Wrong-Way Driving:
Crash Data Analysis and Safety Countermeasures

by

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Abstract

Wrong-way driving (WWD) on controlled-access highways has been a consistent issue since the introduction of Interstate systems in the 1950s. Despite all the efforts to overcome the issue, there is still much to learn. This dissertation, as the first of its kind, tries to systematically address the problem by using a data-driven approach that combines a bolstered database, from the states of Alabama and Illinois, with the appropriate statistical tools. As the first step, WWD crashes are characterized compared to non-WWD crashes on controlled-access highways. This statistical comparison enables the researchers to identify several characteristics that delineates between these two types of crashes and to selectively bring them to the attention of the policy-makers. The method proposed for this analysis is being used for the first time in the traffic and safety engineering literature. As the next step, the aim is to identify variables that significantly affect the driver injury severity in a WWD crash. Given the severe nature of WWD crashes, this analysis can further help characterize these crashes and propose appropriate countermeasures. After characterizing WWD crashes at these levels, the next step is to explore various countermeasures that may affect WWD crashes. To this end, an extensive review on the existing literature was conducted and geometric features of parclo interchanges, as one of the most WWD-prone interchanges, were chosen for further investigation. The analysis of these geometric elements provided a good understanding of the role of these elements on the likelihood of WWD entries using crash data.

Dedication

This dissertation is dedicated to my brilliant, loving, and supportive wife, Maniya, who listened, believed, and taught me to be strong in every single moment of her presence in my life. I also dedicate this dissertation to my always encouraging and ever faithful parents, Farideh and Akbar, for their constant support and endless advice.

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AIC	Akaike Information Criterion
ALDOT	Alabama Department of Transportation
ATSSA	American Traffic Safety Services Association
BIC	Bayesian Information Criterion
Caltrans	California Department of Transportation
CARE	Critical Analysis Reporting Environment
CCTV	Closed-circuit Television
CU	Causal Unit
DMS	Dynamic Message Signs
DNE	DO NOT ENTER
DUI	Driving Under the Influence
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
GOL	Generalized Ordered Logit
HCTRA	Harris County Toll Road Authority
HSIP	Highway Safety Improvement Program
ICN	Illinois Case Number
ICT	Illinois Center for Transportation
IDOT	Illinois Department of Transportation

IID	Ignition Interlock Device
ILD	Inductive Loop Detector
ITS	Intelligent Transportation Systems
LED	Light-emitting Diode
MDOT	Michigan Department of Transportation
MLE	Maximum Likelihood Estimate
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
NTTA	North Texas Tollway Authority
OR	Odds Ratio
Parclo	Partial Cloverleaf Interchange
PDO	Property Damage Only
PO	Proportional Odds
PPO	Partial Proportional Odds
ROW	Right-of-way
RRPM	Retroreflective Raised Pavement Markers
RW	Right Way
SPDI	Single Point Diamond Interchanges
TMC	Traffic Management Centers
TxDOT	Texas Department of Transportation
U.S.	United States
V2	Second Vehicle

VDOT	Virginia Department of Transportation
WW	Wrong Way
WWD	Wrong-Way Driving

1 Introduction

1.1 Background

Wrong-Way Driving (WWD), by definition, happens when a driver, inadvertently or deliberately, drives in the opposite direction of traffic flow along a physically divided highway (freeway, expressway, or Interstate highway), namely controlled-access highway, or its access ramps. These WWD crashes are mainly head-on or opposite direction sideswipes, which tend to be more severe in terms of type of injuries and number of fatalities. A recently conducted inquiry of the Fatality Analysis Reporting System (FARS) database revealed that an average of 355 people were killed in WWD crashes each year over a ten-year period on controlled-access highways (2004 to 2013).

The average number of non-WWD fatalities during the same time period has been 37,354. That is, around 1% of total fatalities on U.S. highways is due to WWD crashes. However, it is worthy of mentioning that non-WWD crashes have shown a downward trend in the last years, while WWD crashes has remained almost steady. Figure 1.1 shows this trend.

Figure 1.2 depicts the annual average frequency of WWD fatalities across all 50 states in the United Stated (U.S.) as well as share of different states within this time period categorized into three groups. In this figure, Group 1 includes 16 states with more than 2% of WWD fatalities, Group 2 represents states with less than 2% but more than 1%, and Group 3 consists of the states with less than 1% WWD fatalities.

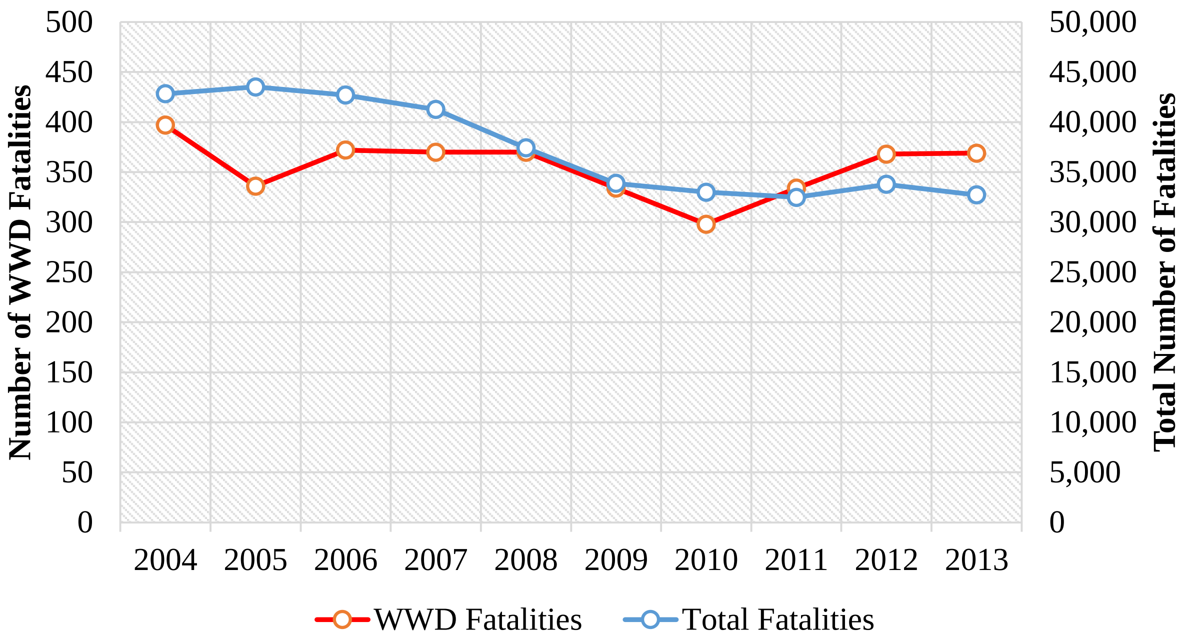
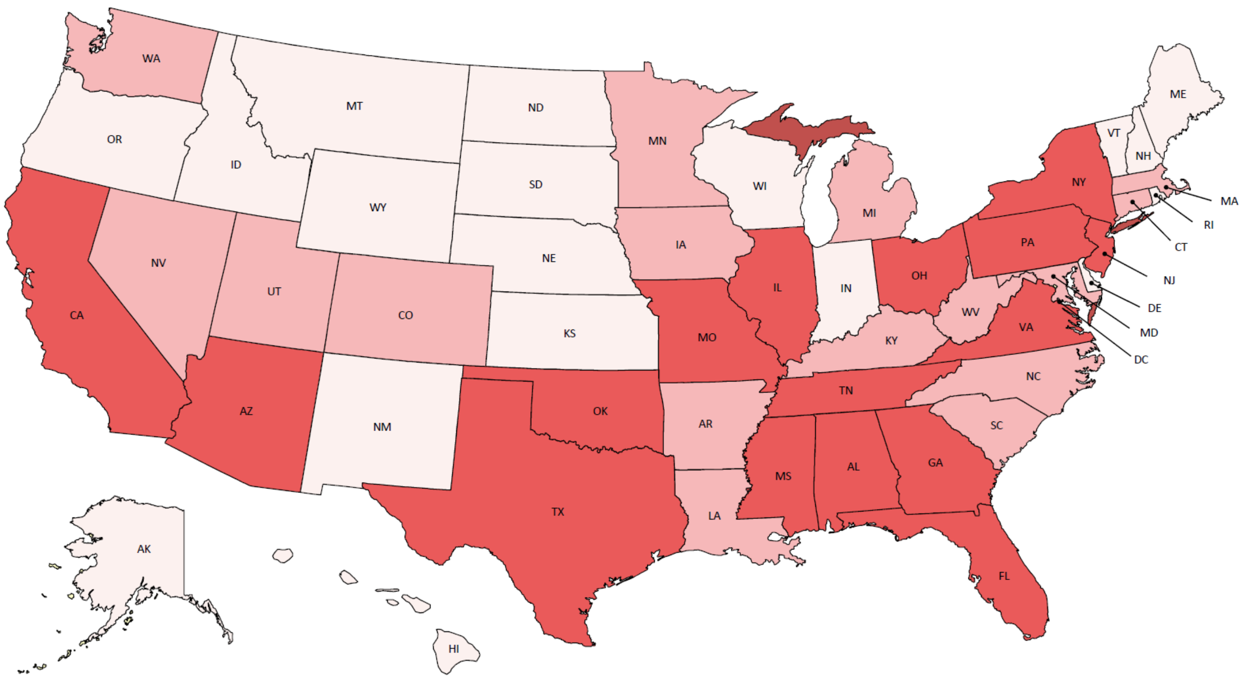


Figure 1.1 National trend of WWD and non-WWD fatalities (2004-2013)

According to this Figure 1.2, Texas is ranked first with more than 15% of WWD fatalities occurring, followed by California and Florida. The three states with the highest frequency comprise approximately one-third of total WWD fatalities in the U.S. Furthermore, these three states have put a considerable amount of effort and investment in solving the WWD issue, given the significance of this problem in their jurisdiction. The states of Illinois and Alabama that were studied are also ranked among the states with high WWD fatality rate, supporting the need for further investigation of the problem. To be specific and referring to Figure 1.2, Illinois is ranked 7th and Alabama is ranked 11th in terms of their share of WWD fatalities in the nation. These rankings are based on the share of 3.2% and 2.5% of total WWD fatalities in the U.S. for Illinois and Alabama, respectively.



Group 1 (2% and Higher)			Group 2 (1 to 2%)			Group 3 (Below 1%)		
State	Frequency	% U.S. Total	State	Frequency	% U.S. Total	State	Frequency	% U.S. Total
Texas	53.8	15.2%	Washington	6.9	1.9%	Oregon	3.1	0.9%
California	34.1	9.6%	Louisiana	6.8	1.9%	Indiana	2.9	0.8%
Florida	28.1	7.9%	Michigan	6.8	1.9%	New Mexico	2.8	0.8%
Pennsylvania	14	3.9%	North Carolina	6.4	1.8%	Wisconsin	2.8	0.8%
Tennessee	13.6	3.8%	Colorado	5.8	1.6%	Kansas	2.7	0.8%
Missouri	13.3	3.7%	Maryland	5.7	1.6%	Idaho	2.1	0.6%
Illinois	11.2	3.2%	Nevada	5.6	1.6%	Montana	2.1	0.6%
Georgia	11	3.1%	West Virginia	5	1.4%	Delaware	1.7	0.5%
Arizona	10.1	2.8%	Connecticut	4.9	1.4%	Rhode Island	1.3	0.4%
Mississippi	9.2	2.6%	South Carolina	4.8	1.4%	Hawaii	1	0.3%
Alabama	8.7	2.5%	Massachusetts	4.5	1.3%	North Dakota	0.9	0.3%
Oklahoma	8.1	2.3%	Arkansas	4.4	1.2%	Wyoming	0.9	0.3%
Ohio	7.7	2.2%	Minnesota	4.2	1.2%	Maine	0.8	0.2%
New York	7.6	2.1%	Kentucky	3.8	1.1%	New Hampshire	0.8	0.2%
New Jersey	7.2	2.0%	Utah	3.6	1.0%	South Dakota	0.8	0.2%
Virginia	7	2.0%	Iowa	3.5	1.0%	Vermont	0.5	0.1%
						Alaska	0.1	0.0%
						Nebraska	0.1	0.0%

Figure 1.2 Average and percentage of WWD fatalities in each state (2004-2013)

Based on different studies, there are a number of factors that may increase the probability of WWD maneuvers on a roadway facility prone to WWD maneuvers. While impaired driving accounts for over half of WWD crashes, studies also found that inconsistency in location, angles, and size of WW-related traffic signs, lack of pavement markings, and improper geometric design are contributing factors. Over the past few decades, various engineering countermeasures have been proposed, implemented, and tested by several state and local agencies to mitigate WWD incidents, including (1) changing the size, location, and angle of WW-related signs, (2) proper use of conventional and innovative pavement markings, (3) implementing proper geometric elements (raised medians, channelizing islands, etc.), and (4) application of Intelligent Transportation Systems (ITS). It should be noted that DO NOT ENTER (DNE) and WRONG WAY (WW) signs are the two widely used engineering countermeasures for WWD mitigation purposes. However, a comprehensive WWD mitigation plan should include all the countermeasures that fall under the 4E's approach and includes engineering, education, enforcement, and emergency response. Despite all these efforts, there is still need to quantify the effect of these countermeasures, whenever the data is available.

According to the previously conducted studies (Zhou et al., 2012; Morena and Leix, 2012), exit ramp terminals are the most likely locations for WW drivers to enter a controlled-access highway. Further in detail, among the exit ramps, those connected to partial cloverleaf (parclo) interchanges are ranked among the top locations in terms of WWD entry rates (number of entries per 100 interchanges per year). For instance, in the studies conducted in Illinois and Alabama, parclo interchanges are ranked third and first, respectively, based on this rate. Therefore, these exit ramps should be given special consideration, particularly in terms of geometric layouts (medians, driveways) in order to minimize driver confusion and discourage WW maneuvers.

Generally, efforts to reduce WW-related fatalities can be a good fit within a state's Highway Safety Improvement Program (HSIP). The HSIP is a core federal aid highway program created to significantly reduce traffic-related fatalities and serious injuries on all public roads in the U.S. Since WWD crashes are very sporadic, it is rare for specific sites to emerge as high crash or "hot spot" locations. However, when data from a statewide, regional, or system level over a sufficient period of time are analyzed, certain risk characteristics become evident. This is referred to by the Federal Highway Administration (FHWA) as the systemic process or approach. According to the FHWA, "the systemic approach to safety involves widely implemented improvements based on high-risk roadway features correlated with specific severe crash types. The approach provides a more comprehensive method for safety planning and implementation that supplements and complements traditional site analysis. It helps agencies broaden their traffic safety efforts and consider risk as well as crash history when identifying where to make low cost safety improvement locations." (Zhou and Pour-Rouholamin, 2014a)

1.2 Objectives

The dissertation herein investigates the WWD problem more in a systematic approach and in depth by using more robust data analysis methods and a comprehensive database of crash records from two states, Illinois and Alabama. The final scope of this dissertation is then to provide a more reliable set of countermeasures at various levels of 4E's safety approach.

The first objective of this research was to distinguish between WWD and non-WWD crashes on controlled-access highways. The rationale behind this effort was to find the difference between the spatiotemporal distributions, crash severity, and other characteristics of WWD and non-WWD crashes in the first place. If there are no significant differences between them, the countermeasures that are effective for non-WWD crashes may also be effective for WWD crashes. The second objective is to go further in detail and identify the parameters that significantly affect the driver injury severity within the WWD domain, given the severe nature of WWD crashes. This objective was fulfilled using the ordered-response models considering the ordered nature of severity sustained by drivers. Lastly, the third objective focused on the countermeasure aspect of WWD crashes, in terms of geometric design and specifically parclo interchanges as one of the most WWD-prone designs. Following this objective, various geometric characteristics of parclo interchanges and their role in affecting the probability of WWD entries were identified.

1.3 Dissertation Organization

Chapter 2 of this dissertation is dedicated to the first objective and identifies various characteristics of WWD crashes considering their statistically significantly difference from those of non-WWD crashes. In Chapter 3, the effect of different variables on the injury severity of WW drivers are recognized. A comprehensive review on the existing countermeasures supplemented with a survey questionnaire to further identify current practices to mitigate the WWD issue in the U.S. is presented in Chapter 4. Chapter 5 quantifies the effect of various geometric design elements and access management techniques at parclo interchanges on the probability of WWD entrance using crash data. Lastly, Chapter 6 concludes this dissertation and summarizes all the findings and provides appropriate countermeasures based on the results of the previous chapters.

2 Comprehensive Analysis of Wrong-Way Driving Crashes

This chapter of dissertation aims to fulfill the first objective of this dissertation, which was to delineate between WWD and non-WWD crashes. To do so, crash data on Illinois and Alabama controlled-access highways were collected across ten-year and five-year time periods, respectively. In addition, actual WWD crashes were identified using the hardcopy of crash reports and existing maps. The crash data contained 18 explanatory variables representing the crash, driver, temporal, vehicle, and environmental information. A Firth's penalized-likelihood logistic regression model was developed to examine the influence of the explanatory variable on the dichotomous dependent variable (type of crash, i.e., WWD vs. non-WWD). This model is an appropriate tool to control the influence of all confounding variables on the probability of WWD crashes while considering the rareness of the event (i.e., WWD). A separate model using the standard binary logistic regression was also developed. Two information criteria (Akaike information criterion, or AIC, and Bayesian information criterion, or BIC) obtained from both developed models as well as the log-likelihood at convergence indicate that for our database, Firth's model outperforms the standard binary logistic model and provides more reliable results. Moreover, a likelihood ratio test confirms the statistically significantly different results obtained from the two models. Using Firth's model, explanatory variables including crash severity, month of the year, time of the day, driver age, driver mental and physical condition, vehicle age, towing condition, seatbelt use, airbag deployment status, and lighting condition were found to characterize WWD crashes. Based on the obtained odds ratio (OR), this Chapter discusses the various effect of the identified variables and recommends several countermeasures for policy makers in order to reduce the WWD issue on controlled-access highways.

2.1 Introduction

While some crash types gain increasing attention due to their prevalence (e.g., run-off-the-road and intersection-related crashes), WWD crashes receive special emphasis due more to their severity than to their frequency (Pour-Rouholamin and Zhou, 2016a). This type of crash can occur on any one-way roadway; however, the concentration of most studies has been on controlled-access highways (i.e., freeways, expressways, and Interstate highways) as the speed limit is relatively high and – given the manner of the WWD crash, which is mostly head-on or opposite-direction sideswipe − the resulting outcome would be more severe (Pour-Rouholamin et al., 2014).

To obtain a better understanding of the importance of the problem, the FARS database was used to identify WWD crashes within a ten-year period (2004-2013) throughout the U.S. (NHTSA, 2015). An average of 265 fatal WWD crashes occurred per year on U.S. controlled-access highways, in which 355 people were fatally injured, resulting in almost 1.34 fatalities per WWD fatal crash. The significance of these kinds of crashes is corroborated when this number is compared to the fatalities per fatal crash rate of 1.10 for all other crash types, which translates to 24 more fatalities per 100 fatal crashes for WWD crashes than for fatal crashes in general. Given this evidence, it becomes necessary to identify the factors that best describe the WWD crashes and improve the knowledge of the underlying factors involved in WWD occurrence.

The purpose of this Chapter is to review the severe WWD crashes in depth, to recognize the contributing factors, to delineate between WWD crashes and non-WWD on controlled-access highways, and to provide safety countermeasures and recommendations based on the obtained results. The rest of this Chapter is organized as follows. A review of the existing literature is provided next. The data used as well as the procedure to identify and verify true WWD crashes is presented. The methodology used in this Chapter, Firth's model, and its difference from standard binary logistic model (hereinafter "binary model") is described. This model then is applied to the data and the parameter estimates and OR are presented. Further, the same data was analyzed with binary model to make a comparison between these two models. Based on the obtained results, several safety countermeasures are proposed.

2.2 Literature Review

Numerous studies have documented, more empirically than statistically, the contributing factors regarding WWD crashes on controlled-access highways. While these studies were rare before the 2000s, various researchers started to examine these factors in the early 2000s, especially in Texas and Illinois; however, this topic of safety has gained renewed attention in recent years in both the U.S. and other countries. Although the majority of these studies have tried to use simple descriptive statistics to identify general characteristics of WWD (e.g., see Cooner et al., 2008; Braam, 2006; Scaramuzza and Cavegn, 2007; Zhou et al., 2012) several studies have been more specific in the database used or the methodology developed.

In a recently published paper by Kemel (2015), a database was used to identify 266 crashes that involved WW drivers from 2008 to 2012 on French divided highways, and their characteristics were compared to those of other crashes (22,120 crashes) on the same highways during the same time period. This empirical research was then followed by a binary model to make it possible to account for the effect of all the variables simultaneously. The results showed that rare, severe WWD crashes are more likely to occur during nighttime conditions (12-6 AM). Regarding the driver's age, this type of crash is more prevalent among drivers 65 and older, which is consistent with the findings of the majority of existing literature. Based on this study, other characteristics of WW drivers that contribute to their likelihood of becoming involved in a WWD crash were identified, including whether they are intoxicated, are local drivers (and not in-transit), and are driving passenger cars alone (without any passengers). However, the database only shows around 1.2% of events (266 WWD vs. 22,120 non-WWD crashes), which may bias the results of a binary model.

Zhou et al. (2015) also collected and analyzed WWD crashes on Illinois freeways over a six-year time period from 2004 to 2009. In their study, WWD crashes were characterized based on three different aspects: the crash (e.g., temporal distribution, roadways characteristics), the vehicle (e.g., characteristics, operation), and the driver (e.g., age, condition). Their study showed that a large proportion of WWD crashes occurred during weekends from 12 to 5 AM. While nearly two-thirds of WW drivers were driving under the influence (DUI), the authors suggested that this number might be even higher as many drivers either refused to take the sobriety test or had no test results recorded in the reports. This study revealed that younger drivers (under 25) are also overrepresented just like older drivers (above 65). Other contributions of their study include a method to identify entry points and to rank different interchange types based on the rate of WWD entries and a guidebook (Zhou and Pour-Rouholamin, 2014a).

Lathrop et al. (2010) explored a 15-year dataset (1990-2004) for fatal crashes on New Mexico's Interstates. Their sample was composed of 875 fatal non-WWD crashes and 49 fatal crashes, which had resulted in 1,092 and 79 fatalities, respectively. Various characteristics of fatal WWD crashes, including decedent demographics, occupant status, safety equipment use, and roadway and environmental conditions, were compared to those of other non-WWD fatal crashes as a comparison group. Driver alcohol consumption was an affecting factor − accounting for 60% of WWD crashes − as was nighttime conditions. It was also identified that WWD vehicle occupants are less likely to be wearing their seatbelts during crashes, which intensifies crash severity.

Another non-U.S. study conducted by Xing (2015) in Japan, analyzed the characteristics of both WWD crashes and incidents with an emphasis on crashes. In doing so, 4,769 WWD incidents and 133 WWD crashes over five years (2005-2009) were considered. This study's database has its advantage compared to that of other studies as it contains more records; however, its disadvantage is that it lacks interviews with WW drivers and therefore lacks other supplementary information. Other than confirming the findings of previous studies, the researcher sought to elaborate more on the application of Intelligent Transportation System (ITS) technologies, such as roadside WW navigation alert systems and WW warning systems with road-to-vehicle communication.

The literature review showed that most recent studies use simple descriptive statistics to identify contributing factors to WWD crashes. Few have focused on comparing WWD crashes with non-WWD crashes to test the significance of the identified contributing factors, which can be done using logistic regression models. There has been a myriad of previous research investigating the effect of several factors on one particular outcome in the field of traffic safety using logistic regression models (Torrão et al., 2014; Perez-Fuster et al., 2013; Haque et al., 2009; Larsen et al., 2013; Qin et al., 2013; Sarkar et al., 2011). In this Chapter, a new logistic method – Firth's penalized-likelihood logistic regression – is used to characterize WWD crashes while accounting for the effect of all confounding parameters. This method is a generalization of the maximum likelihood estimate (MLE) models. The advantage of this type of logistic regression model is that it can handle the bias in the calculations due to the small sample size and rareness of the event (which is the case in this study) satisfactorily. This method has specifically been used in medical science formerly. For example, Xu et al. (2012) analyzed a sample size of 67 patients with just 28 patients developed hypertension, which is pretty small sample size for MLE method. In another study by Mulla et al. (2012), they analyzed a sample of 138 patients with only 16 having preeclampsia that may cause computational problems when being analyzed with MLE methods.

2.3 Data

This study's approach to identifying WWD crashes is twofold: identifying possible WWD crashes and verifying true WWD crashes. The first step used pertinent variables to separate possible WWD crashes from the total crashes in the database. Afterwards, a hardcopy of the crash reports for each of these possible WWD crashes was reviewed carefully, and the true WWD crashes were identified based on crash narratives as well as diagrams and locations. Three variable categories – at the roadway, vehicle, and person levels – were used to define WWD movements in the crash database.

2.3.1 Wrong-way Driving Identification

The statistical data sources used in this study are police-reported roadway crash data in Illinois (2004-2013), which is accessible through the Illinois crash database, and the Alabama crash records database (2009-2013) accessed through the Critical Analysis Reporting Environment, also known as CARE, software (CARE, 2015). The Illinois database is separated into three different text files (crash, person, and vehicle), including a wide range of various characteristics and information regarding each of these categories. Crash records in these three files can be linked together using the variable Illinois Case Number (ICN) in all three files, which is unique to every single crash. Furthermore, CARE software is designed to help identify inherent statistical characteristics of various kinds of crashes from different perspectives, such as driver, roadway, and vehicle. Below, the process of identifying possible WWD crashes for further investigation based on the available crash data sources are presented.

2.3.1.1 Illinois

Based on a thorough review of the variables and according to the class of trafficway on which WWD crashes might occur, those crash records with the variable "class of trafficway" coded as either "controlled rural" or "controlled urban" in the crash file were extracted. The next step was to identify those crashes with the "Cause1Code" or "Cause2Code" equal to "Driving on wrong side/wrong way." These two causes are the factors which are most significant and second most significant in causing the crash, respectively. The code for vehicle maneuver prior to crash was the next factor to be considered. The code for this variable that can determine a WWD crash was "Driving wrong way." The variable "driver action" in the person file was the last variable to filter out non-WWD crashes so that those crashes with this variable coded as "wrong way/side" were kept in the database for further verification. Table 2.1 identifies the variables and corresponding values used to nominate possible WWD crashes in Illinois. Using these criteria, altogether 984 possible WWD crashes were found on Illinois controlled-access highways.

