement in a 48-hour period. The WWD incident data analysis results indicate that the developed model is capable of identifying high-risk exit ramp terminals of parclo interchanges.

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

Table 9. Results of Video Analysis for Exit Ramp Terminals of Parclo Interchanges

Ranking	Locations	Was there any WWD Crash in the Past?	Probability of WW Entry	Number of WW 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.*

It should be noted that no WWD incidents were observed during the 48 hours at I-65 Exit 284 NB 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 peak hour traffic volumes at this location is shown in Figure 7, 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 developed 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 the WWD incidents observed in the field study are caused by left-turn drivers, which further supports this statement.

Figure 7. Existing Afternoon and Morning Peak Hour Traffic Volumes at I-65 Exit 284 Ramps

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 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. Therefore, the mathematical models and network screening tools were developed for full diamond interchanges for state agencies to identify high-risk locations for improvements. The results of the data analysis identified specific geometric characteristics and TCDs that contribute to the probability of WWD crashes. 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 *Green Book* for connecting exit ramps to crossroads, the results show that an obtuse-angle connection can lower the risk of WWD, as it makes the WW 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. Future research can focus on determining the type of angle that results in the fewest overall crashes.
2) The *Green Book* 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 WW 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 WW maneuver difficult, while a non-traversable crossroad median makes the left-turning WW maneuver less likely. Therefore, a combination of these geometric features is likely to ensure the least possibility of WW entry.
4) Although MUTCD recommends using at least one WW sign on exit ramps, the placement of this sign along the exit ramp is not specified. This study results suggest that the first WW 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 WW entry, as they provide more regulated traffic flow. Therefore, the probability of WW 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 WW 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 WW 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.

The Excel spreadsheets developed in this study can be used to conduct statewide network screening to identify high-risk diamond interchanges. Appendix B contains examples of the high and low-risk locations.

7.2 Parclo Interchange

The mathematical models developed 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 mathematical 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 WW 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 WW left-turning movement from the crossroad to exit ramp difficult.
2) A non-traversable median is recommended to obstruct left-turning vehicles from going WW to exit ramps. Non-traversable median should be extended within an intersection functional area to ensure that the WW 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 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) The first set of WW signs should be located within 200 feet along the exit ramp from the crossroad.
7) KEEP RIGHT signs and WW pavement arrows should be placed at suitable locations.
8) 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.

A network screening tool (Excel spreadsheets) was used to successfully identify the ten high-risk parclo interchange terminals in Alabama. The model prediction results were verified by WWD crash data and incident data collected by cameras. The traffic movement data at the top ten high-risk locations revealed that two locations experienced ten or more WWD incidents over a 48-

hour period of a typical weekend. ALDOT regional offices are currently implementing low-cost countermeasures to mitigate WWD activities at the two locations. The research team will continue to monitor these two locations and evaluate the implemented low-cost countermeasures.

7.3 Limitations and Future Study

The main purpose for the developed 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 interchange terminals for improvements.

The developed 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 WW incidents using 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 WW entry.

The model developed in this study can only be applied to freeway exit ramp terminals. Past studies indicated that a significant portion of WWD crashes occurred 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. Predictive models and tools can be developed to identify high-risk intersections on divided highways.