Table 2.1 Summary of Variables to Identify Possible WWD Crashes in Illinois

Variable	Value(s)
Class of Trafficway	- Controlled Rural - Controlled Urban
Cause 1	- Driving on Wrong Side/Wrong Way
Cause 2	- Driving on Wrong Side/Wrong Way
Vehicle Maneuver Prior to Crash	- Driving Wrong Way
Driver Action	- Wrong way/side

2.3.1.2 Alabama

The CARE software, which was used for Alabama, enables researchers to apply filters and extract specific kinds of crashes for further analysis, although WWD crashes cannot be directly extracted from the database. Therefore, it was necessary to define appropriate filters on variables to separate possible WWD crashes for further investigation based on the crash diagram, geographic coordinates, and narrative. All of the variables in the CARE system were reviewed, but only those that could help identify possible WWD crashes were investigated. This effort recognized contributing circumstances, maneuvers, and citations issued for either the crash, the causal unit (CU), or the second vehicle (V2), which may define any possible WWD movements on controlled-access highways. Table 2.2 summarizes the variables as well as the corresponding values used to identify possible WWD crashes for further examination in Alabama.

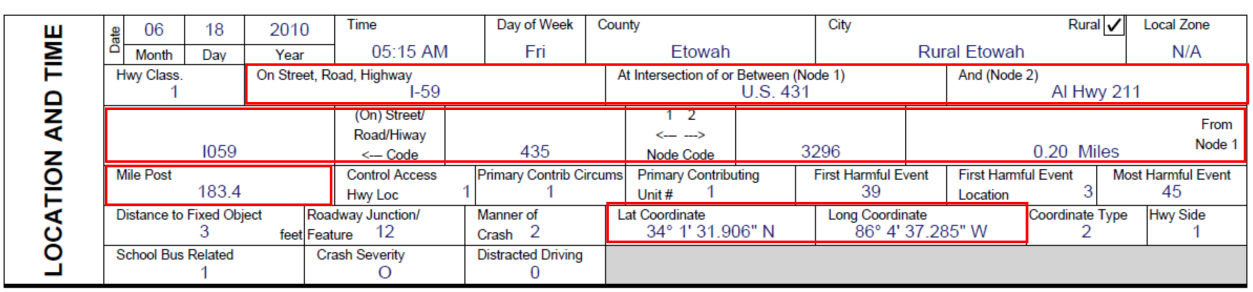
Table 2.2 Summary of Variables and Their Values to Identify Possible WWD Crashes in Alabama

Variable	Value(s)
Primary Contributing Circumstance	- Traveling Wrong Way/Wrong Side - Wrong Side of Road
CU Contributing Circumstance	- Traveling Wrong Way/Wrong Side - Wrong Side of Road
V2 Contributing Circumstance	- Traveling Wrong Way/Wrong Side - Wrong Side of Road
CU Vehicle Maneuvers	- Wrong Side of Road - Wrong Way on One Way
V2 Vehicle Maneuvers	- Wrong Side of Road - Wrong Way on One Way
CU Citation Issued	- Wrong Side of Road
V2 Citation Issued	- Wrong Side of Road

This filter was then applied to Interstate, federal, and state highways in the hierarchy of highway classification in CARE, resulting in 132, 525, and 799 possible WWD crashes (1,456 altogether), respectively. The reason why this filter was also applied to federal and state highways (as non-Interstate highways) was that the preliminary research on WWD crashes revealed that some true WWD crashes happened on exit ramps were coded as crashes on non-Interstate highways (depending on the classification of the crossroad connected to the exit ramp).

2.3.2 Wrong-way Driving Verification

The verification procedure for both states are the same. To verify the actual WWD crashes on controlled-access highways and their access ramps, hardcopy reports for those 2,440 (summation of 984 and 1,456) possible WWD crashes were requested from the IDOT and ALDOT. The first step was to confirm that the crashes had occurred at the target locations. To this end, the crash diagrams were checked, or in the case of no diagram, the crashes were located on Web map services, such as Google Maps, using the information provided in the top portion of crash reports. Figure 2.1 depicts an example of the "Location and Time" portion of an Alabama crash report. As can be seen in this figure, several information can be of use to correctly pinpoint the crash on the map, such as street name, Mile Post, and distance from nodes. Similar information can be found in Illinois crash reports. Figure 2.2 also shows a WWD crash location in a satellite image that can be used to confirm that the crash occurred on a controlled-access highway.


LOCATION AND TIME

Date: Month 06	Day 18	Year 2010	Time 05:15 AM	Day of Week Fri	County Etowah	City Rural Etowah (Rural ✓)	Local Zone N/A
Hwy Class. 1	On Street, Road, Highway I-59	At Intersection of or Between (Node 1) U.S. 431	And (Node 2) Al Hwy 211				
I059	(On) Street/ Road/Hiway <— Code 435	1 2 <— —> Node Code 3296	0.20 Miles From Node 1				
Mile Post 183.4	Control Access Hwy Loc 1	Primary Contrib Circums 1	Primary Contributing Unit # 1	First Harmful Event 39	First Harmful Event Location 3	Most Harmful Event 45	
Distance to Fixed Object 3 feet	Roadway Junction/ Feature 12	Manner of Crash 2	Lat Coordinate 34° 1' 31.906" N	Long Coordinate 86° 4' 37.285" W	Coordinate Type 2	Hwy Side 1	
School Bus Related 1	Crash Severity O	Distracted Driving 0					

Figure 2.1 Location and Time Portion of Alabama Crash Report

Figure 2.2 An Example to Verify the Location of Possible WWD Crash (Google Earth)

The next step was to review the narrative description for all the remaining crash reports in order to confirm that each crash was truly the result of a WWD maneuver. The actual WWD crashes were confirmed with respect to key phrases in the narratives such as “traveling the wrong way,” “traveling northbound on the southbound lanes,” or “turned right on the northbound exit ramp.” Altogether, 398 crashes (305 in Illinois and 93 in Alabama) were verified as true WWD crashes. Our investigation showed that the majority of unverified WWD crashes on these highways were those that happened after a vehicle crossed the median and struck an oncoming vehicle immediately afterwards. In Alabama and for federal and state highways, the majority were those driving on the wrong side of the road, as the code to nominate possible WWD crashes contains “wrong side” that inadvertently brings a lot of non-WWD crashes into the database.

2.3.3 Descriptive Statistics

Table 2.3 represents the total and fatal crashes for all non-WWD and WWD crashes on Illinois controlled-access highways along with their percentage from 2004 to 2013. A similar table (Table 2.4) is also presented for Alabama. As can be seen from these tables, WWD crashes comprise less than 0.14% of crashes on controlled-access highways (indicating a rare event); however, almost 5% of all fatal crashes on these highways are due to WWD. Finally, a spreadsheet of combined crash data from both states with rows representing each crash record and columns representing each attribute in the crash record was prepared for additional analysis.

Table 2.3 Number of Non-WWD and WWD Crashes on Illinois Controlled-access Highways

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Non-WWD Crashes	31,620	29,884	24,427	28,770	29,824	21,601	23,562	21,639	15,375	10,679	237,381
WWD Crashes	40	32	31	38	35	37	24	24	21	23	305
Percent	0.13%	0.11%	0.13%	0.13%	0.12%	0.17%	0.10%	0.11%	0.14%	0.22%	0.13%
Non-WWD Fatal Crashes	127	123	99	111	85	91	85	72	69	20	882
WWD Fatal Crashes	7	3	6	6	4	5	2	1	5	4	43
Percent	5.5%	2.4%	6.1%	5.4%	4.7%	5.5%	2.4%	1.4%	7.2%	20.0%	4.9%

Table 2.4 Number of Non-WWD and WWD Crashes on Alabama Controlled-access Highways

Year	2009	2010	2011	2012	2013	Total
Non-WWD Crashes	11,023	11,433	11,967	11,258	11,358	57,039
WWD Crashes	17	16	25	16	19	93
Percent	0.15%	0.14%	0.21%	0.14%	0.17%	0.16%
Non-WWD Fatal Crashes	64	79	76	73	69	361
WWD Fatal Crashes	4	2	4	2	2	14
Percent	6.3%	2.5%	5.3%	2.7%	2.9%	3.9%

The explanatory variables used in this study are cross-tabulated for both WWD and non-WWD crashes on controlled-access highways in Illinois and Alabama and are presented in frequency and percentage in Table 2.5. It should be noted that the Other/Unknown categories for the variables are not presented in this table; therefore, the total percentage for some variables under the columns may not sum up to 100%. After further examination of this table, a few points are worthy of mentioning:

- Drivers older than 65 years are over-represented in WWD so that 22.6% of WW drivers are older than 65 while this age group are responsible for 14.1% of other crashes.
- Male drivers accounted for a larger percentage of drivers involved in WWD crashes than other crashes on these facilities.
- The share of DUI drivers is also considerably high such that more than half of the WW drivers were intoxicated while this number for non-WWD crashes drops to 2.9%.
- WWD crashes are also disproportionately more frequent during night. More than half of WWD crashes have happened during nighttime periods that may be reflective of the possible abnormal driving conditions (e.g., DUI, drowsy, fatigue).
- Compared to other non-WWD crashes, WWD crashes are more frequent during weekends, while other controlled-access highway crashes are more prevalent during weekdays.
- The number of WWD crashes ranges between 23 and 43 per month. Despite this variation, this distribution seems to be even.
- WWD crashes are slightly more prevalent in rural areas compared other non-WWD crashes on controlled-access highways.
- The percentage of WWD crashes during dark conditions (whether roadway is lit or not) is much higher than other freeway crashes (78.7% vs. 34.3%).

- Most of WWD crashes occurred under clear weather conditions and on dry roadway surfaces.

Table 2.5 Descriptive Statistics of WWD and Non-WWD Crashes on Controlled-access Highways

Variable and Category	WWD Crashes (n=398)		Non-WWD Crashes (n=294,420)	
	Frequency	Percentage	Frequency	Percentage
General Characteristics				
Crash Severity				
Fatal Crash	57	14.3	1229	0.4
Incapacitating	89	22.4	9,985	3.4
Non-Incapacitating	68	17.1	22,971	7.8
Possible Injury	18	4.5	14,430	4.9
PDO	164	41.2	245,281	83.3
Number of Persons				
One	69	17.3	72,093	24.5
Two	158	39.7	126,659	43.0
Three and More	171	43.0	95,668	32.5
Time Information				
Month of the Year				
January	30	7.5	28,291	9.6
February	34	8.5	24,052	8.2
March	38	9.5	21,871	7.4
April	34	8.5	21,413	7.3
May	34	8.5	25,406	8.6
June	24	6.0	26,327	8.9
July	30	7.5	23,842	8.1
August	23	5.8	22,415	7.6
September	36	9.0	21,252	7.2
October	31	7.8	24,398	8.3
November	43	10.8	26,303	8.9
December	41	10.3	28,850	9.8
Day of Week				
Weekday	227	57.0	217,963	74.0
Weekend	171	43.0	76,457	26.0
Time of the Day				
Morning (6-12)	40	10.1	82,006	27.9
Afternoon (12-18)	37	9.3	104,554	35.5

Evening (18-24)	106	26.6	66,237	22.5
Night (0-6)	215	54.0	41,623	14.1
Responsible Driver Characteristics				
Driver Age				
Young (less than 24)	84	21.1	66,514	22.6
Middle-aged (25 to 64)	219	55.0	184,104	62.5
Older (more than 65)	90	22.6	41,370	14.1
Driver Gender				
Male	268	67.3	176,557	60.0
Female	96	24.1	92,127	31.3
Driver Condition				
Apparently Normal	83	20.9	232,526	79.0
DUI	211	53.0	8,642	2.9
Asleep/Fainted/Fatigued	6	1.5	6,432	2.2
Illness	10	2.5	946	0.3
Vehicle Information				
Causal Unit (CU) Type				
Passenger Car	262	65.8	175,907	59.7
Pickup	60	15.1	30,699	10.4
SUV	39	9.8	31591	10.7
Van/Minivan	17	4.3	16230	5.5
Vehicle Age				
Less than 5 years	94	23.6	95,194	32.3
5 to 15 years	228	57.3	157,680	53.6
More than 15 years	48	12.1	16,389	5.6
Environmental Condition				
Setting				
Urban	287	72.1	231,093	78.5
Rural	111	27.9	63,327	21.5
Lighting Condition				
Daylight	74	18.6	182,046	61.8
Dawn/Dusk	9	2.3	10,271	3.5
Dark, Road Lit	138	34.7	44,459	15.1
Dark, Road Not Lit	175	44.0	56504	19.2
Weather Condition				
Clear/Cloudy	325	81.7	230,493	78.3
Precipitation	49	12.3	54,481	18.5
Roadway Condition				
Dry	314	78.9	214,986	73.0
Wet	70	17.6	48,878	16.6

2.4 Methodology

2.4.1 Firth's Penalized-Likelihood Logistic Regression

The aim of this Chapter is to identify the explanatory variables that differentiate WWD crashes from other crashes on controlled-access highways, which can be handled by the introduction of logistic regression analysis. Dependent variable in this study is the probability of WWD vs. non-WWD crashes, which represents a binary outcome warranting the use of binary logistic regression. When looking at the data, two conditions are visible: the rarity phenomenon and imbalanced data. First, for the rareness of the events, only 0.14% of crashes on target facilities are caused by WWD. This rareness of events in binary logistic regression is known to be especially difficult to explain and predict. Furthermore, most well-known statistical analysis methods, e.g., binary logistic regression, can be heavily affected by this phenomenon and, consequently, the probability of the rare event will be sharply underestimated (King and Zeng, 2001). Second, some categories for WWD crashes have very low frequency, which can cause problems in computations (Hosmer at a., 213). These issues might limit the applicability of the standard logistic regression, as it uses the MLE, which is known to suffer from the small-sample bias. In this situation, a penalized-likelihood approach is proposed (i.e., Firth's logistic regression), which can handle the shortcoming of MLE method due to small sample as well as rareness of events (Firth, 1993; Heinze and Schemper, 2002).

To penalize the MLE, Firth replaced the score function of the binary model by a modified score function as follows:

$$U(\beta_n)^* = U(\beta_n) + \alpha_n, \quad n = 1, \ldots, k \tag{1}$$

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 estimated, and α_n has the nth entry and is formulated as:

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

where *tr* is the trace function and $I(\beta)$ is the Fisher's information matrix, which is minus the second derivative of the log-likelihood. For a complete explanation of this model, readers are referred to Heinze and Schemper (2002). Using this method, the MLE estimate will be shrunk towards zero. It is believed that compared to the other classes of generalized linear models on small samples, Firth's method is precise in estimating coefficients and reliable in calculating confidence intervals in terms of coverage probabilities (Van der Paal, 2014).

After calculating parameter estimates for statistically significant variables, the corresponding odds ratios (OR) – as a relative measure of effect – were calculated. The OR can provide a better understanding of the direction and magnitude of the change in the probability of the dependent variable with one unit change in the specific variable. In other words, when OR is greater than one, the study group (here, WWD crashes) is more likely to have the specific characteristic (defined in the category) than the reference category. A similar explanation applies to OR of less than one.

2.4.2 Model Comparison

Given the difference in the score functions of the binary model and Firth's model, a comparison between the outputs of these two models can be made. In doing so, the log-likelihood of the full model (at convergence) as well as two popular information criteria (Akaike Information

Criterion, or AIC, and Bayesian Information Criterion, or BIC) for comparing maximum likelihood models were used. The AIC and BIC can be formulated as follows:

$$AIC = -2LL_{Full} + 2k \quad (3)$$

$$BIC = -2LL_{Full} + \ln(N) \times k \quad (4)$$

where LL_{Full} is the (penalized) log-likelihood of the full model with statistically significant explanatory variables, k is the number of parameters estimated in the final model, and N is the number of observations (294,818 observations). In addition to comparing the model fit, these two measures can also account for the complexity of the model by penalizing the criterion for the number of explanatory variables included in the model. This penalization is carried out by either $2k$ or $\ln(N) \times k$ terms in the equations. Having the models fit on the same dataset, the model with lower LL_{Full}, AIC, and BIC is considered to outperform the other.

Furthermore, a likelihood ratio test is suggested to determine whether the Firth's model is significantly better than the binary model. This test has previously been used by Chen and Chen (2011). To this end, the likelihood ratio test statistic is defined as follows:

$$2[LL_{Firth} - LL_{binary}] \quad (5)$$

where, LL_{Firth} and LL_{binary} are the log-likelihood at convergence of the Firth's model and binary model of the same dataset, respectively. This test statistic is χ^2 distributed with the degrees of freedom equal to the difference between the number of parameters estimated using each of the two models.

2.5 Results and Discussion

Previously, the descriptive statistics of the explanatory variables for each type of crash on controlled-access highways were presented. In this section, these variables will be put into one model for multivariate analysis in order to identify the effect of the explanatory variables on the type of crash altogether. In doing so, Firth's model was found more appropriate than binary model given the nature of the data. The empirical results of this study are presented next. These results include the parameter estimates obtained from Firth's model and the interpretation of these estimates. Moreover, the same dataset was used to fit a binary model and the parameter estimates for this model is also presented. AIC and BIC values for both of these models are calculated and a comparison between these two models are made.

The R software package "logistf" was exploited as a comprehensive tool to estimate the effect of various contributing factors on the probability of WWD crashes (Heinze, 2013). First, a model was fit with all possible contributing factors. Subsequently, a backward elimination procedure based on the penalized-likelihood ratio test (as is the suitable procedure for nested models) was employed to produce a final model that best explains the dependent variable. A forward selection process also yielded a similar result. Table 2.6 summarizes the analysis results of the Firth's model, including parameter estimates along with their corresponding standard errors and OR.

The analysis of the crash characteristics is performed by categorizing the information about each crash into four major groups – time information, responsible driver, vehicle information, and environmental condition. Each of these categories are discussed in the following subsections. The Wald chi-square statistic of 1,396.85 with 10 degrees of freedom, which is substantially larger than the respective chi-square values at any reasonable confidence level, demonstrates that the alternative hypothesis (i.e., "the current model is true") is accepted. Consequently, the explanatory variables given in the model affect the type of crash, or the model with independent variables is statistically better than the model with only the intercept (the null model).

The same data was used to develop a binary model and parameter estimates as well as ORs were calculated. Interestingly, the month of the year was not found significant in the binary model. Furthermore, the binary model could not converge when incorporating variables with low number of observations (e.g., Dawn/Dusk under Lighting Condition), so that the model removed observations with that specific characteristic in the model to make the model converge. For this reason, the parameter Illness under Driver Condition did not enter the final binary model, while it was found to be significant in the Firth's model. Having these two models (Firth's model and binary model) on the same data, AIC and BIC were calculated using equations 3 and 4 and are presented in Table 2.6. As can be seen in this table and clarified in Figure 2.3, Firth's model yields lower values for AIC, BIC, and log-likelihood at convergence, proving better fit compared to the binary model on our imbalanced data and rare event. A likelihood ratio test statistic of 1,338.72 with 2 degrees of freedom evidently shows that there exists a statistically significantly difference between the results obtained from the Firth's model and the binary model.

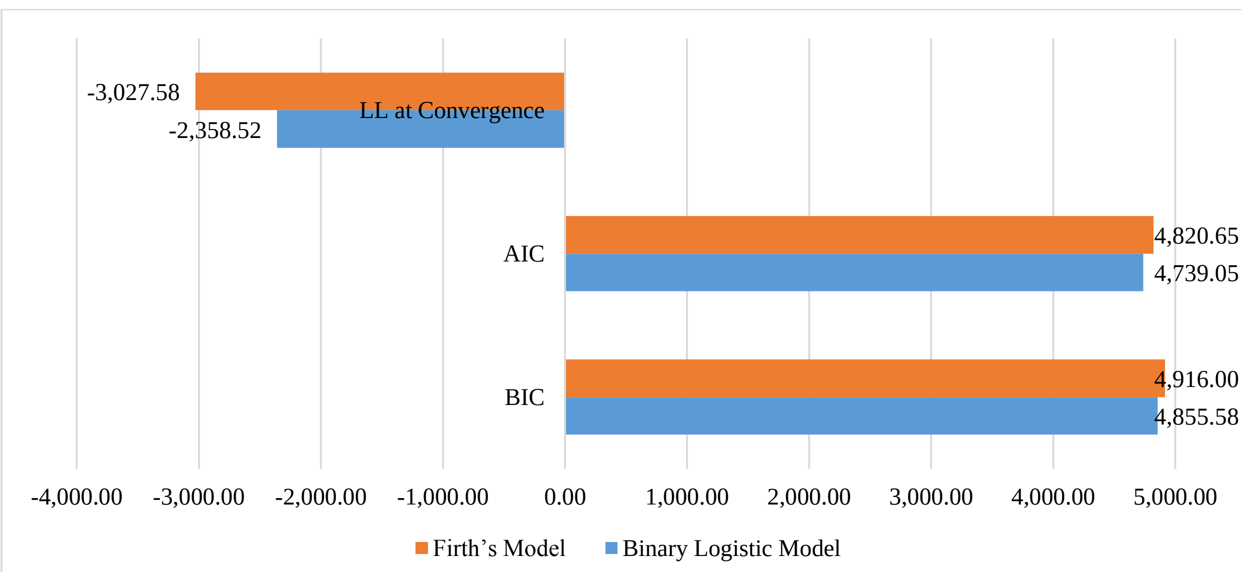


Figure 2.3 Comparison between LL, AIC, and BIC from Firth's and Binary Models

Table 2.6 Final Firth's and Binary Model Results

Explanatory Variable	Firth's Model			Standard Binary Logistic Model		
	β	**S.E.**	**OR**	**β**	**S.E.**	**OR**
Month of the Year						
January	Reference			Reference		
November	0.271*	0.164	1.31	Not Significant		
Time of the Day						
Morning (6-12)	Reference			Reference		
Afternoon (12-18)	-0.503**	0.199	0.60	-0.498**	0.200	0.61
Night (0-6)	0.683***	0.120	1.98	0.670***	0.120	1.95
Driver Age						
Middle-aged	Reference			Reference		
Older	1.555***	0.138	4.73	1.562***	0.138	4.77
Driver Condition						
Apparently Normal	Reference			Reference		
DUI	3.367***	0.122	28.99	3.318***	0.121	27.61
Illness	3.003***	0.323	20.14	Not Significant		
Vehicle Age						
Less than 5 years	Reference			Reference		
5 to 15 years	0.341**	0.118	1.41	0.353**	0.119	1.42
More than 15 years	0.884***	0.177	2.42	0.880***	0.178	2.41
Lighting Condition						
Daylight	Reference			Reference		
Dark, Road Not Lit	0.957***	0.166	2.60	0.969***	0.166	2.64
Dark, Road Lit	0.723***	0.163	2.06	0.723**	0.163	2.06
Constant	-8.504***	0.168	–	-9.446***	0.167	–
Number of Observations:	294,818			294,818		
LL at Convergence:	-2,358.52			-3,027.58		
AIC	4,739.05			4,820.65		
BIC	4,855.58			4,916.00		

Notes:
*** Significant at the 99% confidence interval
** Significant at the 95% confidence interval
* Significant at the 90% confidence interval

2.5.1 Time Information

The variables in this group describe the temporal distribution of the crashes in terms of month, day, and hour. The analysis of the crashes showed statistically significant differences in terms of the month of the year between the two types of crashes. The descriptive statistics shown in Table 2.5 reveals that WWD crashes are almost evenly distributed within the year, just like non-WWD crashes. However, statistical analysis of crashes indicate that crashes that happened in November are 1.31 times more likely to be WWD. Even though the data analysis showed that WWD crashes were more likely during this month, no specific reasons were found to explain this phenomenon. Further studies are needed to determine whether the same trend persists over a longer time period.

Four periods (categories) were considered for the time of day mainly because of the lighting condition. The hourly distribution also varied throughout the hours of the day, with the late-night and early-morning times comprising the highest frequency of WWD crashes. More specifically, evening and night periods account for more than 80% of the total WWD crashes. However, the results showed that crashes happened during the afternoon are less likely to result in WWD maneuvers (0.60 times) compared to those happened during morning hours. For the nighttime condition, this number increases to 1.98, implying the role of lighting condition and time of day in the probability of WWD crashes. This result is in line with some other studies (Cooner and Ranft, 2008; Zhou et al., 2015; Morena and Leix, 2012).

2.5.2 Responsible Driver

According to the estimation results presented in Table 2.6, driver age is found to significantly affect WWD versus non-WWD crashes on controlled-access highway. While statistically significantly different from other types of crashes, drivers older than 65 years are overrepresented when it comes to WWD. Specifically, according to the obtained OR, the odds of having a WWD crash is multiplied by 4.73 when the driver is older than 65, compared to middle-aged drivers as the reference group. This finding which is consistent with the studies by Braam (2005) and Lathrop (2010), is perhaps related to the diminished visual ability by aging that causes difficulties for this age group to see the signage and pavement markings, specifically during nighttime condition when lighting may be inadequate. The findings of a study by Gibbons (2012) could recognize a relationship between aging and nighttime driving behaviors signifying that older drivers have more difficulty detecting objects than younger drivers when the roadway is not lit and suggesting an interaction between these two variables.

The driver's physical/mental condition also delineates between WWD crashes and the other types of crashes since more than half of the WW drivers were DUI, whereas less than 3% of drivers in non-WWD crashes were intoxicated. Being statistically significant, intoxication (DUI) and illness can increase the probability of WWD crashes by 28.99 and 20.14 times, respectively. Previous studies have found extensive correlation between alcohol consumption and impaired driving that causes difficulties for drivers in perceiving roadway information (Christoforou et al., 2012; Kuypers et al., 2006).

2.5.3 Vehicle Information

When comparing WWD with non-WWD crashes, vehicle age was found to be a statistically significant factor affecting WWD. As shown in Table 2.5, WWD vehicles tend to be older compared to non-WWD vehicles. This difference is also reflected in the results, so that the odds of having WWD crash increases by 41% (OR=1.41) when a vehicle between 5 and 15 years is being driven and this number increases to 142% (OR=2.42) when a vehicle more than 15 years old is being driven.

2.5.4 Environmental Condition

This group identifies the other environmental conditions for crashes on controlled-access highways. Based on the results, the type of setting (urban vs. rural) did not enter the final model to make a significant difference among different types of crashes on our target facilities, although this factor was found to be important by Zhou et al. (2015). Lighting conditions were also found to affect WWD crashes so that these kinds of crashes are more prevalent when it is dark. In other words, driving during darkness and when the roadway is not lit can significantly increase the likelihood of WWD crashes by 2.60 times. However, by the provision of any kind of lighting, this number decreases to 2.06.

2.6 Conclusions and Recommendations

This part of dissertation aimed to identify and verify the true WWD crashes using ten years of Illinois crash data (2004-2013) and five years of Alabama crash data (2009-2013). These verified WWD crashes were then combined with other non-WWD crashes within the same time period on controlled-access highways to affect WWD crashes. Given the rareness of the WWD events (around 0.14% of total crashes in our dataset), the Firth's penalized-likelihood logistic regression model was suggested. Using this method, the effect of all the confounding variables was examined and the corresponding OR to indicate the relative effect of the significant variables was calculated. The summary of the results from this model (Table 2.6) clearly indicates a variety of factors that can affect the probability of WWD crashes on controlled-access highways. The estimates of the binary model was also provided. Two information criteria (AIC and BIC) as well as log-likelihood at convergence were calculated for both models. The comparison between these three values shows that given our dataset, the Firth's model outperforms the binary model.

According to the results from the fitted model, several factors were found to affect the probability of WWD crashes, including drivers older than 65 (OR=4.73), driver condition either having an illness (OR=20.14) or being under the influence of alcohol and drugs (OR=28.99), driving during the night (OR=1.98) when darkness is the prevalent condition and there will probably not be ample lighting, either without lighting provided (OR=2.60) or with some kind of lighting provided (OR=2.06), and driving vehicles aged between 5 and 15 years (OR=1.41) or older than 15 years (OR=2.42).

Based on the empirical findings of the present study and, specifically, obtained ORs, several countermeasures and recommendations can be suggested to help mitigate the WWD issue on controlled-access highways. These countermeasures can be grouped into three categories of education, engineering, and enforcement. Educational programs and behavior-based countermeasures should specially target older and DUI drivers given that these two driver groups were significantly overrepresented with higher ORs. Considering that drunk driving occurs most often during night, it was expected that this variable would be significant. As for the driver age, the issue might be related to the diminished eyesight and contrast sensitivity of older drivers due to the aging process. Moreover, as drivers grow older, some other abilities such as attention and perceptual processes decrease and the possibility of experiencing impairment while driving increases (Glisky, 2007), which in turn intensifies the possibility of WWD movements. One key point in educating older drivers is that this age group does not need more information about traffic rules, rather, they need to understand if they are able to safely drive (Keskinen, 2014). This has been the motivation for some states (e.g., Michigan) to provide a self-assessment tool for senior drivers and help them learn about their abilities to drive. Concerning the increasing percentage of older population in both Illinois and Alabama, this age group should be given special attention.

The finding also substantiates the significant role of DUI driving and necessitates the establishment of relevant prevention campaigns and the promotion of stricter rules. In 2014, Alabama joined other 20 states in the U.S. to legislate the use of ignition interlock devices (IIDs) for the first-time convicted drunk drivers. Having the 2014 WWD data can help evaluate the effectiveness of this newly acted law on the number of WWD crashes caused by intoxicated drivers. Studies have shown promising results with the use of IIDs in reducing the recidivism rate among alcohol impaired drivers (Pour-Rouholamin and Zhou, 2014; Raub et al., 2003; Rauch et al., 2011). The present study identified the statically significantly increased probability of WWD crashes during night (2.21). Other than the prevalence of DUI drivers during these hours, the problem with lighting (Pour-Rouholamin and Zhou, 2015) as well as possible drowsiness and fatigue can worsen the situation.

Vehicle age was also the factor that was significant in the Firth's model. The importance of this parameter in the final model can define the economic status of the families based on social processes, such as education. A study by Mohammadian and Miller (2003) demonstrated that people with higher level of education are more likely to purchase new vehicles, which reflects their higher salaries compared to people with less formal education. Finally, WWD crashes could be distinguished by airbag deployment. This variable is related to the type of crash, which is severe and more likely to cause deployment of airbags.

Similar to most studies, this study also has some limitations. For example, the data used in this study is just from two U.S. states. Incorporating more data from other states not only bolsters the sample but also can lead to a more comprehensive result and help in developing nationwide countermeasures and strategies. Another limitation of this study comes from the inevitable role of human error in data collection process by police officers that affects the level of detail and accuracy for the obtained significant variables.

3 Analysis of Driver Injury Severity in Wrong-Way Driving Crashes

This Chapter focuses on identifying the effect of various contributing factors on the severity of injury sustained by WW drivers. For more than five decades, WWD has been notorious as a traffic safety issue for controlled-access highways. Numerous studies and efforts, as reviewed in Chapter 2, have tried to identify factors that contribute to WWD occurrences at these sites in order to delineate between WWD and non-WWD crashes. However, none of the studies investigate the effect of various confounding variables on the injury severity being sustained by the at-fault drivers in a WWD crash. This Chapter tries to fill this gap in the existing literature by considering possible variables and taking into account the ordinal nature of injury severity using three different ordered-response models: ordered logit or proportional odds (PO), generalized ordered logit (GOL), and partial proportional odds (PPO) model. The findings of this study reveal that a set of variables, including driver's age, condition, seatbelt use, time of day, airbag deployment, type of setting, surface condition, lighting condition, and type of crash, has a significant effect on the severity of a WWD crash. Additionally, a comparison was made between the three proposed methods. The results corroborate that the PPO model outperforms the other two models in terms of modeling injury severity using this database. Based on the findings, several countermeasures at the engineering, education, and enforcement levels are recommended.

3.1 Introduction

According to the National Transportation Safety Board (NTSB) Special Investigation Report, three possible mechanisms describe how a driver can end up driving in the wrong direction on controlled-access highways: (1) entering an exit ramp, (2) making a U-turn on the mainline, and (3) using an emergency turnaround through the median (NTSB, 2012). In addition to these mechanisms, a driver who crosses over the median and travels for some distance is also considered to make a WWD movement, despite accounting for a small number of WWD events. Even a short distance traveled means the movement is categorized separately from a cross-median crash where, instead, the driver collides with other vehicle(s) immediately after crossing over the median to an opposing traffic lane.

Regardless of the type of entrance, WWD crashes tend to be more severe and have a greater likelihood of resulting in death or injury when compared to other types of crashes, as also identified in the previous Chapter. Past studies (Copelan, 1989; Cooner et al., 2004a; Cooner et al., 2004b) showed that although a very small percentage of overall traffic crashes were caused by WWD, they result in a relatively large percentage of fatal crashes. Drivers and passengers in both WW and right-way (RW) vehicles can be killed in WWD crashes. For example, of the 49 fatal WWD crashes on the New Mexico interstate highway system between 1990 and 2004, 35 drivers and 11 passengers in the WW vehicles were killed, and 18 drivers and 15 passengers in vehicles traveling in the correct direction were killed, as well (Lathrop et al., 2010). These statistics and accompanying safety issues corroborate the need for analyzing the injury severity of WWD crashes more in depth.

This part of dissertation analyzes the injury severity sustained by the WW (at-fault) drivers in a WWD crash considering the inherently ordered nature of injury severity. To this end, 398

WWD crashes[1] on controlled-access highways identified through the previous Chapter were investigated from the states of Illinois (10 years of data) and Alabama (5 years of data), based on the availability of the data. Three ordered-response models, including ordered logit or proportional odds (PO), generalized ordered logit (GOL), and partial proportional odds (PPO) models were nominated as possible analysis tools. A comparison between these three nominated models was also made to select the best modeling approach for WW driver injury severity analysis. Hence, the main objective of this Chapter is to identify the factors that significantly affect the injury severity of WW drivers in such events. These factors fall under four major categories, which include responsible driver characteristics, temporal variables, vehicle information, and crash variables. The results of this Chapter can provide useful insights into this safety issue and provide appropriate safety countermeasures to address this rare, particular traffic safety problem.

The rest of this Chapter is organized as follows: A review of the prior research on WWD crashes as well as methodological approaches is provided in section 3.2. Section 3.3 elaborates on the databases used for analysis along with descriptive statistics of the multiple possible contributing factors. Ordered-response models (i.e., PO, GOL, and PPO models), their formulations, assumptions, and applications are discussed in section 3.4. In section 3.5, the proposed model is applied to the WWD crash dataset and parameter estimates and average direct pseudo-elasticities as well as model goodness-of-fit tests are presented. Finally, section 3.6 concludes this Chapter and provides safety recommendations.

[1] While the sample size might look small, it should be noted that several studies have already used small sample sizes mainly because of the rareness of this kind of crash. For instance, Kemel (2015), Zhou et al. (2012), and Lathrop et al. (2010) used sample sizes of 266, 217, and 49 for their analyses, respectively.

3.2 Literature Review

As reviewed in Chapter 2, previous research has focused on identifying which factors are correlated with the occurrence of WWD crashes on controlled-access highways. Many States have conducted studies on WWD crashes, including California, Texas, North Carolina, New Mexico, Michigan, Illinois, Alabama, and Florida. In addition to the studies in the U.S., other countries such as Finland, Switzerland, Netherlands, Japan, and France have also worked on WWD issues. The results of these efforts are summarized in Table 3.1.

Table 3.1 Summary of Some of the Studies on WWD

State	Study Period	Contributing Factors	References
Conducted in the U.S.			
California	1983–1987	Darkness; Intoxicated drivers; Half and full diamond interchanges; Trumpet interchanges	Copelan 1989
Texas	1997–2000	Early morning hours; Male drivers; Drivers less than 34 years old; Intoxicated drivers; Left-side exit ramps; Urban areas	Cooner et al., 2004a; Cooner et al. 2004b
North Carolina	2000–2005	Alcohol-related; Older drivers; Two-quadrant parclo interchanges; Full diamond interchanges	Braam, 2006
New Mexico	1990–2004	Darkness; Intoxicated drivers; Older drivers; Male drivers; Passenger cars	Lathrop et al., 2010
Michigan	2005–2009	Darkness; Intoxicated drivers; Younger drivers; Parclo interchanges	Morena and Leix, 2012
Illinois	2004–2009	Darkness; Older Driver; Male drivers; Intoxicated drivers; Time of day; Weekends; Urban areas; Type of interchange	Zhou et al., 2012
Alabama	2009–2013	Time of the day; Older drivers; Intoxicated drivers; Driver residency distance; Vehicles older than 15 years; Roadway condition	Pour-Rouholamin et al., 2016
Florida	2003–2010	Driver age; Driver gender; Urban areas; Darkness; Rainy and foggy weather; Vehicle use; Day of week	Ponnaluri, 2016b
Conducted in Other Countries			
Finland	1999–2002	Older drivers; Intoxicated drivers; Ramp configuration	Karhunen, 2003
Switzerland	2003–2005	Young drivers; intoxicated drivers; Older drivers; Darkness; Female drivers	Scaramuzza and Cavegn, 2007
Netherlands	1996–1998	Older drivers; Younger drivers; Intoxicated drivers	SWOV, 2009
Japan	2005–2009	Older drivers; Younger drivers; Darkness; Type of interchange	Xing, 2014
France	2009–2012	Darkness; Older drivers; Intoxicated drivers; Local drivers; Driving older vehicles; Passenger cars; Driving alone without any passengers	Kemel, 2015

Based on these studies, WWD crashes are more prevalent during non-daylight hours, particularly in the early morning. In Texas, 52% of all WWD crashes occurred during the six hours from 12:00 midnight to 6:00 a.m.; however, only 10.4% of overall freeway crashes occurred during that time period. Past studies (Copelan, 1989; Cooner et al., 2004a; Braam, 2006; NTTA, 2009) indicated that WWD crashes occurred more frequently during the weekends; however, the monthly distribution of WWD crashes varies among different states (Braam, 2006; Cooner and Ranft, 2008; Pour-Rouholamin et al., 2016) and countries (ITARDA, 2002), showing no consistent trend.

Prior research conducted in both Illinois (Zhou et al., 2012) and Texas (Cooner et al., 2004a; Cooner et al., 2004b) found that WWD crashes occur in urban areas more often than in rural areas. Studies in Texas also found that most of the WWD collisions occurred in the inside lane of the correct direction and at locations with left-side exit ramps or one-way streets that transitioned into a freeway section. A study in the Netherlands from 1996 to 1998 found that 79% of WWD crashes took place on the main line of the freeway, 5% on merge/diverge lanes, and 17% on ramps (SWOV, 2009).

The characteristics of WW drivers, such as driver sobriety, age, and gender, have been discussed in many past studies. A significant portion of WWD crashes on controlled-access highways was caused by those who were driving under the influence of alcohol or drugs. Most past studies concluded that young drivers and older drivers are overrepresented in the WWD crashes. Most of the crashes caused by drivers in the young and middle-age range occurred because of distraction, while most crashes caused by drivers in the senior age range occurred because of some physical illnesses such as dementia or confusion (ITARDA, 2002). The findings of a study by Gibbons et al. (2012) established a relationship between aging and nighttime driving behaviors, signifying that older drivers have more difficulty detecting objects than younger drivers when the roadway is not lit well. An overwhelming majority of WWD crashes involved male drivers, and most of the female drivers were in young age groups (ITARDA, 2002).

Despite all the efforts to characterize WWD crashes and delineate between these types of crashes and the others, there is no research into the factors that affect the driver's injury severity within the WWD domain. Along with recognizing the factors that affect the probability of WWD crashes, it is also crucial to identify the extent to which these factors might affect the severity of injuries sustained by the WW driver in terms of safety implications. To this end, several methods have already been used whether they consider the ordered nature of severities or not.

There is an extensive body of literature on application of statistical modeling in transportation science (Theofilatos et al., 2016; Tasic and Porter, 2016; Dailisan and Lim, 2016; Lemoine et al., 2016; Roshandeh et al., 2016; Amoh-Gyimah et al., 2016; Al-Ayyash et al., 2016; Ghasemi et al., 2016; Anastasopoulos, 2016; Pour-Rouholamin and Zhou, 2016b; Hong et al., 2016; Khalilikhah et al., 2016; Soltani-Sobh et al., 2016; Dimitriou and Vlahogianni, 2015; Khalilikhah et al., 2015; Soltani-Sobh et al., 2015; Williamson et al., 2015; Heaslip et al., 2015; Soltani-Sobh, 2015; Heaslip et al., 2014; Chen and Tarko, 2014; Karoń and Mikulski, 2012; Dubey et al., 2012; Shafabakhsh et al., 2012; Wang et al., 2011). Over the past years, numerous disaggregate modeling approaches have been employed to quantify the effect of several contributing factors on various levels of injury severity. Given the ordered nature of the injury severity in crashes (representing an ordinal outcome), these methodological approaches generally fall under two main categories (based on whether this nature is considered or not): ordered-response models and unordered-response models. Ordered logit/probit (Khattak et al., 2002; Kockelman and Kweon, 2002; Khattak and Rocha, 2003; Lee and Li, 2014), generalized ordered logit (Wang and Abdel-Aty, 2008; Kaplan and Prato, 2012; Mergia et al., 2013; Abegaz et al., 2014), and mixed generalized ordered logit (Eluru and Bhat, 2007; Eluru et al., 2008) models are among the models that do consider the ordered nature of crash severity. However, there is an increasing tendency towards using unordered response models, as well. Nested logit (Abdel-Aty, 2003; Patil et al., 2012; Haleem and Abdel-Aty, 2010; Hu and Donnell, 2010), multinomial logit (Tay et al., 2011; Celik and Oktay, 2014; Geedipally et al., 2011; Xie et al., 2012), and mixed logit models (Kim et al., 2013; Romo et al., 2013; Klassen et al., 2014) have also been used to provide in-depth insight into significant contributing factors to crash injury severities. This part of the study considers the ordered nature of crash injury severity; thus, it employs ordered-response models to examine the effect of various contributing factors to the driver injury severity in WWD crashes on controlled-access highways (freeways, expressways, Interstate highways).

3.3 Data

The WWD crash records in this study mainly come from the results of two major WWD studies in Illinois (Zhou et al., 2012; Zhou and Pour-Rouholamin, 2015) and Alabama (Zhou et al., 2016). The process of identifying and verifying WWD crashes are explained in detail in Chapter 2. Both databases encompass three major levels of crash characteristics including person, vehicle, and environment, along with corresponding crash severity. As a reminder, after filtering out non-WWD crashes and screening out a few verified WWD crash records with insufficient information and obviously incorrect values for the studied parameters, altogether 398 WWD crash records (305 records in Illinois and 93 records in Alabama) were collected for further severity analysis. The crash severity used in both the IDOT and CARE databases is in the 5-level scale of KABCO in which fatality is coded as “K,” incapacitating injury as “A,” non-incapacitating injury as “B,” possible (but not evident) injury as “C,” and no injury as “O.” For both databases, if a driver dies within 30 days of a crash due directly to that crash, the severity is defined as a fatality and must be coded as “K.”

A review of the severity of injuries sustained by drivers in these crashes revealed that 212 drivers were not injured, 9 drivers were possibly injured, 61 complained about minor injuries, 74 incurred incapacitating injuries, and 42 were fatally injured either at the scene or within 30 days of the crash. In this study, due to the severe nature of WWD crashes and in order to ensure a sufficient number of observation in each crash severity category, the 5-level scale of KABCO was converted to a 3-level scale of no injury to the driver (comprising property damage only crashes) (53.27%), minor injury comprising C- and B-level injuries (17.59%), and severe injuries (comprising A-injuries and fatalities) (29.15%). The explanatory variables used in this severity study are cross-tabulated with these 3-level injury severities and are presented in Table 3.2. It should be noted that the Other/Unknown categories for the variables are not presented in this table; therefore, the total number for some variables under the columns may not sum up to the corresponding injury severity frequency.

Table 3.2 Description of Explanatory Variables

Explanatory Variable	No Injury		Minor Injury		Severe Injury		Total
Total	212	53.27%	70	17.59%	116	29.15%	398
Responsible Driver Characteristics							
Age							
Young (Less than 24)	39	46.43%	15	17.86%	30	35.71%	84
Middle-aged (25 to 64)	112	51.14%	38	17.35%	69	31.51%	219
Older (65 and over)	56	62.22%	17	18.89%	17	18.89%	90
Gender							
Male	129	48.13%	54	20.15%	85	31.72%	268
Female	50	52.08%	16	16.67%	30	31.25%	96
Condition							
Normal	50	60.24%	17	20.48%	16	19.28%	83
DUI	104	49.29%	36	17.06%	71	33.65%	211
Seatbelt Status							

Used	152	54.87%	58	20.94%	67	24.19%	277
Not used	8	22.22%	5	13.89%	23	63.89%	36
Temporal Variables							
Season							
Spring	50	47.17%	23	21.70%	33	31.13%	106
Summer	36	46.75%	12	15.58%	29	37.66%	77
Autumn	63	57.27%	19	17.27%	28	25.45%	110
Winter	63	60.00%	16	15.24%	26	24.76%	105
Day of Week							
Weekday	114	50.22%	43	18.94%	70	30.84%	227
Weekend	98	57.31%	27	15.79%	46	26.90%	171
Time of Day							
Morning	23	57.50%	7	17.50%	10	25.00%	40
Afternoon	23	62.16%	8	21.62%	6	16.22%	37
Evening	56	52.83%	21	19.81%	29	27.36%	106
Night	110	51.16%	34	15.81%	71	33.02%	215
Vehicle Information							
Number of Vehicles							
One	47	67.14%	13	18.57%	10	14.29%	70
Two	133	53.20%	39	15.60%	78	31.20%	250
Three and more	32	41.03%	18	23.08%	28	35.90%	78
Type							
Passenger Car	140	53.44%	45	17.18%	77	29.39%	262
Pickup	29	48.33%	10	16.67%	21	35.00%	60
SUV	19	48.72%	8	20.51%	12	30.77%	39
Van/Minivan	7	41.18%	5	29.41%	5	29.41%	17
Age							
Less than 5	45	47.87%	17	18.09%	32	34.04%	94
5 to 15 years	117	51.32%	44	19.30%	70	30.71%	228
15 years and over	23	47.92%	8	16.67%	14	29.17%	48
Airbag Status							
Not deployed	49	74.24%	10	15.15%	7	10.61%	66
Deployed	50	29.07%	42	24.42%	80	46.51%	172
Crash Variables							
Type of Setting							
Urban	160	55.75%	48	16.72%	79	27.53%	287
Rural	52	46.85%	22	19.82%	37	33.33%	111
Weather Condition							
Clean/Cloudy	169	52.00%	54	16.62%	102	31.38%	325
Rain	30	61.22%	10	20.41%	9	18.37%	49
Surface Condition							
Dry	158	50.32%	55	17.52%	101	32.17%	314
Wet	43	61.43%	15	21.43%	12	17.14%	70
Lighting Condition							
Daylight	45	60.81%	14	18.92%	15	20.27%	74

Dawn/Dusk	5	55.56%	2	22.22%	2	22.22%	9
Dark – Not Lit	62	44.93%	23	16.67%	53	38.41%	138
Dark – Lit	98	56.00%	31	17.71%	46	26.29%	175
Head-on Crash?							
No	160	72.07%	36	16.22%	26	11.71%	222
Yes	52	29.55%	34	19.32%	90	51.14%	176

3.4 Method

3.4.1 Econometric Model

In this study, driver injury severity was considered as a 3-level ordinal outcome from the lowest, which is No Injury, to the highest, which is Severe Injury. There are three different ordered-response models that have previously been used in the literature. These models are ordered logit (or proportional odds – PO) model, generalized ordered logit (GOL) model, and partial proportional odds (PPO) model. The difference between these models comes from the parallel regression assumption (proportional odds assumption) and how these models handle it. These models are explained more in detail in the following.

The simplest form of these three ordered-response models is the PO model. If *j* denotes the crash severity level (1=no injury; 2=minor injury; 3=severe injury) and *J* represents the number of severity levels (here *J*=3), then the standard form of the PO model is as follows:

$$Pr(Y_i > j) = \frac{exp(\alpha_j + X_i\beta)}{1+[exp(\alpha_j + X_i\beta)]} \qquad j = 1,2,\dots,J-1 \tag{1}$$

where Y_i represents the injury severity sustained by WW driver in crash i, X_i is a vector of explanatory variables that affect the severity of injury, β is a vector of the corresponding parameter estimations, and α_j is the cutoff term for the thresholds in the model. This model tries to estimate β's and α_j's values (Long, 1997), while assumes β's are constant across different severity levels for each variable and the only difference between *J*-1 regression lines is the parameter α. This is called the parallel regression assumption and is often violated in reality (Boes and Winkelmann, 2006). Based on this assumption, each variable may either increase or decrease the likelihood of higher injury severities.

In order to overcome the issue that arose from parallel regression assumption, the GOL model is developed that relaxes this assumption for all the variables in the model. This model can be formulated as follows:

$$Pr(Y_i > j) = \frac{exp(\alpha_j + X_i\beta_j)}{1+[exp(\alpha_j + X_i\beta_j)]} \qquad j = 1,2,\dots,J-1 \tag{2}$$

where β_j is the vector of parameter estimations that, despite the PO model, do vary across equations for different crash severities (Williams, 2006). The other factors were previously introduced. However, the adoption of this method may result in an unnecessary increase in the number of calculated β's as not all the variables in the model will violate this assumption. In other words, just one or more variables in the model may necessitate considering varying β's across those severity levels. This situation has appropriately been handled in the PPO model. The PPO model accounts for the fact that not every single variable will violate the parallel line assumption and is specified as:

$$Pr(Y_i > j) = \frac{exp(\alpha_j + X_{1i}\beta_1 + X_{2i}\beta_2)}{1+[exp(\alpha_j + X_{1i}\beta_1 + X_{2i}\beta_2)]} \qquad j = 1,2,\dots,J-1 \tag{3}$$

where β_1 and β_2 are the vectors of parameter estimations that do and do not violate the parallel line assumption, respectively. The corresponding vector of independent variables that do and do not violate this assumption are X_{1i} and X_{2i}, respectively. This model has previously been employed by some studies (Wang and Abdel-Aty, 2008; Quddus et al., 2010; Kaplan and Prato, 2012).

The identification of the variables that violate the parallel regression assumption can be fulfilled using several tests, such as the likelihood ratio test, the Wolfe Gould test, or the Brant test. In this study, a Brant test (Brant, 1990) is proposed prior to model estimation in order to determine whether any of the variables violates this assumption. This test estimates the coefficients for the underlying binary logistic regressions and examines the equality of all parameter estimates for individual variables using a chi-square statistic. The statistical significance of the test statistic is the indication of an assumption violation for that particular variable.

3.4.2 Elasticity

Elasticities can be calculated in order to quantify the effect of significant variables on the probability of severities. This is because the interpretation of the results from ordered-response models needs more attention as the sign and value of the β's do not always determine the direction and magnitude of the effect of the intermediate levels for crash severity (Kaplan and Prato, 2012). It is worth mentioning that elasticities are applicable to continuous variables, whereas – given the nature of explanatory variables in this study that are dummy variables taking the value of 0 or 1 – direct pseudo-elasticities can instead be used for each injury severity and each crash record. This measure is calculated as the change in the percentage of the crash severity probability when the dummy variable is switched from 0 to 1 or vice versa. Direct pseudo-elasticity can be computed as (Kim et al., 2013):

$$E_{x_{jnk}}^{Pr(Y_i>j)} = \frac{Pr(Y_i>j)[Given\ x_{jnk}=1] - Pr(Y_i>j)[Given\ x_{jnk}=0]}{Pr(Y_i>j)[Given\ x_{jnk}=0]} \quad (4)$$

where $Pr(Y_i > j)$ is defined by equations 1, 2, or 3 (whichever applies) and x_{jnk} is the k^{th} explanatory variable associated with the injury severity j for the individual crash n. The average direct pseudo-elasticities can then be calculated for each injury severity to represent the whole dataset (Kim et al., 2010).

3.4.3 Model Comparison

After selecting the appropriate model based on the Brant test results, the other two models can also be fit on the same dataset and a performance assessment study can be conducted. To this end, three different criteria are proposed to check the performance of the ordered-response models used. These criteria, which are employed to compare maximum likelihood models, include log-likelihood of the full model with statistically significant explanatory variables (LL_{Full}), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). The formulations and explanations of these criteria are previously discussed in Chapter 2.