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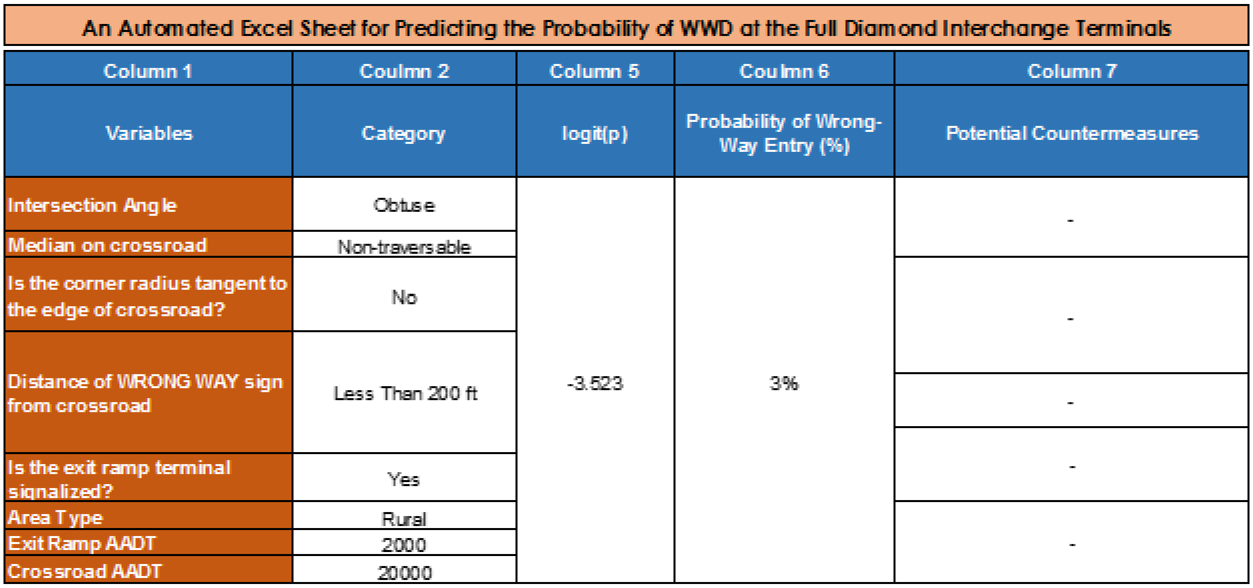
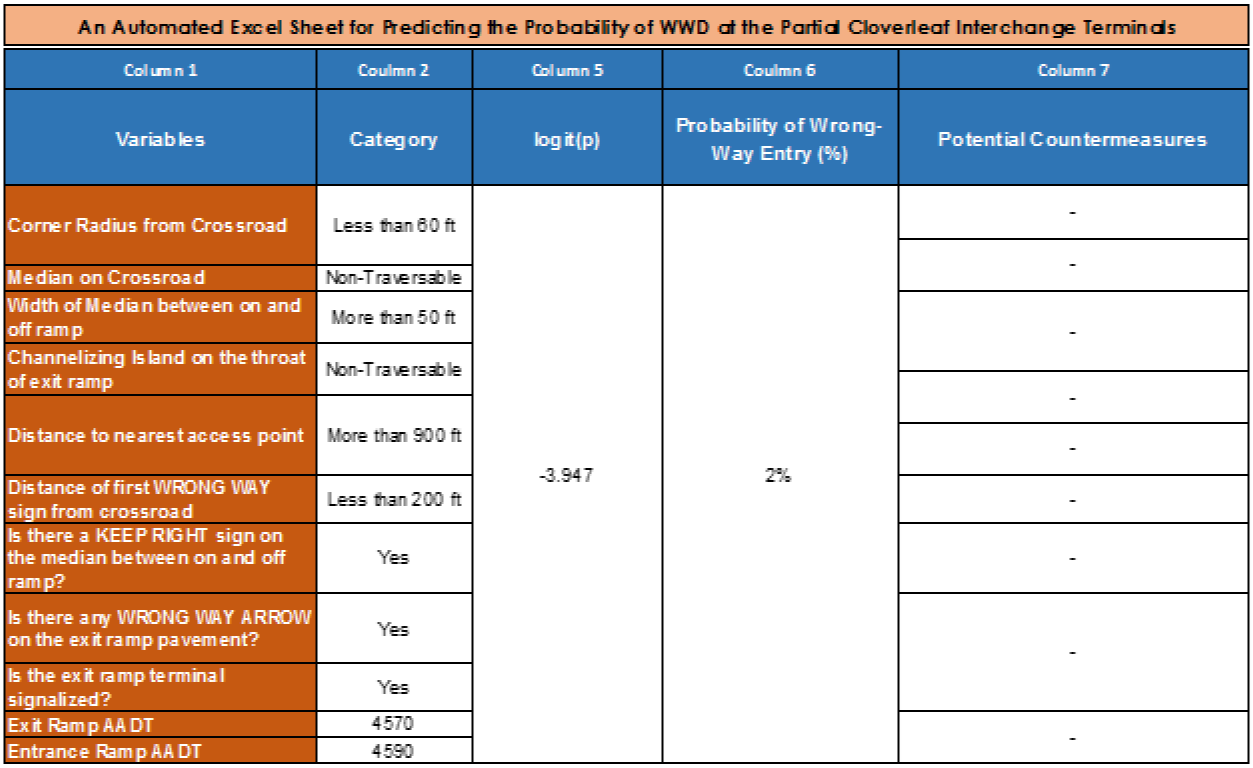
APPENDIX A: SCREENSHOTS OF EXCEL SPREADSHEETS FOR PREDICTING RISK OF WWD