3.5 Results and Discussion

Before estimating the parameters, calculating the associated average direct pseudo-elasticities, and interpreting the results, the first step is to examine the parallel regression assumption to determine the appropriate ordered-response model to use (PO, GOL, and PPO). As mentioned earlier, in this study, a Brant test was employed to examine whether the entire model (all the variables) or any of the variables violate the parallel regression assumption. The results of the Brant test demonstrated that three variables (older drivers, deployed airbag, and head-on collision) violate this assumption, hence requiring the development of PPO model. Table 3.3 summarizes the results of the developed PPO model, including parameter estimates as well as the average direct pseudo-elasticities.

Table 3.3 Estimation Results and Average Direct Pseudo-Elasticities

Explanatory Variable	Parameter Estimates		Average Direct Pseudo-Elasticities		
	No vs. Min. & Sev.	No & Mi. vs. Sev.	No Injury	Minor Injury	Severe Injury
Responsible Driver Characteristics					
Age					
Older [a]	-0.298**	-0.646**	13.9%	21.0%	-45.9%
Condition					
DUI	0.394**	0.394**	-18.4%	9.5%	27.9%
Seatbelt Status					
Not used	1.195***	1.201***	-55.6%	28.9%	85.4%
Temporal Variables					
Time of Day					
Afternoon	-0.263*	-0.263*	11.7%	-7.0%	-18.7%
Night	0.340**	0.340**	-15.1%	9.2%	20.7%
Vehicle Information					
Airbag Status					
Deployed [a]	1.272***	1.272***	-59.2%	31.3%	90.5%
Crash Variables					
Type of Setting					
Rural	0.375**	0.375**	-17.4%	9.2%	26.7%
Surface Condition					
Wet	-0.499**	-0.499**	23.2%	-12.3%	-35.5%
Lighting Condition					
Dark – Not Lit	0.492**	0.492**	-22.9%	12.1%	35.0%
Dark – Lit	0.179*	0.179*	-8.3%	4.4%	12.7%
Head-on Crash?					
Yes [a]	1.491***	1.695***	-69.4%	20.0%	120.6%
Constant	-1.455***	-2.561***	–	–	–
Number of Observations		398			
Log-likelihood at Constant		-370.420			
Log-likelihood at Convergence		-284.750			
McFadden's Pseudo R^2		0.2313			
AIC		601.500			
BIC		665.283			

Notes:
*** Significant at the 99% confidence interval
** Significant at the 95% confidence interval
* Significant at the 90% confidence interval
[a] Explanatory variable violating parallel line assumption

The Wald chi-square statistic of 113.58 with 14 degrees of freedom—which is substantially larger than the respective chi-square values at any reasonable confidence level—demonstrates that the presence of exogenous variables significantly improves the quality of the model's estimation. The McFadden's pseudo R-square of 0.2313 indicates the model enjoys a very good predictive strength. According to Louviere et al. (2000), a model with a McFadden's pseudo R-square value between 0.2 and 0.4 represents a high predictive power. The same dataset was used to fit the other two ordered-response models, which were PO and GOL, to make a comparison between the performances of these models. As previously mentioned, log-likelihood of the full models (at convergence) along with AIC and BIC were used to this end. These three parameters were calculated and presented in Table 3.4. As can be seen in this table, the PPO model provides the lowest LL_{Full}, AIC, and BIC values compared to the other two models in this study. Based on these numbers, the PPO model evidently outperforms both PO and GOL models in analyzing the driver injury severity in WWD crashes.

Table 3.4 LL at Convergence, AIC, and BIC of PO, GOL, and PPO Models

Model	Criterion		
	LL_{Full}	AIC	BIC
PO	-299.975	627.949	683.760
GOL	-286.224	612.449	692.178
PPO	-284.750	601.500	665.283

Considering the specific estimation results in Table 3.3, the parameter age is found to significantly affect the injury severity of drivers in WWD crashes with varying effects across injury severity levels. Accordingly, compared to middle-aged drivers as the reference group, older drivers (65 years and older) are less affected by severe injuries. Specifically, the probability of incurring severe injuries for this age group shows a decrease of 45.9%, while the probability of no injuries and minor injuries are increased by 13.9% and 21.0%, respectively. This finding can be explained so that as the drivers grow older, they follow more cautious and conservative driving behaviors by driving at safer speeds. Researchers have reported various findings on the effect of drivers’ ages on the sustained severity by types of crashes. For example, some studies (Lee and Li, 2014; Lopez et al., 2014) have shown that young drivers are more likely to be severely injured in single-vehicle crashes compared to older drivers, as they are more likely to make errors and get involved in single-vehicle crashes. On the other hand, Russo et al. (2014) identified older drivers as more likely to suffer from more severe injuries in multi-vehicle crashes due to their physiological characteristics and attributes.

Driving under the influence was found as another significant parameters affecting the injury severity of WW drivers. It was determined that driving while intoxicated increases the probability of severe injuries by 27.9%, minor injuries by 9.5%, and decreases the probability of no injuries by 18.4%. Interestingly, more than half of the at-fault drivers in WWD crashes were identified as DUI. Wu et al. (2014) indicated that drivers who were DUI showed delayed perception and reaction times that made them more likely to suffer fatality when getting involved in crashes, including WWD. Stübig et al. (2012) demonstrated that alcohol-intoxicated road users experience higher injury severities due to the higher impact speed difference compared to sober drivers. Additionally, intoxicated drivers may be less likely to take proper evasive/corrective actions at the moment of the crash, which subsequently increases the severity of the crash (Behnood and Mannering, 2015). This result is consistent with the findings by Khorashadi et al. (2005) and Zhang et al. (2000).

Two safety features installed in the vehicles, including the seatbelt and airbag, were both found to significantly affect the severity of injuries sustained by the at-fault drivers in WWD crashes. The sign of the parameter estimates for seatbelt use as well as the associated elasticities in Table 3.3 obviously highlight the critical role of wearing a seatbelt in reducing the severity of

WWD crashes. Based on the results, not wearing a seatbelt considerably increases the likelihood of experiencing minor and severe injuries by 28.9% and 85.4%, respectively. Abu-Zidan et al. (2012) remarked that seatbelt usage not only reduces the severity of the vehicle occupant's injury, but also reduces the hospitalization duration as well as the likelihood of operations on vehicle occupants. Furthermore, seatbelt usage prevents ejection of drivers from the vehicles after the crash, which is believed to be one of the main causes of higher injury severities (Abu-Zidan and Eid, 2015), including WWD (Zhou et al., 2015), although driver ejection was not considered in this study due to its incomplete/inaccurate attributes in the database.

Airbag deployment, however, shows varying effects on injury levels. Interestingly, deployed airbags was found to be associated with increased probability for both minor and severe injuries by 31.3% and 90.5%, respectively. A decrease of 59.2% in the probability of no injuries is also reasonable, as the airbag itself may cause some minor injuries (Savolainen and Ghosh, 2008). It should be noted that out of 80 severe crashes that caused airbag deployment, 24 resulted in fatalities and 56 in A-injuries. This means that the direction of this parameter estimate and the associated obtained elasticity toward a severe crash category in the model is due mainly to A-injury crashes. Airbags are designed to work efficiently in combination with the three-point seatbelts. If there is no such seatbelt in use, airbag deployment can itself permit otherwise preventable injuries that may explain the increase in the probability of minor and severe injuries (Wallis and Greaves, 2002). Cummins et al. (2011) conducted a comprehensive study on the role of seatbelt use and airbag deployment in the severity outcome of crashes using a database of around 185,000 patients involved in crashes between 1988 and 2004. The analysis of the data identified that the use of seatbelts and airbag deployment reduced the mortality rate by more than 50% and 32%, respectively.

The obtained results indicate the significant effect of the time of day on the driver injury severity in WWD crashes. It is determined that the occurrence of a WWD crash during afternoon and nighttime conditions have various effects on injury severity so that the former decreases the probability of severe injuries while the latter shows an inversed effect. This change in the severity is more pronounced for nighttime conditions so that the probability of severe injuries during the night increases by a factor of 20.7%. To explain this finding, it should be noted that generally, the probability of WWD crashes is significantly higher during the night. For example, Pour-Rouholamin et al. (2016) found a 5.5-time increase in the probability of WWD crashes at night. Moreover, factors like sleepiness, glare, dark adaption, reduced visibility of roadway, signs and markings, and a higher proportion of drunk drivers contribute to higher injury severities at nighttime (Bella et al., 2014). Based on the results obtained in Chapter 2, the probability of experiencing a WWD crash during afternoon and night is 0.62 and 1.77, respectively.

As would be expected, drivers are exposed to higher injury severities when the lighting condition is not appropriate. According to the results, darkness (whether the roadway is lit or not) increases the severity of WWD crashes significantly. The average direct pseudo-elasticities show that darkness without any lighting may cause a 35.0% increase in the probability of driver severe injuries in WWD crashes. This number is decreased to 12.7% when lighting provided during dark hours. Clarke et al. (2006) and Williams (2003) have demonstrated the disproportionality between fatality risks during nighttime and daytime conditions so that fatality risk at night is more than four times the fatality risk during daylight.

Driver injuries tend to be more severe when the WWD crash happens in rural areas compared to urban areas, despite not being found significant in Chapter 2 to characterize WWD crashes. The findings of this study show an increase of 26.7% and 9.2% in the likelihood of severe and minor injuries in rural WWD crashes as opposed to urban WWD crashes, respectively. Some reasons might explain this finding. For example, it is claimed that rural road users are more likely to be speeding and be DUI drivers compared to urban road users, which consequently result in higher injury severities (Boufous et al., 2008; Clark, 2001). Furthermore, emergency medical services (EMS) are more accessible and faster in urban areas, which may reduce the severity of injuries when a crash happens. This is because EMS confronts several challenges specific to rural areas, such as getting notified, locating, and transporting victims in a timely and effective manner (Minge, 2013). This delayed response becomes more significant as the studied states (Illinois and Alabama) update the injury severity level within 30 days of the crash.

A wet surface, which is a surrogate measure of inclement weather condition, is shown to significantly decrease the severity of injuries incurred by drivers in WWD crashes, compared to a dry surface condition. Specifically, a reduction of 12.3% and 35.5% is observed in minor and severe injuries, respectively, whereas no injuries increased by 23.2%. It is noteworthy that drivers seem to decrease their driving speeds while driving on wet surfaces which decreases the severity of crashes either with other vehicles or other objects (Christoforou et al., 2010). Moreover, drivers tend to be more vigilant of their surroundings during these conditions.

Regarding the effect of collision type, the obtained results show that there is a significant difference between the severity outcomes of head-on crashes compared to non-head-on crashes so that head-on crashes are found to significantly increase the probability of severe outcomes. Notably, this parameter shows various effects across different severity levels (i.e., violates the parallel line assumption). Relative to non-head-on crashes, head-on crashes are associated with a decrease of 69.4% in no injuries, an increase of 20.0% in minor injuries, and a considerable increase of 120.6% in the probability of severe injuries. This highly increased severity outcome is due mainly to the higher speed of vehicles driving on controlled-access highways, which in turn intensifies the severity of crashes. A review on the existing literature studying head-on crashes on highways shows the same result, bolstering the significant effect of this parameter among the others in terms of increasing the severity of injury (Jafari-Anarkooli and Hadji-Hosseinlou, 2016; Deng et al., 2006).

3.6 Conclusions and Recommendations

This Chapter of dissertation analyzed at-fault drivers' injury severity in 398 WWD crashes obtained through the extensive identification/verification process in Chapter 2. In order to account for the ordinal nature of the injury severity, three ordered-response models (i.e., PO, GOL, and PPO) were nominated to fit the data. The main difference between these models is whether they account for the parallel regression assumption and how they handle it. The data used was categorized using a three-level injury severity of no injury, minor injury, and severe injury. Based on the results of the Brant test, three variables (i.e., older drivers, deployed airbag, and head-on collision) were found to violate the parallel regression assumption, thus the PPO model was finally employed for analysis. This study is the first to identify and quantify the effect of various significant variables on the injury severity of at-fault drivers in WWD crashes. The identification of these variables can contribute to the development of appropriate safety countermeasures, and the quantification of their effects can help prioritize these possible countermeasures when the implementation of all countermeasures is not possible under financially-restricted conditions. Accordingly, the prioritization should be based on the variables with a higher expected increase in the probability of severe injuries, assuming that addressing these variables is potentially related to more effectively alleviating the severity of driver injuries.

The estimation results of this study identified several risk factors at 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. Based on these findings, several countermeasures, grouped into categories of engineering, education, and enforcement, can be recommended to help address the driver injury severity in WWD crashes.

The findings of this study demonstrates the role of intoxicated driving in significantly increasing the probability of more severe crashes and suggests the implementation of appropriate countermeasures for drunk driving. For example, DUI driving prevention campaigns are recommended to be established, and stricter enforcement rules seem to be necessary. Illinois has already published the "DUI Fact Book" to enhance awareness of driving while intoxicated. For repeat violators, the use of ignition interlock devices (IIDs) are suggested (Zhou and Pour-Rouholamin, 2014a). Drivers, especially middle-aged drivers, should be educated to understand the risk associated with WWD and drunk driving and the potential effects on families and society. These educational programs and enforcement rules can also cover seatbelt use because not using this restraint system is found to considerably increase the fatality probability by a factor of 85.4%.

WWD crashes that occurring during the night when the roadway is dark are associated with higher injury severities for drivers. As the lighting condition at WWD entry points are shown to be of high importance (Pour-Rouholamin et al., 2014), the method developed and proposed by Zhou et al. (2012) can be used to identify entry points of WWD crashes, and a field review of these locations can be conducted to identify whether appropriate lighting is provided at entry locations. It is suggested to provide uniform lighting at the intersection of exit ramps and crossroads, especially when exit and entrance ramps are closely spaced (e.g., parclo interchanges). In addition to adjusting the lighting level at possible entry points, the use of red retroreflective strips can be helpful, when applied to the supports of DNE and WW signs, at the intersection of exit ramps and crossroads, and along the exit ramp and freeway mainline. These strips are capable of increasing the nighttime visibility of signs, reducing the frequency of WWD incidents, and helping decrease the severity of these crashes by alerting the at-fault drivers. The investigation shows that Illinois has recently adopted the use of these strips, but their use is not a current practice in Alabama. Other innovative countermeasures, such as LED-illuminated signs might also be considered.

WWD crashes in rural areas were also 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.

In addition to finding the contributing factors to injury severity of drivers in WWD crashes, a comparison between three commonly used ordered-response models (PO, GOL, and PPO) were made using log-likelihood at convergence, AIC, and BIC. This comparison demonstrates that, given our database, the PPO model surpasses the performance of the other two models. Of course, this result is based solely on the available database with the given sample size, and, therefore, a more general conclusion needs more investigation based on data with varying sizes.

4 Current Practices of Safety Countermeasures for Wrong-Way Driving Crashes

Despite employing numerous countermeasures to combat WWD issues in the nation, no recent research has been conducted to investigate the effectiveness and level of acceptance of these countermeasures and current practices. The purpose of this Chapter is to fill this gap by assessing the information gathered from a survey at the first National WWD Summit held in July 2013 and by studying emerging countermeasures currently employed in various jurisdictions. On the basis of analyzing the survey results and developed countermeasures, an insight into various characteristic aspects of WWD countermeasures is provided.

4.1 Introduction

As previously discussed, WWD, which was defined as the movement against the stream of traffic on freeways, expressways, interstate highways, and their access ramps, has been found to be a major concern for more than six decades (NTSB, 2012; Zhou et al., 2012; Zhou and Pour-Rouholamin, 2014b). To overcome this, various countermeasures, ranged from low-cost (e.g., signs and pavement markings), to more expensive (e.g., geometric modification and ITS technologies), have been applied to minimize the frequency and severity of the problem. However, there is still a lack of a comprehensive insight of the current practices and regulations to make a consistent guideline for WWD mitigation at the national level.

The first National Wrong-way Driving Summit, sponsored by the Illinois Center for Transportation (ICT) and the Illinois Department of Transportation (IDOT), was held on July 18-

19, 2013, in Edwardsville, Illinois. The purpose of this Summit was to provide a platform for both practitioners and researchers to exchange ideas, to evaluate current countermeasures, and to develop the best practices to reduce WWD crashes and incidents through a 4E's approach (Engineering, Education, Enforcement, and Emergency Response). In order to enhance the quality of this Summit, a significant number of representatives were brought together to discuss various topics during presentations as well as during group discussion sections from all around the nation, including the National Transportation Safety Board (NTSB), the Federal Highway Administration (FHWA), the American Traffic Safety Services Association (ATSSA), and members from state departments of transportation, state police, state highway patrols, Tollway authorities, universities, and consulting firms. Approximately 130 attendees participated in this Summit from 23 states, including states that have already implemented and tested various countermeasures (e.g., California, Florida, and Texas) and states that have labeled WWD as a major concern (e.g., Rhode Island). Based on the survey results, and the Summit's discussions and presentations, the countermeasures outlined in Table 4.1 were found to be either implemented by various agencies or worthy of implementation for mitigating WWD incidents and crashes. These countermeasures are categorized into three main groups of engineering, enforcement, and education.

The purpose of this Chapter is to give an overview of current practices of WWD countermeasures through the Summit's survey results and to identify the emerging WWD countermeasures through 10 case studies in which these countermeasures have been successful in addressing the issues. Table 4.2 summarizes the 10 case studies of various emerging countermeasures and their corresponding locations.

Table 4.1 Various WWD Countermeasures Implemented by Different Agencies

<table>
<tr><th colspan="4">Engineering Countermeasures</th></tr>
<tr><th>Signing</th><th>Pavement Marking</th><th>Geometric Improvement</th><th>ITS Technologies</th></tr>
<tr>
<td>• Implementing Standard Wrong-way Sign Package
• Improved Static Signs
• Lowering Sign Height
• Using Oversized Signs
• Mounting Multiple Signs on the Same Post
• Applying Red Retroreflective Strip to the Vertical Posts
• “Freeway Entrance” Sign for All Entrance Ramps (Ensure the Right Way)</td>
<td>• Stop Line
• Wrong-way arrow
• Turn/Through Lane Only Arrow
• Red Raised Pavement Markers
• Short Dashed Lane Delineation Through Turns</td>
<td>• Entrance/Exit Ramp Separation
• Raised Curb Median
• Longitudinal Channelizers
• Change in Ramp Geometrics:
  - Obtuse Angle
  - Sharp Corner Radii
• Roundabouts</td>
<td>• LED Illuminated Signs
• Dynamic Signs – Warn Other Drivers
• Use Existing GPS Navigation Technologies to Provide Wrong-way Movement Alerts
• Provide Consistent Messages or Alerts That Are Intuitive to the Driver</td>
</tr>
<tr><th colspan="4">Enforcement Countermeasures</th></tr>
<tr><td colspan="4">• Alert law enforcement agency
• DUI enforcement
• Dynamic message sign to give warning to right-way drivers
• Portable spike barriers to stop WW drivers</td></tr>
<tr><th colspan="4">Education Countermeasures</th></tr>
<tr><td colspan="4">• Public awareness and understanding of:
  - Basics of road designs and interchange types
  - Acts to do (witnessing a wrong-way driver)
• Focus groups:
  - Older drivers
  - DUI drivers
  - Young drivers</td></tr>
</table>

Table 4.2 Case Studies of Emerging Countermeasures

Countermeasure	Location
1. Low-Mounted DO NOT ENTER and WRONG WAY Signs	Various Locations in California
2. Flashing LED Border WRONG WAY Signs	San Antonio, Texas
3. Red Retroreflective Strips and Red Retroreflective Raised Pavement Markers	Various Locations in Texas
4. Access Management near Interchange Ramp	Dallas, Texas
5. Raised and Vertical Longitudinal Channelization	Detroit, Michigan
6. ITS Detection System	Houston, Texas
7. Wrong-Way Entry ITS Warning System	Buffalo, New York
8. Enhanced DO NOT ENTER and WRONG WAY Signs	Various Locations in Illinois and Texas
9. Enhanced Pavement Markings	Various Locations in Illinois and Texas
10. Countermeasure Package for Partial Cloverleaf Interchanges	Various Locations in Michigan

4.2 Literature Review

Some studies have already been conducted to evaluate the effectiveness of the WWD-related countermeasures both in the U.S. and outside the country. While some of these studies have focused merely on one specific countermeasure, some others evaluated the effectiveness of a countermeasure package instead. In other words, they were not able to quantify the effect of each countermeasure separately or to relate a portion of the reduction in the number of WW maneuvers to one specific countermeasure (e.g., Delineation, DNE sign).

In 2005, Chrysler and Schrock (2005) conducted a before-after study to investigate the effect of directional arrows painted on two-way frontage roads on the number of WW maneuvers. In doing so, one location, which was a short section of a two-way frontage road transitioned into an exit ramp, in College Station, Texas, was chosen for experiment. The pavement marking treatment was actually a pair of nine-foot, thorough lane-use arrows, as defined by the MUTCD, located 120 feet away from the gore of the exit ramp. Analysis of the results demonstrated a 90% reduction in the number of WW maneuvers. In other words, incorrect movements dropped from 7.4% of the correct movements in the before to only 0.7% in the after period.

Campbell and Middlebrooks (1988) studied the effect of a package of countermeasures for WWD of an exit ramp in Atlanta, Georgia, using actual counts. These countermeasures include: trailblazers, lowering WW signs, placing stop bar at the end of the studied exit ramp, and installation of the yellow ceramic buttons to improve the visibility of longitudinal pavement markings. Their observations revealed that the rate of WW maneuvers reduced from 88.6 per month to 2.0 per month after the countermeasure application, representing more than 97% reduction.

Vaswani (1977), in a research sponsored by Virginia Department of Transportation (VDOT), conducted a before/after study to evaluate the effectiveness of a “Divided Highway Crossing” sign on mitigating WW movements. Route 29 was chosen for the experiment and the signs were placed at the intersections along the corridor. Their study included three years before the improvement data collection and a period of seven months after the installation of sign. Field observations showed nine WW maneuvers during the before study while these movements were completely eliminated after sign implementation.

4.3 Methodology and Data Collection

A survey questionnaire (provided in Appendix A) was designed to collect the data concerning current practices of WWD countermeasures from the Summit. Questions and sections of the questionnaire were assembled and organized based on a thorough review of previous studies that were refined according to the feedback received from a panel of experts. These questions were arranged to gather necessary data in a logical, hierarchical order of sections, from general data to more specific with conclusive questions, as follows:

- The first section of the questionnaire was dedicated to the general questions, such as the importance of the problem in the specific jurisdiction, the types of countermeasures implemented, the employment of any monitoring program, etc.
- The second section was concerned with the characteristics of WWD signage, including type, size, and location of signs, and the methods used for augmenting the visibility of WW-related signs.
- The third section was aimed to decipher the types and characteristics of WW-related pavement markings as well as their retroreflectivity.

- The fourth and fifth sections of the questionnaire were concerned with traffic signals and geometric modifications, respectively.
- ITS and its role in mitigating WWD issues in various states were evaluated in the sixth section.
- Lastly, the questionnaire was finalized with closing questions to gather new ideas from the participating states.

The survey questionnaires were distributed to representatives from 23 states. Sixteen states responded to the survey, including states that have already implemented and tested various countermeasures (e.g., Illinois, California, Texas, Michigan) and those that have future plans to address this problem. Of these participants, half had already conducted WWD studies in their jurisdictions; the remaining had been planning to conduct similar studies or to implement some type of countermeasure they learned from the Summit. Nearly half of the WWD fatalities from 2004 to 2013 occurred in these 16 participating states, providing a reliable sample for the purpose of this research (ATSSA, 2014).

In addition to the questionnaire, presentations and discussions from the Summit recognized current, undergoing efforts made by the represented states. These efforts were all reviewed to investigate their consistency with current practices. In addition, 10 case studies, mostly chosen from this Summit, were conducted to investigate the effectiveness of those emerging safety countermeasures. This study was funded by ATSSA and co-sponsored by FHWA and IDOT.

4.4 Findings and Discussion

After collecting all the required data from a thorough literature review, contact persons, and respondents for each of the questions and cases, an analysis on the data was performed to disclose any possible trends, to draw conclusions, and to provide suggestions. These findings are presented below and organized into two major groups: survey questionnaire and case examples.

4.4.1 Survey Questionnaire

4.4.1.1 General Information

Initially, respondents were asked if the WWD is a severe problem in their jurisdiction with nearly 70.0% agreed it is a severe issue in their state. Regarding employing pertinent countermeasures, 63.0% of the state representatives admitted they have implemented exclusive countermeasures to reduce WWD incidents and crashes, while the remaining claimed they are following regular policies and guidelines without specific emphasis on WWD mitigation. In terms of type of countermeasure, Engineering (91.7%), Program and Funding (50.0%), Enforcement (33.3%), and Education (16.7%) were the most popular ones. Only one state confirmed employing a comprehensive 4E's program. A WWD monitor program has been developed in 31.0% of participating states. This program is designed to obtain information about the location, severity, time of day, etc. for WWD collisions.

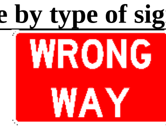
While current guidelines and manuals (e.g., Green Book, MUTCD) ask practitioners to meet minimum requirements in order to combat WWD issues, around one-fifth of the states have added supplements to the MUTCD and have intensified the regulations. On the other hand, just one state has supplements to the American Association of State Highway and Transportation Officials (AASHTO) Green Book.

Based on the the findings in the Chapters 2 and 3 of this dissertation that have identified a relationship between low light conditions and possibility of WW maneuvers as well as increased severity of injuries, extra lighting at locations susceptible to WW maneuvers is perceived as a good solution to help drivers distinguish the entrance ramp from the exit ramp when they are closely spaced; however, only one state currently provides extra lighting for such locations.

4.4.1.2 Wrong-way Related Signage

Several questions in the survey were directed toward the WW-related signs. The first question was to identify the type and placement of two popular WW-related signs: DNE and WW. Table 4.3 summarizes the placement of these signs based on the type of facility where a WWD incident or crash may originate or occur.

Table 4.3 Percentage of States Considering Particular Type of Sign Based on the Location

Location	**Percentage by type of sign**	
		
Exit Ramp	87.5	100.0
Frontage Road	68.8	56.3
Divided Highway (along non-ramp sections)	81.3	75.0

One noteworthy conclusion drawn from Table 4.3 is the lack of attention to frontage roads. In regard to this, 68.8% of states implement the installation of DNE signs at frontage roads while this percentage drops to 56.3% for the installation of WW signs. This situation persists as past studies (Zhou et al., 2012; Zhou et al., 2014) have ranked frontage roads, which are connected to diamond interchanges, among locations with a high rate of WWD entries (entries per 100 interchanges per year); and additionally, two-way frontage roads are more confusing to drivers than one-way frontage roads when it comes to WWD (Schrock et al., 2005). This fact implies that frontage roads need more attention in terms of WWD.

Various combinations of DNE and WW signs were identified through a review of existing documents and survey respondents were asked to figure out the level of their applicability. These signs include: combined DNE signs above WW signs and doubled-up DNE and WW signs. These signs, along with the possible placement and pertinent findings (provided in percent), are compiled and presented in Table 4.4. The findings reveal that combined DNE and WW signs are the more popular choice currently used by respondent agencies compared to the remaining two.

Table 4.4 Usage Percentage of Combination of DNE and WW Signs

	Sign		
Location			
Exit Ramp	50.0	Not Used	6.3
Frontage Road	18.8	Not Used	Not Used
Divided Highway (along non-ramp sections)	18.8	Not Used	Not Used

Signs conspicuity and its methods were the two other significant questions. Figure 4.1 depicts the percentage of each method's application to improve the visibility of WW-related signs. As illustrated, the majority of respondents use additional identical sign(s) on the left-hand side and they increase the size of sign to make it proportionate to the width of the target facility.

In terms of sign height, the vast majority of respondents (81.3%) used standard height for the signs as mentioned in the 2009 MUTCD (7 ft. in urban settings vs. 5 ft. in rural settings), and nearly half of the states lowered the signs in special conditions to the minimum height allowed by their manual (3 ft. in the MUTCD). Moreover, there were two states choosing to mount signs overhead.

Another issue with WW-related signs is that they do not face the intended user. In other words, the MUTCD requires (but does not mandate) the signs to be oriented toward the target users so that the highest possible visibility is attained. The survey indicates that while 62.5% of states chose to leave the signs perpendicular to roadways, the remaining have angled the signs toward potential WW drivers (Figure 4.2).

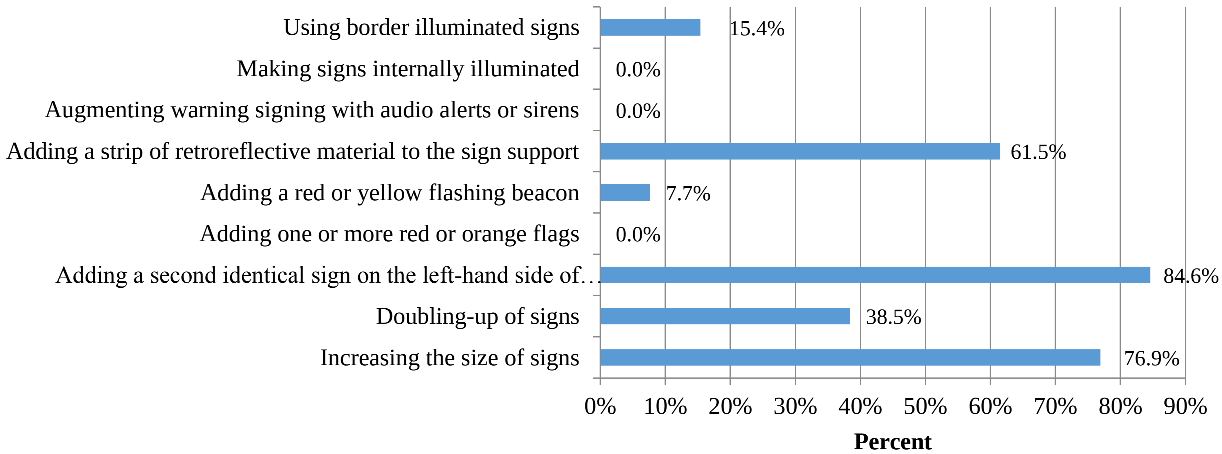


Figure 4.1 Various Methods of Enhancing Sign Visibility with Application Percentage

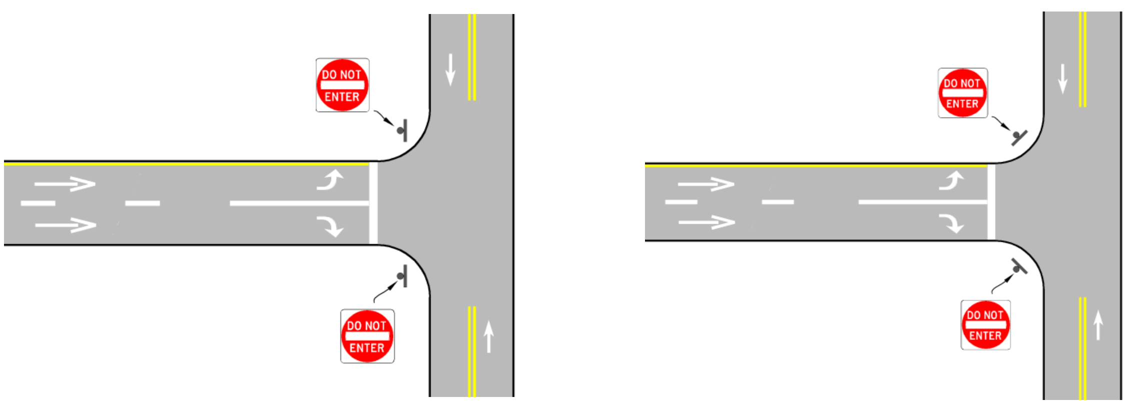


Figure 4.2 Schemes of Perpendicular Signs (left) and Angled Signs toward Intended Users (right) at Exit Ramps

4.4.1.3 Pavement Marking

Pavement markings (e.g., lane-use and WW arrows, lane line extensions, and stop lines at the end of exit ramps) efficiently guide drivers through lanes by providing visual cues on the roadway. Conversely, the absence of proper pavement markings and/or improper or faded ones could lead to driver confusion.

While roughly 70.0% of respondents use the WW arrow as described in the 2009 MUTCD, the remaining do not place this type of arrow or employ other ones. As for the placement of these markings, the majority of agencies place these arrows on the exit ramp near the intersection with a crossroad (71.4%) and at the middle of the exit ramp (64.3%); however, there are situations in which these kinds of pavement markings are located on the exit ramp near the gore point off the main line (21.4%) and on the main line (7.1%). All the respondents claimed that they are using retroreflective pavement markings and no agency is utilizing other types of illumination. Additionally, more than half (56.3%) of the states have equipped the pavement markings at problematic roads with red retroreflective raised pavement markers (RRPM). These devices are proven to be effective in helping drivers realize when they are traveling the wrong direction (Miles, 2008).

4.4.1.4 Traffic Signal

Zhou et al. (2012) have found that changing traffic signal indication from a green circle to a green arrow at the intersection of one-way exit ramps and crossroads (e.g., diamond interchanges) can provide a better understanding of the allowed movements at the intersections and can reduce the possibility of WWD incidents. The findings show that 37.5% of the respondents claimed that their jurisdiction made this change to combat WW problems.

4.4.1.5 Geometric Modification

Past studies (NTSB, 2012; Zhou et al., 2012; Copelan, 1989; Moler, 2002; Braam, 2006; Leduc, 2008) have identified that interchange configurations as well as various geometric design elements can greatly affect the WWD entrances. These geometric elements can include: exit/entrance ramps, frontage roads, raised medians, and control radii.

In the questionnaire, respondents were asked to rank these various geometric elements with reference to the level of given attention in their jurisdictions. Afterward, these individual rankings were combined together using weighted percentage to get to a final weighted ranking. As would be expected, exit ramps (i.e., their angle with crossroad, their shape such as button-hook or J-shaped, etc.), were ranked the top priority because they constitute the most frequent origin of WWD incidents. Type of interchange was the second-ranked priority with channelizing islands as the third most important geometric considerations. Control radius at the ramp-crossroad intersection and the application of medians and their openings were the fourth and fifth remarkable geometric elements, respectively. Finally, frontage roads (i.e., their continuity, outer separation, one-way vs. two-way, etc.) were also the next geometric considerations for WWD mitigation. Table 4.5 summarizes these findings altogether with their corresponding weighted ranking.

Table 4.5 Ranking of Various Geometric Elements based on Weighted Percentage

Geometric Element	Weighted Percentage	Weighted Ranking
Exit Ramps	75.0	1
Type of Interchange	61.1	2
Channelizing Islands	58.3	3
Control Radius	50.9	4
Medians	47.2	5
Frontage Roads	37.0	6

4.4.1.6 Intelligent Transportation Systems (ITS) Technologies

ITS technologies can help in addressing WWD issues following three main steps: (1) Detection, which can be accomplished by application of numerous detectors, such as Inductive Loop Detectors (ILDs) and Video Image Processing (VIP); (2) Warning, which uses various methods, such as in-pavement warning lights, flashing WW signs, warning lights, and Dynamic Message Signs (DMSs); and (3) Action, which is taken by responsible units coordinated with traffic management centers (TMC) to correct or intercept the at-fault driver.

A typical scheme of ITS detection and warning systems for WWD can be found in Figure 4.3. As shown, a WW driver is first detected using sensor technologies, and s/he is immediately notified of the mistake by means of warning devices such as LED WW signs. These work well in rural areas where modern TMCs and quick responses by police are not available. In some large metropolitan areas, TMCs can receive the signals from field detectors and sensors and further verify WWD using video cameras.

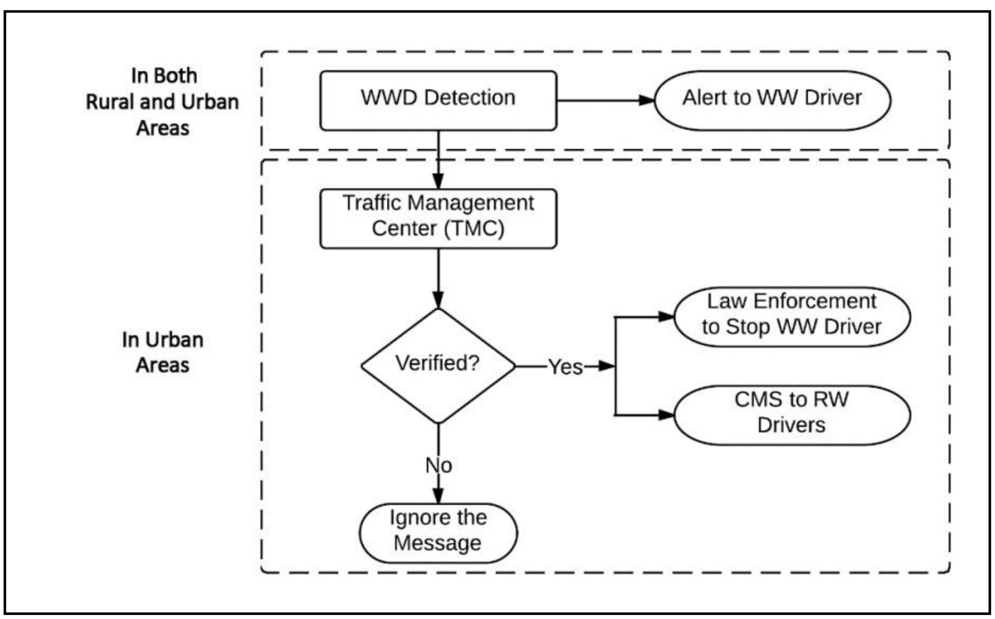


Figure 4.3 Typical Scheme of WWD Detection and Warning System

Given that the vast majority of WW drivers are DUI, the effectiveness of traditional and innovative WWD countermeasures might be questionable. Therefore, WWD detection systems may be more required (Finley et al., 2014). Surprisingly, just one-third of agencies are found to exploit ITS technologies to identify WW drivers and to take prompt and proactive actions. Radar detectors, closed-circuit television (CCTV) cameras, and ILDs were used as popular detectors. After detection, flashing WW signs, warning signs, and DMS are available means of warning other drivers of an imminent danger ahead. Various messages may appear on DMS such as "Wrong Way Driver Ahead" and "All Traffic Move to Shoulder and Stop" (HCTRA, 2012). After detection and verification of the at-fault driver, patrol units may step in and position ahead of the WW driver to either help the driver pull over or to correct his or her direction. If it is not possible to position, responding units may attempt to intercept the vehicle by deploying tire deflation devices (e.g., portable spike) to slow or stop the WW driver or by using extra force to stop the vehicle.

4.4.1.7 Closing Remarks

At the end, respondents were asked to recommend elements of the WWD program based upon their experience. These recommendations include:

- Having a consistent approach or standard design for various geometrics of exit ramps;
- Prioritizing interchange types that are problematic and limiting their implementation to necessary situations;
- Conducting an analysis on using language versus symbols;
- Recommending data queries to use to research high-impact locations;
- Strengthening driving under the influence (DUI) legislations; and
- Using the ignition interlock devices (IIDs) for repeat DUI offenders.

4.4.2 Case Studies

4.4.2.1 Wrong-way-related Signage

Many researchers have connected the WWD issue not to the lack of appropriate signage, but to the signs' invisibility (or low visibility), especially during nighttime conditions where the chance of entering an exit ramp mistakenly is higher in relation to daytime conditions. Following, four real-world case examples and their outcomes are presented.

1. The California Department of Transportation (Caltrans) has been using lower mounting signs since the early 1970s (Figure 4.4). Evaluations of the treated sites show this method to be an effective treatment, reducing the frequency of WWD incidents from 50-60 per month to 2-6 per month at some problematic locations (Leduc, 2008). The decrease in incidents is attributed to putting the signs directly in the path of vehicle headlight beams. Impaired and older drivers are two major groups more positively affected by this kind of countermeasure.

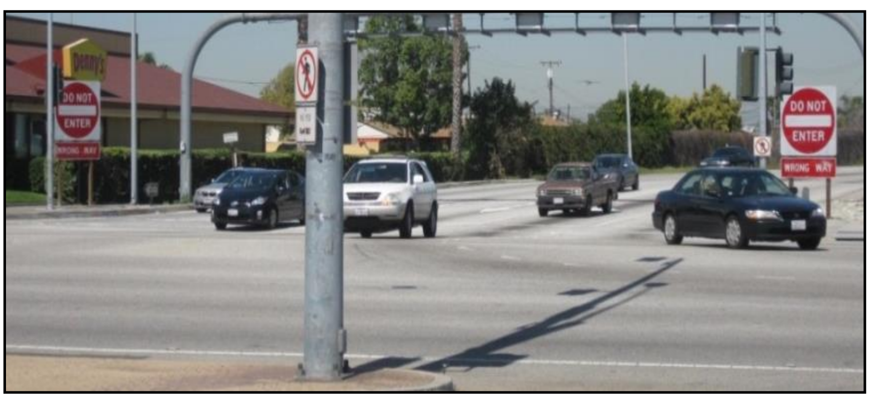


Figure 4.4 Lower-mounted Sign during the Day in California

2. A study conducted by the Texas Department of Transportation (TxDOT) estimated that nearly 80.0% of WWD incidents occur at night, with 45.0% between 2 a.m. and 4 a.m.

(Clay, 2011). Therefore, various methods were identified and assessed to enhance the conspicuity WW-related signs. For instance, flashing LED-bordered WW signs were installed at 29 exit ramps along a corridor in San Antonio, Texas, where a high number of WWD crashes had previously occurred (Figure 4.5). Initial investigations on WWD incidents after treatment in this corridor revealed a 30.0% reduction in frequency. Further analysis indicated a 13.1:1 benefit ratio with 1.5 years as the projected cost recovery time period (ATSSA, 2014; Chacon and Fariello, 2014).

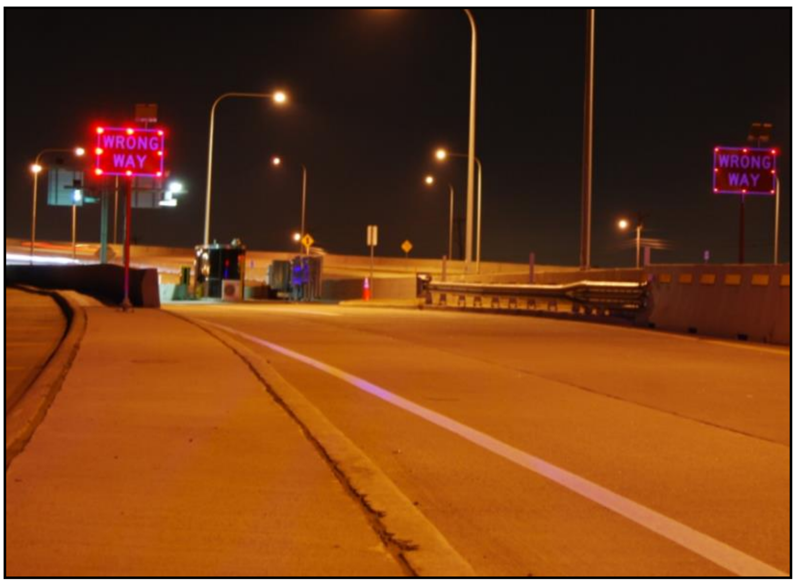


Figure 4.5 A Sample of Flashing LED WRONG WAY Signs at South End of Dallas North Tollway

3. Red retroreflective strips on sign supports (DNE and WW signs) in combination with other countermeasures have also been employed by a number of agencies, such as the North Texas Tollway Authority (NTTA), as their proposed program to reduce the frequency of future WWD incidents (NTTA, 2009). The NTTA, after noticing a sudden increase in WW-related crashes on one facility in 2009, implemented red retroreflective strips on all

DNE and WW signs and red RRPM-supplemented WW arrows at every exit ramp (Figure 4.6). Although no statistical analysis has been conducted, these two countermeasures combined are expected to lessen the probability that treated exit ramps will cause WWD problems.

Figure 4.6 NTTA Exit Ramp with Red Retroreflective Strips on Sign Supports and Red RRPM-supplemented Wrong Way Arrow Pavement Markings

4. In response to an increase in WWD crashes in the Chicago area, the IDOT replaced nominal-sized DNE signs with larger ones, going from 30”×30” to 36”×36” to increase the visibility of these signs at multiple exit ramps (Figure 4.7). Another example of oversizing signs to address WWD comes from the NTTA in the Dallas area. Adding a second set of identical signs on the left-hand side of the roadway was one of several considered treatments by the NTTA. Since the implementation of these countermeasures in Dallas, the number of WWD incidents has decreased. While this reduction cannot be solely related to these treatments, as they are utilized and combined with other countermeasures, they do

help in enhancing visibility of the signs and reducing the likelihood of wrong-way incidents (ATSSA, 2014).

Figure 4.7 Before (top) and After (bottom) Pictures of DNE Signs at IL 394/US 30

4.4.2.2 Pavement Markings

5. The IDOT, as part of its efforts to address WWD incidents, improved the pavement markings at several exit ramp intersections to provide additional guidance for motorists (Figure 4.8). Furthermore, the NTTA has also improved 22 lane-use arrows at a number of exit ramps within the Dallas area in 2011. Statistics demonstrated a reduction from five incidents in a six-month period before the change to three in the same time-period after the treatment, representing 40.0% reduction (ATSSA, 2014).

Figure 4.8 Before (left) and after (right) Conditions of the Pavement Marking Improvements at Ohio Street, IL

4.4.2.3 Geometric Modification

6. A location was identified in Wycliff Avenue in Dallas as the originating point of several WWD incidents due to the presence of an adjacent two-way street and exit ramp. This situation could confuse drivers who were turning left from the crossroad toward the side street, leading them to enter the exit ramp mistakenly. As a countermeasure, the responsible agency proposed to close the median opening at the crossroad to completely eliminate the possibility of wrong-way, left-turn movements. Figure 4.9 provides an aerial comparison of the geometric configurations "before" (2009) and "after" (2011) the median enhancement. Consequently, no other WWD incidents were observed in this location after the project completion. Table 4.6 summarizes WWD statistics at this location before and after the median closure (Ouyang, 2014).

Figure 4.9 Before (left figure, 2009) and after (right figure, 2011) Pictures of the Modified Median at Wycliff Avenue (Image: Google)

Table 4.6 WWD Statistics before (2010) and after (2011, 2012) Median Closure

WWD Incidents	2010	2011	2012
Associated with This Location	2	0	0
In the Proximity Area without Hard Evidence Linking to This Location	7	3	2

7. Raised/vertical longitudinal channelizing devices as low-cost countermeasures have been used by a number of transportation agencies to alleviate various traffic issues, such as WWD problems. For example, in 2010, the Michigan Department of Transportation (MDOT) identified a feature of parclo interchanges that makes them prone to WWD maneuvers, which includes: parallel, closely-spaced exit and entrance ramps. Accordingly, 161 parclo interchanges were recognized for treatment, including one needing additional attention because the location was the originating point for 10 out of the 35 studied WWD crashes. Further analyses could not relate these crashes to nighttime conditions nor to impaired drivers; therefore, geometric modification using raised/vertical longitudinal channelization, was thought to be helpful (Morena, 2014). Figure 4.10 shows the

combination of preformed curbing and vertical panels. Investigation of crashes after completion of this project revealed that since June 2012, zero WWD crashes have occurred at this intersection, revealing complete elimination of these events.

Figure 4.10 Application of Longitudinal Channelizers in Restriction of Wrong-way Left-turn (Image: MDOT)

4.4.2.4 Intelligent Transportation Systems (ITS) Technologies

8. Based on WWD incident reports from the public and law enforcement involving their Westpark Tollway, the Harris County Toll Road Authority (HCTRA) in Houston decided to implement a radar-based WWD detection system. This system was designed for 12 sites at exit ramps and along the mainline, all connected to the HCTRA TMC, with an overall cost of $337,000 (Thurman, 2014). According to the HCTRA, in 2012, 30 WWD incidents were detected by the system. Moreover, since the implementation of the WWD detection system in 2008, law enforcement units succeeded in stopping 19 WWD motorists; eleven of those nineteen motorists were determined to be impaired and were arrested, while three others were arrested for other traffic violations. The remaining five motorists were issued

WWD-related citations (HCTRA, 2009). Taken as a whole, these results confirm that ITS is an effective strategy for addressing WWD at a system level.

9. The New York State Thruway Authority (Thruway) engineers began closely examining WWD incidents and crashes following a series of fatal crashes that had occurred in different locations across their system in recent years. Upon reviewing incident data, examining existing interchange characteristics, and consulting local Thruway staff and State Police, the Thruway decided to install an ITS-based warning system at a handful of locations with histories of WWD problems. The system implemented by the Thruway consists of two major components: Doppler radar detection and programmable, changeable message signs. The initial installation in Buffalo directs a series of messages to a WW driver in the following sequence: “WRONG WAY”, “STOP” and “PULL OVER”, as shown in Figure 4.11. Since this countermeasure was recently implemented, there is no data showing the effect it has on wrong-way incidents or crashes.

Figure 4.11 NY Thruway Wrong-way Entry ITS Warning System

4.4.2.5 Countermeasure Package

10. A recent study (Morena and Leix, 2012) by the MDOT and FHWA concluded that 60.0% of total WWD crashes in 2010 in Michigan could be traced to WWD entries at parclo

interchanges. The MDOT then assembled a package of multiple low-cost countermeasures that would address the situation by providing more extensive and comprehensive visual cues, targeting these interchanges across the state for treatment. The WWD countermeasure package consisted of lower DNE and WW sign mounting height (four feet from the edge of the pavement), red retroreflective strips on sign supports, stop lines, exit ramp WW arrows, pavement marking extensions, painted islands, and WW delineations. The MDOT estimated the average cost of implementing this countermeasure package at approximately $6,500 per treated exit ramp.

4.5 Summary and Conclusion

Various countermeasures have already been developed by agencies to combat WWD issues, among which engineering countermeasures (with 91.7%) are given the top priority. According to the survey questionnaire, adding a second identical sign on the left-hand side of the roadway and increasing the size of WW-related signs, as implemented by the IDOT and the NTTA, are the most acceptable and beneficial countermeasures. Caltrans' case study justified the application of lower mounting signs with about 90.0% reduction in WWD incident frequency and the TxDOT experienced a 30.0% reduction in WWD incident frequency after adding LEDs to DNE and WW sign borders; however, it was found that there is a lack of attention to placement of WW signs at frontage roads. Pavement marking applications and improvement at problematic locations show promising outcomes with a decreasing frequency of WWD incidents by 40.0% in the NTTA. Access management in the vicinity of an interchange area, using geometric elements, was found to be an efficient method. As perceived to be the most considerable elements by respondents, controlling access to exit ramps was able to eliminate WWD entries in one problem exit ramp in

Michigan entirely. Lastly, while only one-third of participating agencies claim to deploy ITS technologies, the HCTRA had successful experience, authenticating the use of these devices.

The considerable effect of geometric design elements, specifically at parclo interchanges as explored in this Chapter, was the motivation for further analysis of these elements, which is presented in the next Chapter.

5 The Effect of Various Geometric Design Elements on the Probability of Wrong-Way Entries at Partial Cloverleaf Interchanges

Following the last objective of this dissertation, and based on the crash narratives and available methods, entry points of those 398 WWD crashes were determined and those WWD crashes that had resulted from entering parclo interchanges were studied. As previously discussed, these interchanges are known by their exit and entrance ramps close together (two-way ramp), which are among the interchanges that are most prone to have WWD crashes. The geometric features of these interchanges and their connections with crossroads that could affect the probability of WWD entries were also collected. These features and their possible role in WWD were identified through a literature review, crash narratives, and field observations. A Firth's penalized-likelihood logistic regression model, which was introduced in Chapter 2, was developed to differentiate between locations with and without a history of WWD entries. The results of the study indicated that various factors can delineate between locations in terms of WWD entries, including the turning radius from crossroads to two-way ramps, the type of median on the crossroad (i.e., non-traversable vs. traversable), the width of the median between the exit and entrance ramps, and the distance to nearby access points. It is expected that these findings will help policy makers as well as highway geometric design engineers in updating and improving current practices.