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			

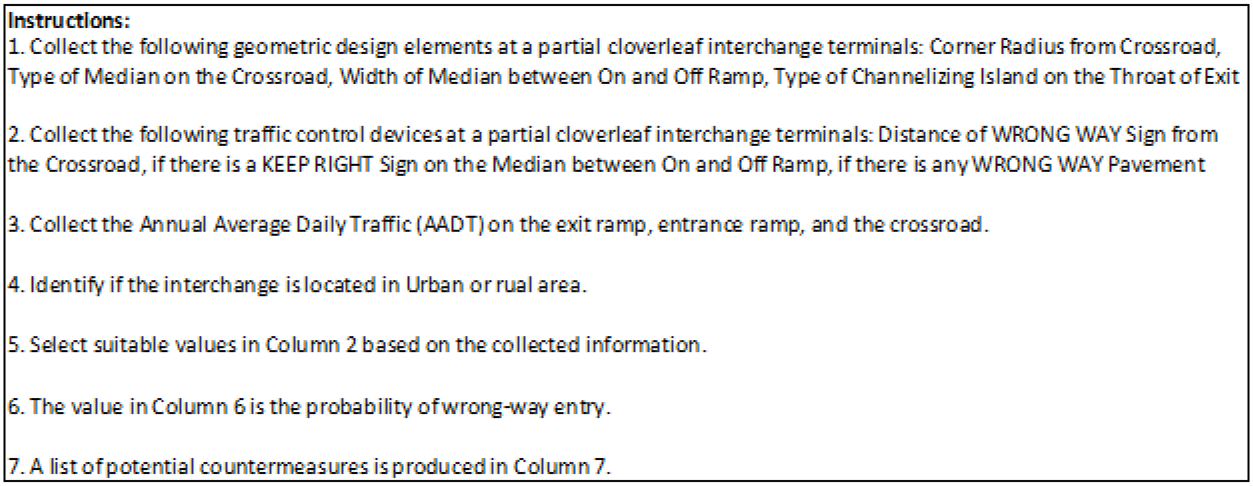
Figure A.1 Excel Spreadsheet for Predicting Risk of WWD at the Exit Ramp Terminals of Full Diamond interchanges



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 A.2 Excel Spreadsheet for Predicting Risk of WWD at the Exit Ramp Terminals of Parclo interchanges



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 A.3 Instructions for Using Excel Spreadsheet Shown in Figures A.1 and A.2