5.1 Introduction

As already discussed earlier and according to the existing literature, there are various ways to enter a freeway system in the wrong direction, such as executing a U-turn on the freeway mainline, crossing the median through an emergency turnaround, or entering from an exit ramp with the latter being the most prevalent (Pour-Rouholamin and Zhou, 2015). The problem is compounded when there are exit and entrance ramps adjacent to each other (Pour-Rouholamin and Zhou, 2016c; Pour-Rouholamin and Zhou, 2016d). This situation is seen in parclo interchanges and their connections with the crossroad, and they traditionally have had one of the highest rates of WWD entries (Zhou et al., 2012). In addition to the proximity of the exit and entrance ramps (making two-way ramps) of parclo interchanges, it is generally accepted that some geometric elements at the intersection of two-way ramps and crossroads or within their vicinity are capable of causing further confusion (if designed improperly) or physically stopping the WWD maneuver (if designed properly). For instance, a non-traversable median on the crossroad is believed to help alleviate WWD left-turn movements from crossroad, whereas a side street or access driveway close to these two-way ramps may confuse drivers. Although based on the findings of previous Chapters, several factors, such as drunk driving and driver age, have been found to significantly affect the likelihood of WWD occurrence and entry, some WWD crashes can be prevented with appropriate design of geometric elements. Even though such elements have significant potential for preventing WWD, very few research documents are available to quantify their level of effectiveness in reducing the incidents of WWD entries.

The methodology used predominantly in the existing literature is also not vigorous enough, because most researchers rely solely on comparing the frequency of WWD entries before and after geometric features are changed. For example, as reviewed in the previous Chapter, the NTTA found that the proximity of one side street to an exit ramp was an issue that led to several WWD left-turn entries from the crossroad over the period of a year. This situation confused drivers turning left from the crossroad toward the side street, causing some of the drivers to enter the nearby freeway exit ramp mistakenly. To deal with this issue, the NTTA closed the median opening on crossroad, making left turns impossible. This improvement completely eliminated the occurrence of WWD at that location in the following year (ATSSA, 2014). Another study by Chassande-Mottin and Ganneau (2008) suggested that the complexity of the intersections of exit ramps and crossroads as a result of having more than one channelizing island at exit ramp throat could confuse drivers, leading to WWD maneuvers. However, they did not mention the method they employed or the statistics used to form their conclusion.

Zhou et al. (2015) conducted a comprehensive study that was supplemented by field observations at various locations in Illinois, and they offered some countermeasures in terms of geometric design as a means of reducing or eliminating WWD maneuvers. Their geometric design countermeasures included the use of raised medians and channelizing islands, increasing the distance from the gore of the exit ramp to the entrance ramp for parclo interchanges, reducing the turning radius for WWD movements, and not joining exit ramps to two-way frontage roads. A guideline for reducing WWD movements on freeways (Zhou and Pour-Rouholamin, 2014a) also was developed as an outcome of this project, which elaborates on the use of different geometric design elements, as well as other traffic control devices, to deter WWD.

In their study, Schrock et al. (2005) found that the connection of a two-way frontage road and an exit ramp makes the area more vulnerable to WWD than the connection of a one-way frontage road and an exit ramp. An explanation for the intersection of two-way frontage roads and exit ramps being a safety issue could be that making turning movements at such an intersection is more complex than doing so on one-way frontage roads (Eisele et al., 2012). Another study on frontage roads by the Minnesota Department of Transportation (MnDOT, 2009) found that continuous multi-lane frontage roads with numerous intersections may be undesirable and may lead to a high potential for WWD crashes despite providing more favorable access from controlled-access highways to local streets. The presence of two-way frontage roads instead of one-way frontage roads further intensifies the issue. Another finding of this study was that the connection angle between the slip ramp and the frontage road can distract drivers and potentially result in WWD maneuvers. Accordingly, slip ramps connected to two-way frontage roads at acute angles are prone to WWD movements.

The analysis in this Chapter focused on WWD entries at parclo interchanges and the geometric features of their connections at crossroads. In order to determine which geometric features and to what extent can affect WWD entries, a group of parclo interchanges with no history of WWD crashes was selected for comparison with a group with WWD crashes, making a dichotomous (binary) dependent variable (i.e., with and without history of WWD entry). Considering the dichotomous nature of the dependent variable, the next step was to develop a binary logistic regression model using the Akaike Information Criterion (AIC) to ascertain the relative importance of various factors in predicting the probability of WWD entry. Highlighting the role of various geometric design elements in the occurrence of WWD is a legitimate and interesting step that can improve our understanding of these elements so they can be considered in the future interchange design projects.

5.2 Data Collection

It is essential to determine the WWD crashes and corresponding entry points in order to examine the geometric design elements that can affect the occurrence of WWD. Therefore, a three-step data collection method was proposed, i.e., 1) collecting WWD crash data, 2) identifying WWD entry points and parclo interchanges with and without a history of WWD entry, and 3) selecting appropriate geometric features that could affect WWD maneuvers and collecting pertinent information about those features. The first step has already been accomplished and the results of this step was used to follow the other two steps. The remaining two steps are explained in detail in the following sub-sections.

5.2.1 Wrong-Way Driving Entry Data at Parclo Interchanges

After determining the true WWD crashes obtained from the previous Chapters, their corresponding entry points were located using the narratives and the method proposed by Zhou et al. (2015). Since the focus of this research was parclo interchanges, these interchanges along controlled-access highways in both states of Illinois and Alabama were identified. Altogether, 172 adjacent entrance and exit ramps, 65 WWD crashes originating from these locations, and 54 corresponding entry points were found within this time period in these two states. The reason the number of entry points was less than the total number of WWD crashes was that 11 locations had more than one WWD entry. There were 118 other parclo interchanges with no history of WWD entry as comparison group. These numbers indicated that about one-fifth of WWD crashes originated from parclo interchanges, which is pretty considerable, while this type of interchange makes up less than 10% of total number of interchanges in the two states.

5.2.2 Geometric Design Data

The geometric design elements that can affect WWD entries at parclo interchanges were selected based on the review of the past studies and existing geometric guidelines (AASHTO green book and other state DOT design manuals). Eight geometric design variables, including both continuous and categorical variables, were recognized to affect the probability of WWD entries. The continuous variables included intersection angle, control/corner radius from crossroad to two-way ramp, control/corner radius from two-way ramp to crossroad, width of the median between the exit and entrance ramps, intersection balance, and distance to a nearby access point. Categorical variables were the type of median on crossroad and the type of channelizing island at the exit ramp throat. Keeping continuous variables the way they are (i.e., continuous) and not categorizing them depends on the nature of the study. In other words, categorical variables and continuous variables each answer different research questions. Given the research question in this study, i.e., the effect of several independent variables (geometric features) on a dependent variable (WWD entry) as well as identifying their critical thresholds for future implementations, the continuous variables were placed into categories.

5.2.2.1 Intersection Angle

Intersection angle is defined as the angle at which the ramp connects to the crossroad, and it depends primarily on the functionality of the crossroad (Eyler, 2005). This angle is measured between the centerlines of the crossroad and the ramp, from the right side of the ramp, so it theoretically can range from 0 to 180 degrees. Given the fact that minor deviations from the right angle are barely distinguishable by drivers and generally are acceptable (Caltrans, 2014), a 5-degree tolerance from the right angle also was considered to be a right angle. Therefore, this variable was categorized as follows: acute (less than 85 degrees), right (85 to 95 degrees), and obtuse (more than 95 degrees). Investigation of this variable at the studied parclo interchanges showed its value ranging from 59 to 137 degrees, with an average of 89 degrees. As a common practice, two-way ramps generally are designed to intersect crossroads at right angles for both operational and safety considerations, but single exit ramps (e.g., diamond ramps) are designed to connect to the crossroad at angles other than 90 degrees.

5.2.2.2 Control/Corner Radius

This geometric design element is the minimum left-turn path for a design vehicle that affects the radius of the corner of the intersection as well as the location and opening length of the median, if any (Harwood and Glauz, 2000). According to the existing literature, a corner curve with a large radius may encourage WWD movements, while an angular break or short-radius curve may discourage WWD maneuvers. This element was studied by Vaswani (1977), and it showed promising results after making an angular break, eliminating all WWD maneuvers for 1.5 years after its implementation compared to six WWD maneuvers that were observed in the two years prior to the modification at one specific location.

A sharp corner radius from the crossroad to the two-way ramp defines the opening of the median and its extension into the intersection, making WWD left turns less likely, whereas the corner radius from the two-way ramp to the crossroad makes it awkward to make WWD right turns. According to the data collected from the locations that were studied, the average radius from the crossroad to the two-way ramps is about 76 ft, and the average radius to the crossroad from the two-way ramp is about 96 ft. Therefore, the categorizations of these two variables are different to account for the nearly 20-ft variation in the averages and to avoid categories with zero frequencies that may bias the results. The control/corner radius was categorized at 10-ft incremental intervals, as found appropriate.

5.2.2.3 Median

The AASHTO Green Book (AASHTO, 2011) defines a median as an elongated divisional island built as a portion of highway that primarily serves as a means of separating opposing traffic flows on the same roadway. One of the fundamental capabilities of this geometric element is that it deters cross-median WWD movements. Three characteristics of medians are critical to their role in WWD mitigation, i.e., their type (traversable or non-traversable), their opening, and their width. While the first two characteristics are important for medians on a crossroad, the latter is of importance for the medians between two abutting exit and entrance ramps at parclo interchanges.

Medians on crossroads are categorized as non-traversable and traversable. A non-traversable (raised) median on a crossroad can effectively discourage WWD left-turn movements onto parclo interchanges; however, its effectiveness also depends on the median opening, which sometimes can be identified by the control/corner radius (Pour-Rouholamin et al., 2015). The narrower the median opening on a crossroad is, the lower the possibility of WWD movement becomes (Wang et al., 2016). The width of the median between entrance and exit ramps is also believed to affect the possibility of WWD maneuvers. While there is no national guideline on the width of the median to discourage WWD maneuvers, the IDOT's Bureau of Design and Environment (BDE) Manual specifies the width of a median as at least 50 ft between two adjacent entrance and exit ramps for WWD mitigation purposes (IDOT, 2010). This parameter was found to range from as low as 2 ft to up to 150 ft, with an average of about 31 ft. The data also show that medians with widths of more than 60 ft are rarely used; therefore, categories with 10-ft incremental intervals for medians up to 60 ft, plus a separate category for medians more than 60 ft, were considered.

5.2.2.4 Channelizing Island

These elements, in addition to their benefit in defining desirable paths and separating conflict points at intersections (Wolshon, 2004; FHWA, 2013), can be utilized to prohibit or at least discourage undesirable movements, such as WWD. Two types of channelizing islands existed at the studied locations, i.e., flush (traversable) and raised (non-traversable), which are the two categories used for model development. Raised channelizing islands can reduce the width of an exit ramp appropriately compared to the width of adjacent entrance ramp, make WWD movements less probable, and, in case of possible WWD maneuvers, potentially stop at-fault drivers. A height of at least four inches is required for raised channelizing islands to physically reduce WWD maneuvers (IDOT, 2010). Almost all of the locations we studied with raised channelizing islands met this requirement.

5.2.2.5 Intersection Balance

Specifically in case of having two closely-spaced entrance and exit ramps, providing drivers on the crossroad with a better view of the two-way ramp terminals can help drivers distinguish between entrance and exit ramps, thereby alleviating the WWD problem. At these locations, intersection balance requirements can be satisfied with the proper placement of stop lines so that vehicles intending to enter the intersection and proceed to entrance ramps have already entered some percentage of the way into the intersection. However, these percentages for stop line placement in intersections have not been proven mathematically based on crash history.

Washington State DOT manual suggests placing a stop line on the crossroad 51% to 60% (a 10% interval) of the way through the intersection (WSDOT, 213) (Figure 5.1). Therefore, the same incremental intervals (i.e., 10%) were used. Our investigation of the studied locations showed that only 84 out of 172 (i.e., less than half) locations had this feature. Since this variable ranges from 31 to 70% with an average of 53% at the locations in this study, four categories, as defined in Table 5.1, were suggested.

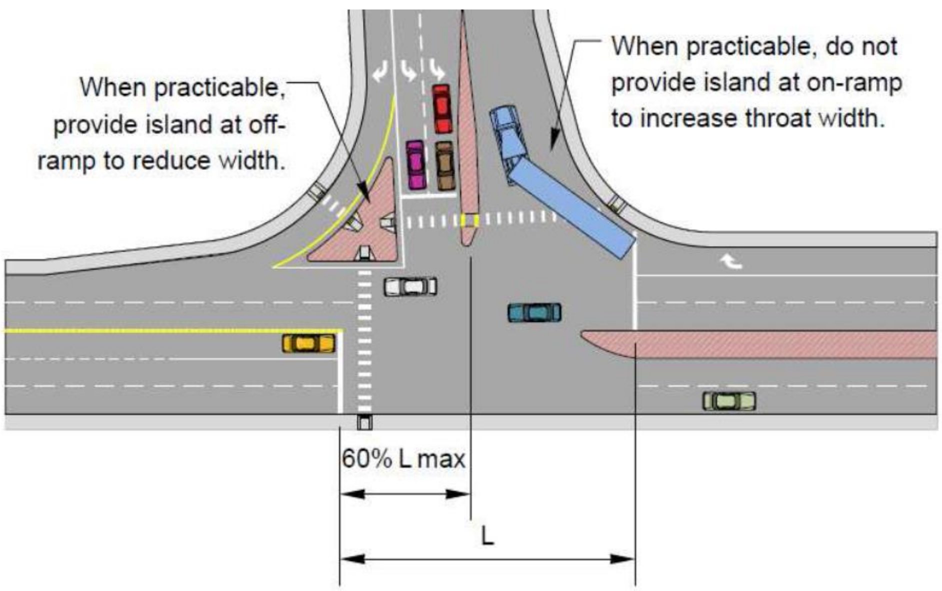


Figure 5.1 Intersection Balance Definition Based on the WSDOT Manual (WSDOT, 2013)

5.2.2.6 Distance to Access Point in the Vicinity of the Interchange

One of the most important challenges in access management literature is the immediate vicinity of access points/side streets and exit ramps. This spacing should be optimized because short spacing disturbs vehicular movements and affects the service life of the interchange, while long distances can reduce vehicular throughput (Zhou et al., 2008; Schultz et al., 2009; Mauga and Kaseko, 2010; Lutin, 2010). Some design manuals specify a minimum distance from the interchange to the first connection along the crossroad. However, the extent to which this spacing can lead to possible WWD maneuvers is unknown. Initial investigation of WWD crash histories showed a correlation between this spacing and the possibility of WWD maneuvers, since some of the studied locations that had a history of WWD were located less than 300 ft from the closest access point. The categories for this variable were defined based on the 300-ft intervals to make a trade-off between the accuracy of the estimations and the capability of developing the model (avoid having categories with zero observations). The values of this variable ranged from 91 to 2,248 ft, with an average of 763 ft.

To get a better visual understanding of these studied elements, Figure 5.2 depicts these elements, including intersection angle, control/corner radius, median, and channelizing island. Intersection balance was also represented in Figure 5.1. The variable access point in the vicinity of interchange is also clearly defined in Figure 5.3.

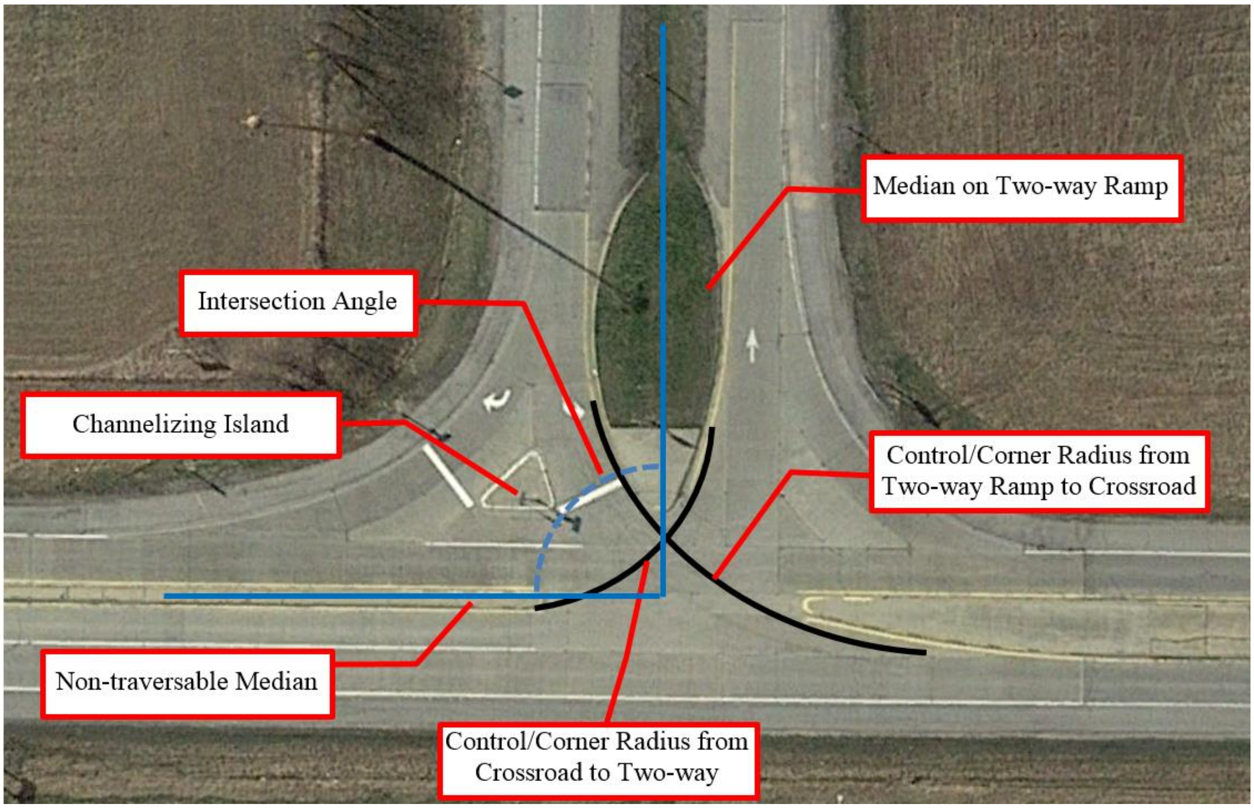


Figure 5.2 Studied Geometric Design Features of the Parclo Interchanges

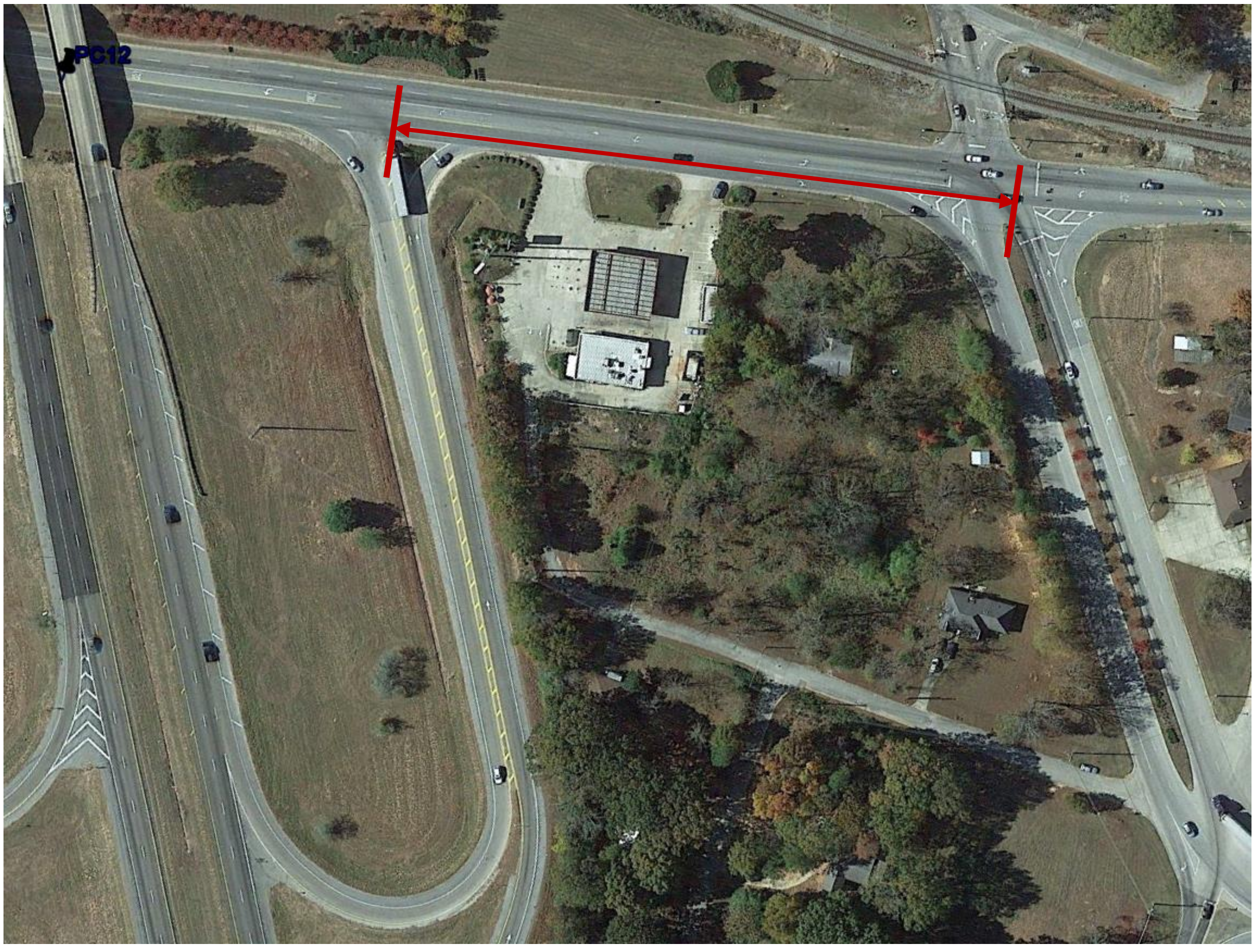


Figure 5.3 Access Point in the Vicinity of Interchange

Table 5.1 presents the descriptive statistics of the abovementioned variables along with defined categories used in the final analysis.

Table 5.1 Descriptive Statistics of the Geometric Design Features

Variable	Category	Locations With History of WWD (n = 54, 31.4%)		Locations Without History of WWD (n = 118, 68.6%)	
		Frequency	Percent	Frequency	Percent
Intersection Angle					
	Acute	9	16.7	33	28.0
	Right	37	68.5	67	56.8
	Obtuse	8	14.8	18	15.3
Control/Corner Radius from Crossroad					
	50 ft and less	5	9.3	12	10.2

51 to 60 ft	5	9.3	13	11.0
61 to 70 ft	10	18.5	24	20.3
71 to 80 ft	13	24.1	31	26.3
81 to 90 ft	11	20.4	18	15.3
91 to 100 ft	6	11.1	10	8.5
More than 100 ft	4	7.4	10	8.5
Control/Corner Radius to Crossroad				
70 ft and less	9	16.7	25	21.2
71 to 80 ft	4	7.4	14	11.9
81 to 90 ft	6	11.1	17	14.4
91 to 100 ft	9	16.7	13	11.0
101 to 110 ft	13	24.1	14	11.9
111 to 120 ft	7	13.0	13	11.0
More than 120 ft	6	11.1	22	18.6
Median on Crossroad				
Non-traversable	30	55.6	79	66.9
Traversable	24	44.4	39	33.1
Median between Exit and Entrance Ramps				
10 ft and less	16	29.6	24	20.3
11 to 20 ft	10	18.5	16	13.6
21 to 30 ft	8	14.8	5	4.2
31 to 40 ft	8	14.8	36	30.5
41 to 50 ft	9	16.7	22	18.6
51 to 60 ft	2	3.7	7	5.9
More than 60 ft	1	1.9	8	6.8
Channelizing Island				
Non-traversable	46	85.2	99	83.9
Traversable	8	14.8	19	16.1
Intersection Balance				
31% to 40%	2	6.9	4	7.3
41% to 50%	6	20.7	19	34.5
51% to 60%	11	37.9	22	40.0
61% to 70%	10	34.5	10	18.2
Distance to Access Point in the Vicinity of the Interchange				
300 ft and less	10	18.5	16	13.6
301 to 600 ft	14	25.9	21	17.8
601 to 900 ft	15	27.8	42	35.6
901 to 1200 ft	7	13.0	17	14.4
1201 to 1500 ft	2	3.7	5	4.2
More than 1500 ft	6	11.1	17	14.4

5.3 Methodology

Given the response variable of the current research, which is dichotomous (i.e., having a history of WWD entry or not), ordinary linear regression will not fit properly because the dichotomous variable does not satisfy the assumptions of homoscedasticity and normality of the error distribution (O'Connell, 2006). Therefore, the problem can appropriately be formulated and handled using a binary logistic model that deals with binary outcomes. This technique has been used extensively in earlier studies related to road safety (Torrão et al., 2014; Larsen et al., 2013; Qin et al., 2013; Sarkar et al., 2011). However, given the low sample size of our data and low number of observation in some categories, which was discussed and determined in Chapter 2 to bias the results, the Firth's model seems more appropriate. This model was explained and used in Chapter 2, showing promising results and outperforming the standard binary logistic model.

In this method, after identifying all possible independent variables, the next step is to determine the subset of these variables that makes the most parsimonious logistic model. A backward elimination method could be proposed using two model selection criteria that are most often utilized for generalized linear models, AIC and BIC. In this research, the AIC was used as follows (Pan, 2001):

$$AIC = 2k - 2L_{\beta} \tag{1}$$

where k is the number of independent variables in the model, and L_{β} is the maximum log-likelihood of the model. As a rule of thumb, the lower the AIC, the better the developed model. Hence, the procedure of using AIC in the backward elimination model selection is so that a full model could be developed that contained all of the independent variables, and the corresponding AIC could be calculated. This process continues by eliminating one variable at a time and comparing the corresponding AIC values until the model with the minimum AIC value is found.

A useful outcome of the model that was developed using binary logistic regression is called the odds ratio (OR). The vector of this value, which is calculated by exponentiating the vector of the resulted β's, defines the change in the odds of an independent variable by increasing it by one unit while the other variables remain constant. Ranging from 0 to infinity, an OR of more than one indicates an increase in the relative odds of the occurrence of WWD, and, conversely, an OR of less than one indicates a decrease in the odds of the occurrence of WWD with one unit increase in the value of the corresponding independent variable.

5.4 Results and Discussion

As can be seen in Table 5.1, more than 50% of the values for the variable Intersection Balance is missing. To avoid any unbiased results due to the high proportion of missing values, this variable was excluded from the final model. However, a separate analysis using crash rate was ran for this variable. For this purpose, the ratio of the locations with a history of WWD to those without WWD history was calculated for each category under this variable and plotted against the categories. The resulting line chart is depicted in Figure 5.4. Based on this figure, with an increase in the intersection balance provided, the WWD-to-non-WWD ratio decreases firstly and an upward trend is observed afterwards. This line chart shows that an intersection balance of 41% to 50% has the lowest crash ratio. This result is not consistent with the proposed intersection balance of 51% to 60% based on the WSDOT Manual. Note that the intersection balance that is provided should not block the path of left-turn vehicles proceeding from the exit ramp to the crossroad.

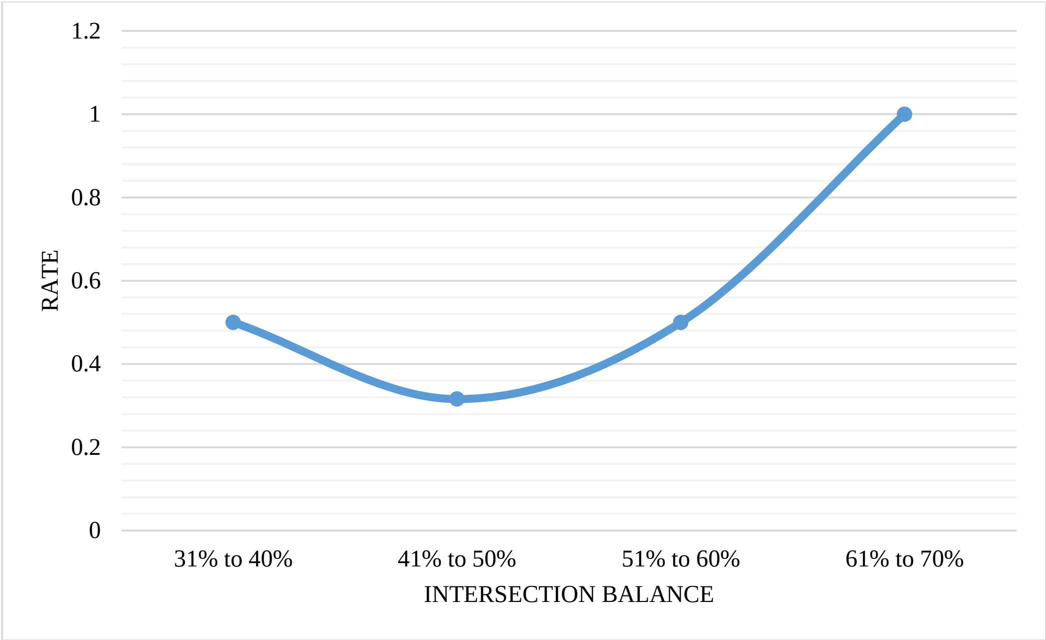


Figure 5.4 The Effect of Intersection Balance of WWD Entries

Excluding the Intersection Balance variable, the remaining independent variables were put in one model, called the full model, and the final model was developed using the backward elimination method based on AIC to minimize this value. Table 5.2 contains the results of the developed Firth's logistic model, including parameter estimates, t-stat, and OR, with the variables (geometric design features) that best explain the probability of WWD entry at the studied intersections. According to this table, among seven identified variables, three of them (angle of intersection, control radius to crossroad, and type of channelizing island) did not enter the final model. The analysis revealed that the independent variables were capable of significantly predicting the probability of WWD entries, indicating the final Firth's logistic model fits significantly better than an empty model with only the intercept.

Table 5.2 Summary of the Final Firth's Logistic Regression Model

Explanatory Variable	Parameter Estimates	t-stat	OR
Control/Corner Radius from Crossroad			
50 ft and less	Reference		
51 to 60 ft	0.352	1.073	1.42
61 to 70 ft	0.729	1.893	2.07
71 to 80 ft	1.150	2.130	3.16
81 to 90 ft	1.499	4.290	4.48
91 to 100 ft	1.138	2.150	3.12
More than 100 ft	0.636	1.247	1.89
Type of Median on Crossroad			
Non-traversable	Reference		
Traversable	0.718	2.331	2.05
Median between Exit and Entrance Ramps			
10 ft and less	Reference		
11 to 20 ft	0.313	2.245	1.37
21 to 30 ft	0.430	1.772	1.54
31 to 40 ft	-1.141	-2.470	0.32
41 to 50 ft	-0.576	-1.752	0.56
51 to 60 ft	-1.037	-1.956	0.35
More than 60 ft	-1.598	-2.769	0.20
Distance to Access Point in the vicinity of the Interchange			
300 ft and less	Reference		
301 to 600 ft	0.315	1.970	1.37
601 to 900 ft	-0.516	-2.371	0.60
901 to 1,200 ft	-0.415	-1.741	0.66
1,201 to 1,500 ft	-0.454	-2.026	0.63
More than 1,500 ft	-0.327	-1.373	0.72
Constant	-1.104	-1.729	–
Number of Observations:	172		
LL at Convergence:	-82.24		
AIC	202.48		
BIC	262.28		

The parameter OR was used to quantify the effect of the geometric design variables of the intersections in the final model on the probability of WWD entry at these locations. As for the radius from the crossroad, its relative effect varied between different categories. As can be seen, the odds of making a WWD entry based on this variable increases until the radius reaches a value of 81 to 90 ft, and a decreasing trend is visible afterwards. To be more specific, the odds of making a WWD entry is almost doubled (OR=2.07) when the radius is in the range of 61 to 70 ft (compared to the range of less than 50 ft as the reference category); however, a sharp increase of more than four times is found when the radius was increased to 81 to 90 ft. This result matches up with the common practice that increasing radius also can increase the possibility of making WWD movements. An important finding regarding this factor was the threshold of the increase in the radius and its effect on the probability of WWD. Based on the findings, engineering judgment, practical constraints, and available data, it is suggested to keep this radius less than 70 ft, since there was a significant change in the probability of a WWD entry when the radii were wider. The review of various locations indicated that this factor defines the opening of the median on the crossroad (if any) and also affects the width of the ramp throat and, consequently, the probability of WWD entries.

Regarding the type of median on the crossroad, traversable medians increase the odds of having WWD entry by more than 100% (OR=2.05). This result coincides with the studied literature, corroborating the role of making non-traversable medians on crossroads to mitigate the problem of WWD entries. Based on the previous research we reviewed, a greater difference between the effects of having non-traversable median instead of a traversable median might have been expected; however, the extension of the median into the intersection, which is usually defined by the radius from crossroad, also should be considered. Furthermore, the visibility and height of the median can also affect their effectiveness in deterring WWD movements and alerting possible at-fault drivers.

In relation with the width of the median between exit and entrance ramps, it was found that two-way ramps with medians of 30 ft or less are more likely to have a history of WWD entries; however, the odds of this occurring was decreased to 0.32 when the width of the median was between 31 and 40 ft. While some states, such as Illinois, suggest having a minimum width of 50 ft for medians between adjacent ramps, which can be a problem at locations with restricted right-of-way (ROW) (IDOT, 2010), this mathematical model indicated that, based on the available data, this minimum value could be reduced to the range of 31 to 40 ft.

With regard to the vicinity of access points to the investigated locations, the access points within 600 ft of the exit ramps appeared to be problematic, having a higher likelihood of resulting in WWD entries than other categories in the final model. Therefore, it was suggested that access points be located at least 600 ft away from two-way ramps to reduce the probability of making WWD maneuvers. One reason these results were obtained for this variable might be the fact that the majority of the studied locations are in urban areas where access points are closer to exit ramps and interchanges, either because of the lower available ROW or higher demand for access to adjacent properties. Either way, it leads to more vehicular activities near the exit ramp, increasing the possibility of distraction and WWD.

5.5 Conclusions

Although there have been publications, guidelines, and manuals on the role of various geometric design elements in WWD entries, no statistical or mathematical approach has ever been used to quantify this role. In this Chapter, a Firth's penalized-likelihood logistic regression model was used, which was introduced and applied earlier, to explore the effect of various geometric design elements at parclo interchanges, as one of the most frequent WWD entry points, based on the available WWD crash data. Despite several previous research projects that have made conclusions based on simple before-and-after studies or by using a few pre-selected, high-crash locations (that biases the results and overestimates the effectiveness of the countermeasures), in this study, a mathematical approach was employed that used data from two states without emphasizing high-crash locations.

It was recognized that a diversity of geometric design factors are capable of significantly affecting the likelihood of the WWD entries, including the control radius from the crossroad, the type of median on the crossroad, the width of the median between the exit and entrance ramps, and the vicinity of the nearest access point to the exit ramp. All of these design factors can have significant effects on WWD events (Pour-Rouholamin et al., 2014). Based on the results, the highest change in OR within the variables belongs to the radius from the crossroad, indicating that this factor should be given special attention in designs that are considering WWD. This variable can define both the extension of the median on the crossroad and between exit and entrance ramps. Furthermore, the presence of non-traversable medians on crossroads was found to decrease the likelihood of WWD entries. Medians with widths of 31 ft or more between exit and entrance ramps also were determined to be less vulnerable to WWD entries at parclo interchanges. The presence of access points within 600 ft of the two-way ramp was found to increase the likelihood of WWD crash entries at the adjacent intersections. Figure 5.5 shows a good example of the application of median on two-way ramp with a width of 42 ft, control/corner radius from crossroad with a radius of 78 ft, and presence of non-traversable median on crossroad.

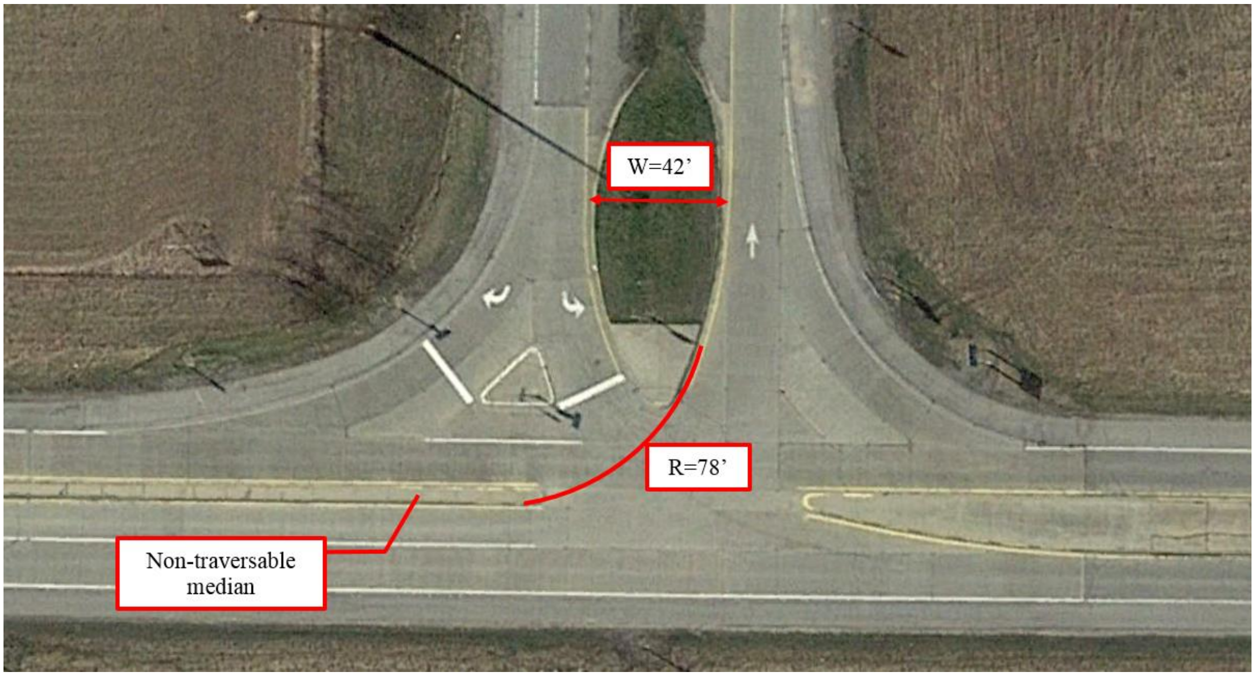


Figure 5.5 A Good Example of the Application of Geometric Design Features At Parclo Interchanges

The results presented in this Chapter indicate that there are differences between the influences of various variables on the probability of WWD entries. Of course, conclusions that are derived based on WWD crashes (and not just WWD incidents, since a high proportion of WWD incidents do not result in WWD crashes) might seem restricted to this severe, high-end outcome, identifying the geometric characteristics of parclo interchanges and their proactive role in preventing those extreme situations is of high importance. Also, this study used crash data from two states in order to support the results that were deduced from a larger database; however, incorporating WWD crash data from other states can strengthen the conclusions even further. Conclusions derived from multiple states will provide more comprehensive knowledge of these geometric features and will help in the development of effective design policies focused on the WWD-prone characteristics of intersections and interchanges.

6 Conclusions and Recommendations

6.1 Conclusions

This dissertation attempted to achieve various objectives: to identify the factors that affect WWD crashes versus non-WWD crashes on controlled-access highways based on the data from Illinois and Alabama, to quantify the role of several factors in the injury severity of WW drivers involved in a WWD crash, to review the existing literature and current practices for mitigating WWD events, and to quantify the effect of various geometric design elements of parclo interchanges on the probability of WWD crash entries. The IDOT and ALDOT crash databases, along with the hardcopy of possible WWD crashes, were used to identify the crashes that were truly caused by WW drivers. Different methods were used and various models were developed to follow the objectives of this dissertation.

At first, a logistic regression model between WWD and other crashes on controlled-access highways was developed to quantify the effect of the contributing factors to WWD crashes and those that affect WWD. Based on the results of the crash data analysis, factors including month of the year, time of day, driver age, driver condition, vehicle age, and lighting conditions were found to affect the likelihood of WWD crashes. Odds ratios (OR) as a measure of relative effectiveness were estimated to quantify the effect of these variables. Accordingly, drivers of age 65 years and older are more likely to affect WWD crashes (OR=4.73), to suffer from illness (OR=20.14), to be under the influence of alcohol and drugs (OR=28.99), to drive during the nighttime (OR=1.98) when there will probably not be ample lighting, and to drive vehicles older than five years ($OR_{5\text{-}15years}$=1.41; $OR_{more\ than\ 15\ years}$=2.42).

The next step was to go further in detail of the contributing factors and quantify the effect of various factors in the injury severity outcome for the WW driver. In doing so and considering the ordered nature of severity sustained by the drivers, three ordered-response models (i.e., PO, GOL, and PPO models) were proposed and based on the AIC, BIC, and likelihood at convergence, the PPO model was found most appropriate. The results of this model showed that factors such as DUI driving, not using seatbelt, driving during nighttime when the darkness condition is prevalent, airbag deployment, crashes happened in rural areas, and having a head-on WWD crash significantly increase the severity of injuries. On the other hand, older drivers, crashes happened in the afternoon, and crash occurrence on wet roadways are shown to decrease the driver injury severity in a WWD crash.

In addition to analyzing crash data, a Firth's penalized-likelihood logistic regression model was used to identify the role of various geometric design elements at parclo interchanges (as one of the most WWD-prone interchange type). Accordingly, it was found that having a control/corner radius (from crossroad) of more than 80 feet can considerably increase the probability of WWD crashes (OR=4.48). Non-traversable medians on crossroads are also more than twice (OR=2.05) more likely to experience WWD crash entries. As for the median width on two-way ramps, medians of more than 31 feet can considerably decrease the likelihood of WWD crash entries at parclo interchanges. Regarding the vicinity of access points to the investigated locations, the access points within 600 feet of the exit ramps appeared to be problematic, having a higher likelihood of resulting in WWD entries than other categories in the final model.

6.2 Recommendations

The results of this dissertation identified the significant contributing factors to WWD crashes and its severity as well as those that can affect WWD entries based on crash data. The general countermeasures can be recommended to be implemented in two phases. Phase one focuses on short-term, low-cost countermeasures, such as regular maintenance and inspection of the existing signage and pavement markings. Phase two is a long-term, systematic approach on improving geometric design elements and implementing advanced ITS technologies.

6.2.1 Short-term, Low-cost Countermeasures

As discussed in Chapter 4, a potential WWD maneuver might occur due to lack of supplemental signage for preventing such a maneuver, lack of proper supplemental pavement markings, or lack of a directional traffic signal head for guiding the driver in the correct direction. These types of countermeasures are mainly related to traditional signage, pavement markings, and traffic signal indications. For instance, given the fact that WWD crashes are more likely to happen during night and in the darkness condition based on the findings of Chapter 2, the use of optional visual enhancement, such as red retroreflective strips on sign supports, is suggested. Furthermore, signs need to be checked regularly to assure the highest visibility to convey the intended message is achieved (Khalilikhah and Heaslip, 2016). As for the traffic signal for the intersection of an exit ramp and crossroad, changing the signal indication from circular green to green arrow for through traffic only lanes might be helpful. Other visibility enhancement techniques that presented in Chapter 4 can also be considered.

6.2.2 Long-term, Systematic Countermeasures

Long-term countermeasures can entail a more comprehensive 4 E's approach (engineering, education, enforcement, and emergency response). Ponnaluri (2016a) suggested a policy-oriented framework to address WWD crashes that incorporates several aspects of WWD crashes including engineering and educational countermeasures. It is recommended that a multidisciplinary WWD inspection team conduct further field reviews of the confirmed WWD entry points and develops site specific countermeasures. In addition to improving WW-related traffic control devices, some geometric design improvements can also be recommended at parclo interchanges. One of the recommendations regarding interchange design is to avoid parclo interchanges in the future design, where possible. However, if not practically feasible, the following recommendations and considerations may help address the issue based on this study results. It is suggested to use a raised median and extend it into the intersection (if possible), as it is shown to help mitigate WWD entries. Furthermore, use of channelizing islands is proposed at the exit ramp throat. The data analysis indicates the proper control/corner radius from the crossroad into two-way ramps can reduce the probability of WWD crash entries at parclo interchanges. Accordingly, radii of more than 80 feet for left turns from crossroads are not recommended as they are associated with higher probability of WWD entries. Although the vicinity of access points to the exit ramps is shown to increase the probability of WWD crashes, relocating these access points may be difficult, as this is governed by factors such as accessibility and vehicular movement and throughput as well as availability of ROW. However, the increased probability of WWD crashes when the access point is within 600 feet of the two-way ramp of parclo interchanges should be kept in mind. Another suggestion under geometric improvements is the use of roundabouts at the exit ramp-crossroad intersection as a roundabout has a directional movement geometric form which is very effective at reducing the occurrence of WW entries.

Taking a systemic approach to WWD can help identify the higher risk characteristics associated with this problem, which in turn leads to identification of strategies and countermeasures to mitigate or reduce these risks. A systemic process to address WWD is not limited to engineering countermeasures. It can also inform strategies for enforcement, such as campaigns or locations to reduce impaired driving; and education, by targeting older and potential DUI audiences.

Education strategies can be implemented to improve public awareness and understanding of (1) the basics of road designs and interchange types, (2) potential risks, (3) what to do when witnessing a WW driver, and (4) possible damages to family and/or society. Education programs should emphasize older drivers and DUI drivers. These programs can focus on the driving abilities of senior drivers and be supplemented with a self-assessment questionnaire to help senior drivers identify their challenges and abilities to drive safely. In terms of driver's condition, specifically drunk driving as one of the contributing factors, campaigns to raise awareness of drunk driving can reduce the frequency and severity of WWD crashes.

Enforcement strategies that were reviewed in Chapter 4 and could be implemented include data-driven DUI checkpoints, stopping WW drivers by using portable spike barriers, and using radio and DMS to warn RW drivers of oncoming WW drivers. An advanced detection and warning system can be implemented by coordinating with TMCs and incident responders to enable quick actions to stop WWD before crashes occur. Some ITS automatic WW monitoring and warning systems were found to be effective because they quickly notify law enforcement, who can respond immediately. In the future of vehicle industry and with the advent of Automated vehicles (autonomous and connected vehicle or AV/CV), WWD can be more effectively targeted with advanced detection and notification. Finley et al. (2016) have recently completed a task that develops concept of operations and functional requirements for a CV WWD detection and management system.

References

Abdel-Aty, M. (2003). Analysis of driver injury severity levels at multiple locations using ordered probit models. *Journal of safety research*, *34*(5), 597-603.

Abegaz, T., Berhane, Y., Worku, A., Assrat, A., & Assefa, A. (2014). Effects of excessive speeding and falling asleep while driving on crash injury severity in Ethiopia: A generalized ordered logit model analysis. *Accident Analysis & Prevention*, *71*, 15-21.

Abu-Zidan, F. M., & Eid, H. O. (2015). Factors affecting injury severity of vehicle occupants following road traffic collisions. *Injury*, 46(1), 136-141.

Abu-Zidan, F. M., Abbas, A. K., Hefny, A. F., Eid, H. O., & Grivna, M. (2012). Effects of seat belt usage on injury pattern and outcome of vehicle occupants after road traffic collisions: prospective study. *World journal of surgery*, 36(2), 255-259.

Al-Ayyash, Z., Abou-Zeid, M., & Kaysi, I. (2016). Modeling the demand for a shared-ride taxi service: An application to an organization-based context. *Transport Policy*, *48*, 169-182.

American Association of State Highway and Transportation Officials (AASHTO). (2011). *A Policy on Geometric Design of Highways and Streets (Green Book)*. Washington, D.C.

American Traffic Safety Services Association (ATSSA). (2014). *Emerging Safety Countermeasures for Wrong-way Driving*. Fredericksburg, VA, 2014.

Amoh-Gyimah, R., Saberi, M., & Sarvi, M. (2016). Macroscopic modeling of pedestrian and bicycle crashes: a cross-comparison of estimation methods. *Accident Analysis & Prevention*, *93*, 147-159.

Anastasopoulos, P. C. (2016). Random parameters multivariate tobit and zero-inflated count data models: Addressing unobserved and zero-state heterogeneity in accident injury-severity rate and frequency analysis. *Analytic Methods in Accident Research*, *11*, 17-32.

Behnood, A., & Mannering, F. L. (2015). The temporal stability of factors affecting driver-injury severities in single-vehicle crashes: Some empirical evidence. *Analytic Methods in Accident Research*, 8, 7-32.

Bella, F., Calvi, A., & D'Amico, F. (2014). Analysis of driver speeds under night driving conditions using a driving simulator. *Journal of safety research*,*49*, 45-e1.

Boes, S., & Winkelmann, R. (2006). Ordered response models. In *Modern Econometric Analysis* (pp. 167-181). Springer Berlin Heidelberg.

Boufous, S., Finch, C., Hayen, A., & Williamson, A. (2008). The impact of environmental, vehicle and driver characteristics on injury severity in older drivers hospitalized as a result of a traffic crash. *Journal of safety Research*, *39*(1), 65-72.

Braam, A. C. (2006). Wrong-way Crashes: Statewide Study of Wrong-way Crashes on Freeways in North Carolina. North Carolina Department of Transportation.

Brant, R. (1990). Assessing proportionality in the proportional odds model for ordinal logistic regression. *Biometrics*, 1171-1178.

California Department of Transportation (Caltrans). (2014). *Highway Design Manual*. Sacramento, CA.

Campbell, B. E., & Middlebrooks, P. B. (1988). *Wrong-way Movements on Partial Cloverleaf Ramps. Final Report* (No. FHWA-GA-88-8203).

CARE. (2015). Critical Analysis Reporting Environment. Alabama Traffic Crash Statistics. http://care.cs.ua.edu. Accessed October 10, 2015.

Celik, A. K., & Oktay, E. (2014). A multinomial logit analysis of risk factors influencing road traffic injury severities in the Erzurum and Kars Provinces of Turkey. *Accident Analysis & Prevention*, *72*, 66-77.

Chacon, M. A., and B. G. Fariello. Wrong Way Driver Initiative. In *Proceedings of the 2013 National Wrong-Way Driving Summit*, 2014, pp. 173-185.

Chassande-Mottin, R., and F. Ganneau. (2008). How to Fight Wrong Way Driving Accidents. *Proceedings of the Transport Research Arena Europe (TRA)*, Ljubljana, Slovenia.

Chen, E., & Tarko, A. P. (2014). Modeling safety of highway work zones with random parameters and random effects models. *Analytic methods in accident research*, *1*, 86-95.

Chen, F., & Chen, S. (2011). Injury severities of truck drivers in single-and multi-vehicle accidents on rural highways. *Accident Analysis & Prevention*, *43*(5), 1677-1688.

Christoforou, Z., Cohen, S., & Karlaftis, M. G. (2010). Vehicle occupant injury severity on highways: an empirical investigation. *Accident Analysis & Prevention*, 42(6), 1606-1620.

Chrysler, S. T., & Schrock, S. D. (2005). *Field Evaluations and Driver Comprehension Studies of Horizontal Signing* (No. FHWA/TX-05/0-4471-2). Texas Transportation Institute, Texas A & M University System.

Clark, D. E. (2001). Motor vehicle crash fatalities in the elderly: rural versus urban. *Journal of Trauma and Acute Care Surgery*, *51*(5), 896-900.

Clarke, D. D., Ward, P., Bartle, C., & Truman, W. (2006). Young driver accidents in the UK: The influence of age, experience, and time of day. *Accident Analysis & Prevention*, *38*(5), 871-878.

Clay, R. S. (2011). *The San Antonio Wrong Way Driver Initiative - US 281 Pilot Project*. San Antonio District. Texas Department of Transportation (TxDOT). Austin, TX.

Cooner S. A., A. S. Cothron, and S. E. Ranft. (2004a). *Countermeasures for Wrong-way Movement on Freeway: Guidelines and Recommendation Practices*. Publication FHWA/TX-04/4128-2. Texas Transportation Institute.

Cooner S. A., A. S. Cothron, and S. E. Ranft. (2004b). *Countermeasures for Wrong-way Movement on Freeway: Overview of Project Activities and Findings*. Publication FHWA/TX-04/4128-1. Texas Transportation Institute.

Cooner, S. A., & Ranft, S. E. (2008). Wrong-Way Driving on Freeways: Problems, Issues, and Countermeasures. In *Transportation Research Board 87th Annual Meeting*.