APPENDIX B: HIGH AND LOW-RISK DESIGN EXAMPLES

Figure B.1 High-Risk Exit Ramp Terminal of Full Diamond Interchange

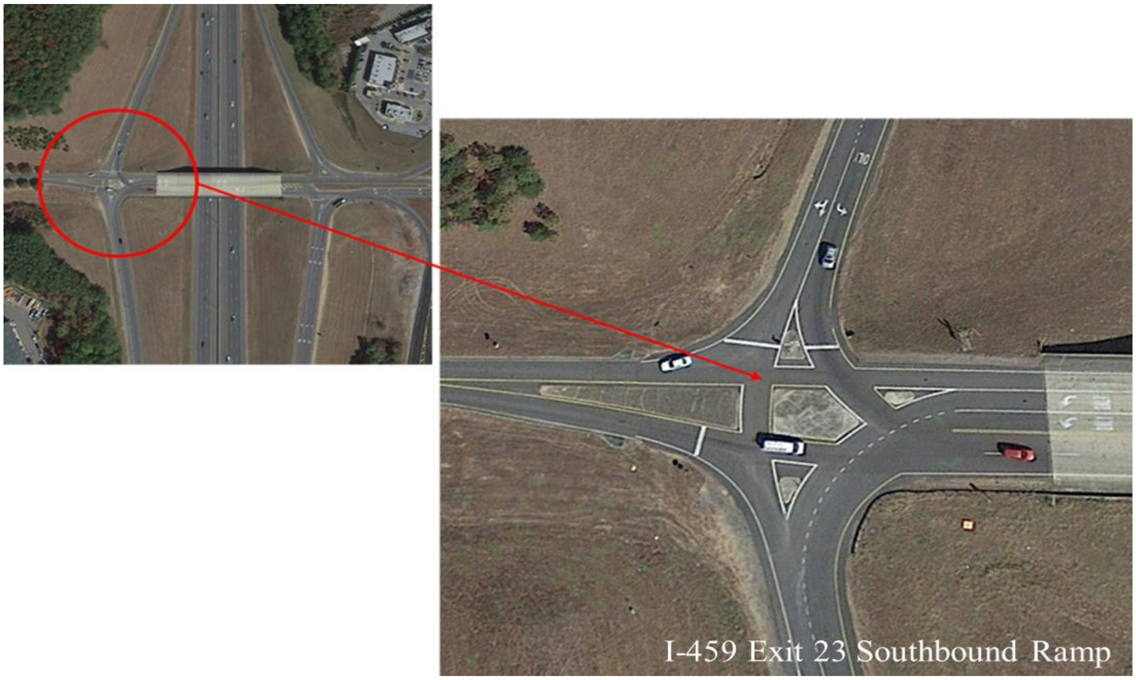


Figure B.2 Low-Risk Exit Ramp Terminal of Full Diamond Interchange

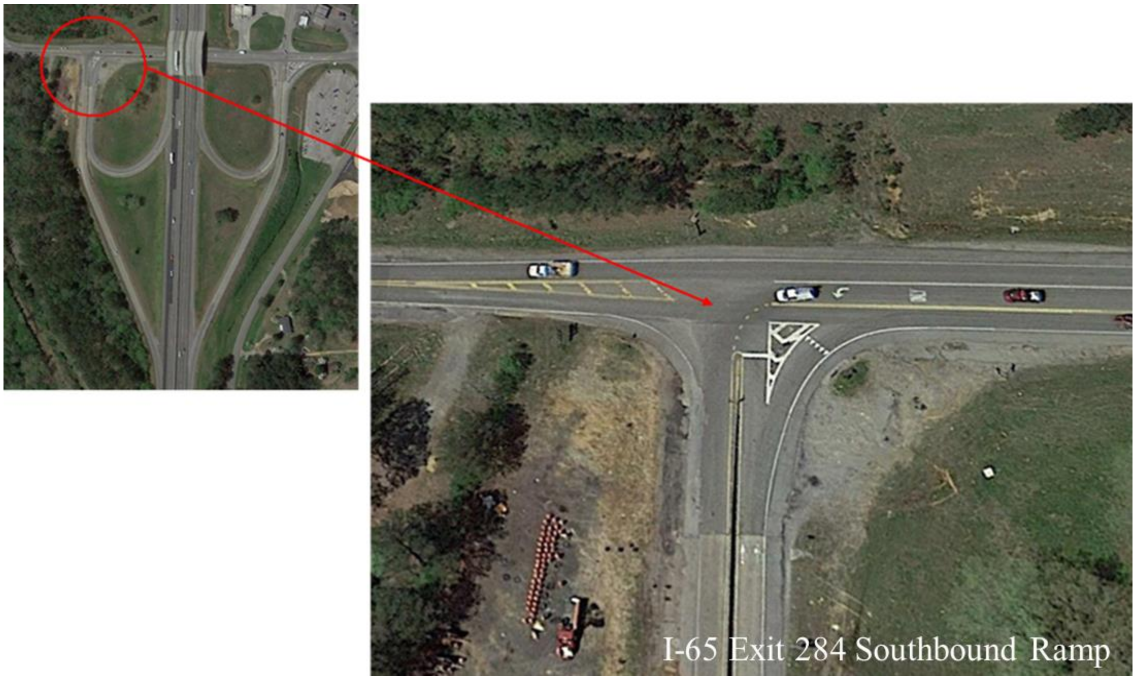


Figure B.3 High-Risk Exit Ramp Terminal of Parclo Interchange

Figure B.4 High-Risk Exit Ramp Terminal of Parclo Interchange

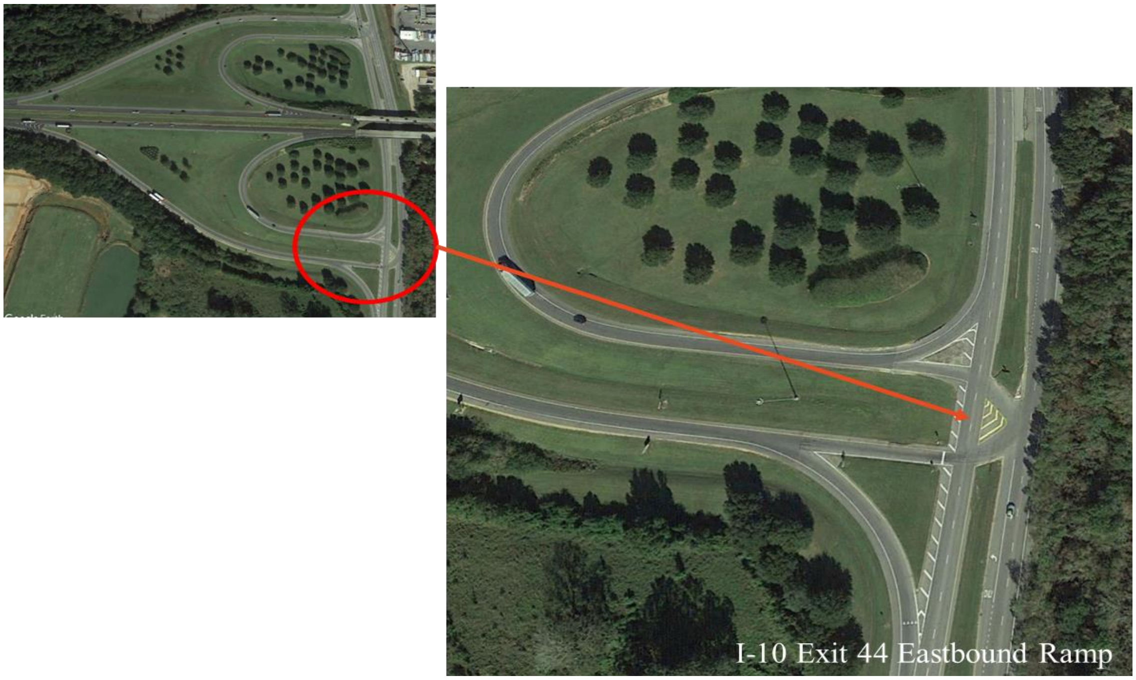


Figure B.5 Low-Risk Exit Ramp Terminal of Parclo Interchange