Copelan, J. E. (1989). *Prevention of wrong way accidents on freeways*. Publication FHWA/CA-TE-89-2. California Department of Transportation

Cummins, J. S., Koval, K. J., Cantu, R. V., & Spratt, K. F. (2011). Do seat belts and air bags reduce mortality and injury severity after car accidents. *Am J Orthop* (Belle Mead NJ), 40(3), E26-E29.

Dailisan, D. N., & Lim, M. T. (2016). Agent-based modeling of lane discipline in heterogeneous traffic. *Physica A: Statistical Mechanics and its Applications*, *457*, 138-147.

Deng, Z., Ivan, J., & Gårder, P. (2006). Analysis of factors affecting the severity of head-on crashes: Two-lane rural highways in connecticut. *Transportation Research Record: Journal of the Transportation Research Board*, (1953), 137-146.

Dimitriou, L., & Vlahogianni, E. I. (2015). Fuzzy modeling of freeway accident duration with rainfall and traffic flow interactions. *Analytic Methods in Accident Research*, *5*, 59-71.

Dubey, S. K., Ponnu, B., & Arkatkar, S. S. (2012). Time gap modeling under mixed traffic condition: A statistical analysis. *Journal of Transportation Systems Engineering and Information Technology*, *12*(6), 72-84.

Eisele, W., Frawley, W., Park, E., & Robertson, J. (2012). Safety and economic impacts of converting two-way frontage roads to one-way operation. *Transportation Research Record: Journal of the Transportation Research Board*, (2301), 66-75.

Eluru, N., & Bhat, C. R. (2007). A joint econometric analysis of seat belt use and crash-related injury severity. *Accident Analysis & Prevention*, *39*(5), 1037-1049.

Eluru, N., Bhat, C. R., & Hensher, D. A. (2008). A mixed generalized ordered response model for examining pedestrian and bicyclist injury severity level in traffic crashes. *Accident Analysis & Prevention*, *40*(3), 1033-1054.

Eyler, D. (2005). Arterial interchange. *Transportation Research Record: Journal of the Transportation Research Board*, (1912), 65-71.

Federal Highway Administration (FHWA). (2013). *Signalized Intersections Informational Guide, 2nd Edition*. http://safety.fhwa.dot.gov/intersection/signalized/13027/index.cfm.

Finley, M.D., Balke, K. N., Rajbhandari, R., Chrysler, S. T., Dobrovolny, C. S., Trout, N. D., Avery, P., Vickers, D., & Mott, C. (2016). *Conceptual Design of a Connected Vehicle Wrong-Way Driving Detection and Management System*. FHWA/TX-16/0-6867-1, Austin: Texas Department of Transportation.

Finley, M. D., Venglar, S. P., Iragavarapu, V., Miles, J. D., Park, E. S., Cooner, S. A., & Ranft, S. E. (2014). *Assessment of the Effectiveness of Wrong Way Driving Countermeasures and Mitigation Methods*. FHWA/TX-15/0-6769-1, Austin: Texas Department of Transportation.

Firth, D. (1993). Bias reduction of maximum likelihood estimates. *Biometrika*, *80*(1), 27-38.

Gao, S., & Shen, J. (2007). Asymptotic properties of a double penalized maximum likelihood estimator in logistic regression. *Statistics & probability letters*, *77*(9), 925-930.

Geedipally, S., Turner, P., & Patil, S. (2011). Analysis of motorcycle crashes in Texas with multinomial logit model. *Transportation Research Record: Journal of the Transportation Research Board*, (2265), 62-69.

Ghasemi, S. H., Jalayer, M., Pour-Rouholamin, M., Nowak, A. S., & Zhou, H. (2016). State-of-the-art model to evaluate space headway based on reliability analysis. *Journal of Transportation Engineering*, 04016023.

Gibbons, R., Edwards, C., Bhagavathula, R., Carlson, P., & Owens, D. (2012). Development of visual model for exploring relationship between nighttime driving behavior and roadway visibility features. *Transportation Research Record: Journal of the Transportation Research Board*, (2298), 96-103.

Glisky, E. L. (2007). Changes in cognitive function in human aging. *Brain aging: models, methods, and mechanisms*, 3-20.

Haleem, K., & Abdel-Aty, M. (2010). Examining traffic crash injury severity at unsignalized intersections. *Journal of safety research*, *41*(4), 347-357.

Haque, M. M., Chin, H. C., & Huang, H. (2009). Modeling fault among motorcyclists involved in crashes. *Accident Analysis & Prevention*, *41*(2), 327-335.

Harwood, D. W., & Glauz, W. D. (2000). Synthesis of Highway Practice 281: Operational Impacts of Median Width on Larger Vehicles. *National Cooperative Highway Research Program (NCHRP), Transportation Research Board, Washington, DC, 26*.

HCTRA. (2012). *Incident Management: Annual Report*. Harris County Toll Road Authority (HCTRA). Houston, TX.

Heaslip, K., Bosworth, R., Barnes, R., Soltani-Sobh, A., & Thomas, M. (2015). *Do Changing Prices Portend a Shift in Fuel Consumption, Diminished Greenhouse Gas Emissions, and Lower Fuel Tax Revenue?* (No. MPC 15-278).

Heaslip, K., Bosworth, R., Barnes, R., Soltani-Sobh, A., Thomas, M., & Song, Z. (2014). *Effects of natural gas vehicles and fuel prices on key transportation economic metrics* (No. WA-RD 829.1).

Heinze, G., & Schemper, M. (2002). A solution to the problem of separation in logistic regression. *Statistics in medicine*, *21*(16), 2409-2419.

Heinze, G., Ploner, M., Dunkler, D., & Southworth, H. (2013). logistf: Firth's bias reduced logistic regression. *R package version*, *1*.

Hong, J., Shankar, V. N., & Venkataraman, N. (2016). A spatially autoregressive and heteroskedastic space-time pedestrian exposure modeling framework with spatial lags and endogenous network topologies.*Analytic methods in accident research*, *10*, 26-46.

Hosmer Jr, D. W., Lemeshow, S., & Sturdivant, R. X. (2013). *Applied logistic regression* (Vol. 398). John Wiley & Sons.

Hu, W., & Donnell, E. T. (2010). Median barrier crash severity: Some new insights. *Accident Analysis & Prevention*, *42*(6), 1697-1704.

Illinois Department of Transportation (IDOT). (2010). *Bureau of Design and Environment (BDE) Manual*. Springfield, IL.

Institute of Traffic Accident Research and Data Analysis (ITARDA) (2002.. Highway Accidents Involving Dangerous Wrong-way Traveling. http://www.itarda.or.jp/itardainfomation/english/info36/36top.html, Accessed November 11, 2015.

Jafari-Anarkooli, A., & Hadji-Hosseinlou, M. (2016). Analysis of the Injury Severity of Crashes by Considering Different Lighting Conditions on Two-Lane Rural Roads. *Journal of Safety Research*, 56, 57-65.

Kaplan, S., & Prato, C. G. (2012). Risk factors associated with bus accident severity in the United States: A generalized ordered logit model. *Journal of safety research*, *43*(3), 171-180.

Karhunen, M. (2003). Wrong way driving on motorways; Frequency, reasons and prevention. Helsinki: Tiehallinto, Finnish National Road Administration.

Karoń, G., & Mikulski, J. (2012). Modelling of Transportation Systems in Agglomerations for ITS Solutions. *IFAC Proceedings Volumes*, *45*(4), 74-79.

Kemel, E. (2015). Wrong-way driving crashes on French divided roads.*Accident Analysis & Prevention*, *75*, 69-76.

Keskinen, E. (2014). Education for older drivers in the future. *IATSS research*, *38*(1), 14-21.

Khalilikhah, M., & Heaslip, K. (2016). Important Environmental Factors Contributing to the Temporary Obstruction of the Sign Messages. In *Transportation Research Board 95th Annual Meeting* (No. 16-3785).

Khalilikhah, M., Habibian, M., & Heaslip, K. (2016). Acceptability of increasing petrol price as a TDM pricing policy: A case study in Tehran. *Transport Policy*,*45*, 136-144.

Khalilikhah, M., Heaslip, K., & Song, Z. (2015). Can daytime digital imaging be used for traffic sign retroreflectivity compliance?. *Measurement*, *75*, 147-160.

Khattak, A. J., Pawlovich, M. D., Souleyrette, R. R., & Hallmark, S. L. (2002). Factors related to more severe older driver traffic crash injuries. *Journal of Transportation Engineering*, *128*(3), 243-249.

Khattak, A., & Rocha, M. (2003). Are SUVs" Supremely Unsafe Vehicles"?: Analysis of Rollovers and Injuries with Sport Utility Vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, (1840), 167-177.

Khorashadi, A., Niemeier, D., Shankar, V., & Mannering, F. (2005). Differences in rural and urban driver-injury severities in accidents involving large-trucks: an exploratory analysis. *Accident Analysis & Prevention*, 37(5), 910-921.

Kim, J. K., Ulfarsson, G. F., Kim, S., & Shankar, V. N. (2013). Driver-injury severity in single-vehicle crashes in California: a mixed logit analysis of heterogeneity due to age and gender. *Accident Analysis & Prevention*, *50*, 1073-1081.

Kim, J. K., Ulfarsson, G. F., Shankar, V. N., & Mannering, F. L. (2010). A note on modeling pedestrian-injury severity in motor-vehicle crashes with the mixed logit model. *Accident Analysis & Prevention*, *42*(6), 1751-1758.

King, G., & Zeng, L. (2001). Logistic regression in rare events data. *Political analysis*, *9*(2), 137-163.

Klassen, J., El-Basyouny, K., & Islam, M. T. (2014). Analyzing the severity of bicycle-motor vehicle collision using spatial mixed logit models: A City of Edmonton case study. *Safety science*, *62*, 295-304.

Kockelman, K. M., & Kweon, Y. J. (2002). Driver injury severity: an application of ordered probit models. *Accident Analysis & Prevention*, *34*(3), 313-321.

Kuypers, K. P., Samyn, N., & Ramaekers, J. G. (2006). MDMA and alcohol effects, combined and alone, on objective and subjective measures of actual driving performance and psychomotor function. *Psychopharmacology*, *187*(4), 467-475.

Larsen, K., Buliung, R., & Faulkner, G. (2013). Safety and School Travel: How Does the Environment Along the Route Relate to Safety and Mode Choice?. *Transportation Research Record: Journal of the Transportation Research Board*, (2327), 9-18.

Lathrop, S. L., Dick, T. B., & Nolte, K. B. (2010). Fatal Wrong-Way Collisions on New Mexico's Interstate Highways, 1990–2004. *Journal of forensic sciences*, *55*(2), 432-437.

Leduc, J. K. (2008). *Wrong-way Driving Countermeasures*. http://www.cga.ct.gov/2008/rpt/2008-r-0491.htm

Lee, C., & Li, X. (2014). Analysis of injury severity of drivers involved in single-and two-vehicle crashes on highways in Ontario. *Accident Analysis & Prevention*, *71*, 286-295.

Lemoine, P. D., Cordovez, J. M., Zambrano, J. M., Sarmiento, O. L., Meisel, J. D., Valdivia, J. A., & Zarama, R. (2016). Using agent based modeling to assess the effect of increased Bus Rapid Transit system infrastructure on walking for transportation. *Preventive medicine*, *88*, 39-45.

Liaw, A., and M. Wiener. Package 'randomForest'. https://cran.r-project.org/web/packages/randomForest/randomForest.pdf.

Long, J. Scott (1997). Regression Models for Categorical and Limited Dependent Variables. Thousand Oaks, CA: Sage Publications.

López, G., Abellán, J., Montella, A., & de Oña, J. (2014). Patterns of Single-Vehicle Crashes on Two-Lane Rural Highways in Granada Province, Spain: In-Depth Analysis Through Decision Rules. *Transportation Research Record: Journal of the Transportation Research Board*, (2432), 133-141.

Louviere, J. J., Hensher, D. A., & Swait, J. D. (2000). *Stated choice methods: analysis and applications*. Cambridge University Press.

Lutin, J. (2010). Proposal for Incorporating Public Transit Provisions into a State Highway Access Management Code. *Transportation Research Record: Journal of the Transportation Research Board*, (2171), 52-56.

Mauga, T., & Kaseko, M. (2010). Modeling and evaluating safety impacts of access management features in the Las Vegas, Nevada, Valley. *Transportation Research Record: Journal of the Transportation Research Board*, (2171), 57-65.

Mergia, W. Y., Eustace, D., Chimba, D., & Qumsiyeh, M. (2013). Exploring factors contributing to injury severity at freeway merging and diverging locations in Ohio. *Accident Analysis & Prevention*, *55*, 202-210.

Miles, J., Carlson, P., Ullman, B., & Trout, N. (2008). Red Retroreflective Raised Pavement Markings: Driver Understanding of Their Purpose. *Transportation Research Record: Journal of the Transportation Research Board*, (2056), 34-42.

Minge, E. D. (2013). *Emergency Medical Services Response to Motor Vehicle Crashes in Rural Areas,* The National Cooperative Highway Research Program (NCHRP), Synthesis 451, (No. Project 20-05 (Topic 43-15)).

Minnesota Department of Transportation (MnDOT). (2009). *Design-Build Modifications to the Road Design Manual*. St. Paul, MN.

Mohammadian, A., & Miller, E. (2003). Empirical investigation of household vehicle type choice decisions. *Transportation Research Record: Journal of the Transportation Research Board*, (1854), 99-106.

Moler, S. (2002). Stop. You're going the wrong way!. *Public Roads, 66*(2), 24-29.

Morena, D. A., & Leix, T. J. (2012). Where These Drivers Went Wrong.*Public Roads, 75*(6).

Morena, D. A., and K. Ault. (2014). *Michigan Wrong-Way Freeway Crashes*. In *Proceedings of the 2013 National Wrong-Way Driving Summit*, 126-153.

Mulla, Z. D., Eziefule, A. A., & Carrillo, T. (2012). Preeclampsia in Early Adolescence: Dealing With Sparse Data. *Annals of Epidemiology*, *22*(9), 676-677.

National Highway Traffic Safety Administration (NHTSA). (2015). Fatality Analysis Reporting System (FARS) Encyclopedia, Washington, D.C., http://www-fars.nhtsa.dot.gov/main/index.aspx.

National Transportation Safety Board (NTSB), (2012). *Highway Special Investigation Report: Wrong-way Driving*, Publication NTSB/SIR-12/01.

NTTA (2009). Keeping NTTA Roadways Safe: Wrong-Way Driver Task Force Staff Analysis. *North Texas Tollway Authority Board of Directors*.

O'Connell, A. A. (2006). *Logistic regression models for ordinal response variables*. SAGE Publications, Inc., Thousand Oaks, CA.

Ouyang, Y. North Texas Tollway Authority’s (NTTA) Wrong Way Driving Program: from a Traffic Engineer’s Perspective. In *Proceedings of the 2013 National Wrong-Way Driving Summit*, 2014, pp. 81-106.

Pallant, J. (2001). *SPSS Survival Manual: A Step by Step Guide to Data Analysis Using SPSS for Windows (Versions 10 and 11): SPSS Student Version 11.0 for Windows*. Milton Keynes, UK, USA: Open University Press.

Pan, W. (2001). Akaike's information criterion in generalized estimating equations. *Biometrics*, *57*(1), 120-125.

Patil, S., Geedipally, S. R., & Lord, D. (2012). Analysis of crash severities using nested logit model—accounting for the underreporting of crashes. *Accident Analysis & Prevention*, *45*, 646-653.

Perez-Fuster, P., Rodrigo, M. F., Ballestar, M. L., & Sanmartin, J. (2013). Modeling offenses among motorcyclists involved in crashes in Spain. *Accident Analysis & Prevention, 56*, 95-102.

Ponnaluri, R. V. (2016a). Addressing wrong-way driving as a matter of policy: The Florida Experience. *Transport Policy*, *46*, 92-100.

Ponnaluri, R. V. (2016b). The odds of wrong-way crashes and resulting fatalities: A comprehensive analysis. *Accident Analysis & Prevention*, *88*, 105-116.

Pour-Rouholamin, M., & Zhou, H. (2015). Mitigating Wrong-Way Movements Near Interchange Areas Using Access Management Techniques. In *Transportation Research Board 94th Annual Meeting*.

Pour-Rouholamin, M., & Zhou, H. (2016a). Analysis of driver injury severity in wrong-way driving crashes on controlled-access highways. *Accident Analysis & Prevention*, *94*, 80-88.

Pour-Rouholamin, M., & Zhou, H. (2016b). Investigating the risk factors associated with pedestrian injury severity in Illinois. *Journal of safety research*, *57*, 9-17.

Pour-Rouholamin, M., & Zhou, H. (2016c). Effects of Median Widths on Wrong-Way Incidents on Multilane Divided Highways. In *Transportation Research Board 95th Annual Meeting*.

Pour-Rouholamin, M., & Zhou, H. (2016d). Logistic Model to Predict Effect of Various Geometric Design Elements on the Probability of Wrong-Way Entries at Partial Cloverleaf Interchanges. In *Transportation Research Board 95th Annual Meeting* (No. 16-4068).

Pour-Rouholamin, M., H. Zhou, B. Zhang, and R. E. Turochy. (2016). *Comprehensive Analysis of Wrong-Way Driving Crashes on Alabama Interstates*. In *Transportation Research Board 95th Annual Meeting*.

Pour-Rouholamin, M., Huaguo Zhou, & Jeffrey Shaw. (2014). Overview of Safety Countermeasures for Wrong-Way Driving Crashes. *Institute of Transportation Engineers. ITE Journal*, *84*(12), 31.

Pour-Rouholamin, M., Zhou, H., Jalayer, M., & Williamson, M. (2015). Application of Access Management Techniques to Reduce Wrong-Way Driving Near Interchange Areas. *Access Management Theories and Practices*, 236-246.

Pour-Rouholamin, M., Zhou, H., Shaw, J., & Tobias, P. (2015). Current Practices of Safety Countermeasures for Wrong-Way Driving Crashes. In *Transportation Research Board 94th Annual Meeting*.

Qin, X., Wang, K., & Cutler, C. (2013). Logistic regression models of the safety of large trucks. *Transportation Research Record: Journal of the Transportation Research Board*, (2392), 1-10.

Quddus, M. A., Wang, C., & Ison, S. G. (2010). Road traffic congestion and crash severity: econometric analysis using ordered response models. *Journal of Transportation Engineering*, *136*(5), 424-435.

Raub, R. A., Lucke, R. E., & Wark, R. I. (2003). Breath alcohol ignition interlock devices: controlling the recidivist. *Traffic injury prevention*, *4*(3), 199-205.

Rauch, W. J., Ahlin, E. M., Zador, P. L., Howard, J. M., & Duncan, G. D. (2011). Effects of administrative ignition interlock license restrictions on drivers with multiple alcohol offenses. *Journal of Experimental Criminology*, *7*(2), 127-148.

Romo, A., Hernandez, S., & Cheu, R. L. (2013). Identifying precrash factors for cars and trucks on interstate highways: mixed logit model approach. *Journal of transportation engineering*.

Roshandeh, A. M., Agbelie, B. R., & Lee, Y. (2016). Statistical modeling of total crash frequency at highway intersections. *Journal of traffic and transportation engineering (English edition)*, *3*(2), 166-171.

Russo, B. J., Savolainen, P. T., Schneider, W. H., & Anastasopoulos, P. C. (2014). Comparison of factors affecting injury severity in angle collisions by fault status using a random parameters bivariate ordered probit model. *Analytic methods in accident research*, *2*, 21-29.

Sarkar, S., Tay, R., & Hunt, J. (2011). Logistic regression model of risk of fatality in vehicle-pedestrian crashes on national highways in Bangladesh. *Transportation Research Record: Journal of the Transportation Research Board*, (2264), 128-137.

Savolainen, P., & Ghosh, I. (2008). Examination of Factors Affecting Driver Injury Severity in Michigan's Single-Vehicle—Deer Crashes. *Transportation Research Record: Journal of the Transportation Research Board*, (2078), 17-25.

Scaramuzza, G., & Cavegn, M. (2007). Wrong-way drivers: extent-interventions. In The European Transport Conference, Leeuwenhorst Conference Centre, The Netherlands.

Schrock, S., Hawkins Jr, H., & Chrysler, S. (2005). Effectiveness of lane direction arrows as pavement markings in reducing wrong-way movements on two-way frontage roads. *Transportation Research Record: Journal of the Transportation Research Board*, (1918), 63-67.

Schultz, G., Braley, K., & Boschert, T. (2009). Prioritizing access management implementation. *Transportation Research Record: Journal of the Transportation Research Board*, (2092), 57-65.

Shafabakhsh, G., Pour-Rouholamin, M., & Motamedi, M. (2012). Application of Mathematical Approach in Identifying Behavioral Patterns of Route Choice. *Journal of Basic and Applied Scientific Research*, 2(11), 10859-10868.

Soltani-Sobh, A. (2015). *Transportation economics and energy* (Doctoral dissertation, Utah State University).

Soltani-Sobh, A., Heaslip, K., Bosworth, R., & Barnes, R. (2015). Effect of Improving Vehicle Fuel Efficiency on Fuel Tax Revenue and Greenhouse Gas Emissions. *Transportation Research Record: Journal of the Transportation Research Board*, (2502), 71-79.

Soltani-Sobh, A., Heaslip, K., Bosworth, R., Barnes, R., & Yook, D. (2016). An Aggregated Panel Data Analysis to Model Electric Vehicle Adoption Rates. In *Transportation Research Board 95th Annual Meeting* (No. 16-4010).

Stübig, T., Petri, M., Zeckey, C., Brand, S., Müller, C., Otte, D., ... & Haasper, C. (2012). Alcohol intoxication in road traffic accidents leads to higher impact speed difference, higher ISS and MAIS, and higher preclinical mortality. *Alcohol*,46(7), 681-686.

SWOV (2009). Fact sheet: Wrong-way Driving. Leidschendam, the Netherlands. http://www.swov.nl/rapport/Factsheets/UK/FS_Wrong_way_driving.pdf, Accessed November 23, 2015.

Tasic, I., & Porter, R. J. (2016). Modeling spatial relationships between multimodal transportation infrastructure and traffic safety outcomes in urban environments. *Safety science*, *82*, 325-337.

Tay, R., Choi, J., Kattan, L., & Khan, A. (2011). A multinomial logit model of pedestrian–vehicle crash severity. *International journal of sustainable transportation*, *5*(4), 233-249.

Theofilatos, A., Yannis, G., Kopelias, P., & Papadimitriou, F. (2016). Predicting road accidents: a rare-events modeling approach. *Transportation Research Procedia*, *14*, 3399-3405.

Thurman, T. HCTRA's Law Enforcement Approach for Wrong Way Detection & Correction. In *Proceedings of the 2013 National Wrong-Way Driving Summit*, 2014, pp. 160-172.

Torrão, G., Coelho, M., & Rouphail, N. (2014). Modeling the Impact of Subject and Opponent Vehicles on Crash Severity in Two-Vehicle Collisions. *Transportation Research Record: Journal of the Transportation Research Board*, (2432), 53-64.
Torrão, G., Coelho, M., & Rouphail, N. (2014). Modeling the Impact of Subject and Opponent Vehicles on Crash Severity in Two-Vehicle Collisions. *Transportation Research Record: Journal of the Transportation Research Board*, (2432), 53-64.
Van der Paal, B. (2014). A comparison of different methods for modelling rare events data.

Vaswani, N. K. (1977). *Experiments with a divided highway crossing sign to reduce wrong-way driving: progress report no. 1* (No. VHTRC 77-R36).

Wallis, L. A., & Greaves, I. (2002). Injuries associated with airbag deployment. *Emergency medicine journal*, *19*(6), 490-493.

Wang, H., Li, J., Chen, Q. Y., & Ni, D. (2011). Logistic modeling of the equilibrium speed–density relationship. *Transportation research part A: policy and practice*, *45*(6), 554-566.

Wang, X., & Abdel-Aty, M. (2008). Analysis of left-turn crash injury severity by conflicting pattern using partial proportional odds models. *Accident Analysis & Prevention*, *40*(5), 1674-1682.

Washington State Department of Transportation (WSDOT). (2013). *Design Manual*. Olympia, WA.

Williams, A. F. (2003). Teenage drivers: patterns of risk. *Journal of safety research*, *34*(1), 5-15.

Williams, R., 2006. Generalized ordered logit/partial proportional odds models for ordinal dependent variables. *The Stata Journal*, 6 (1), 58–82.

Williamson, M., Jalayer, M., Zhou, H., & Rouholamin, M. P. (2015). A Sensitivity Analysis of Crash Modification Factors of Access Management Techniques in Highway Safety Manual. *Access Management Theories and Practices*, 76.

Wolshon, B. *Toolbox on Intersection Safety and Design*. Louisiana State University, Baton Rouge, LA, 2004.

Wu, Q., Chen, F., Zhang, G., Liu, X. C., Wang, H., & Bogus, S. M. (2014). Mixed logit model-based driver injury severity investigations in single-and multi-vehicle crashes on rural two-lane highways. *Accident Analysis & Prevention*, 72, 105-115.

Xie, Y., Zhao, K., & Huynh, N. (2012). Analysis of driver injury severity in rural single-vehicle crashes. *Accident Analysis & Prevention*, *47*, 36-44.

Xing, J. (2014). Characteristics of wrong-way driving on motorways in Japan. *IET Intelligent Transport Systems*, *9*(1), 3-11.

Xu. S. H., HaiBo, W., QingSong, Z., XiaoFeng, S., XiRong, G., & FuZhou, W. (2012). The median effective volume of crystalloid in preventing hypotension in patients undergoing cesarean delivery with spinal anesthesia. *Revista brasileira de anestesiologia*, *62*(3), 318-324.

Zhang, J., Lindsay, J., Clarke, K., Robbins, G., & Mao, Y. (2000). Factors affecting the severity of motor vehicle traffic crashes involving elderly drivers in Ontario. *Accident Analysis & Prevention*, 32(1), 117-125.

Zhou, H., & Pour-Rouholamin, M. (2014a). *Guidelines for Reducing Wrong-Way Crashes on Freeways*. Illinois Center for Transportation/Illinois Department of Transportation.

Zhou, H., & Pour-Rouholamin, M. (2014b). *Proceedings of the 2013 National Wrong-Way Driving Summit*. Publication FHWA-ICT-14-009. Illinois Center for Transportation, 2014.

Zhou, H., & Pour-Rouholamin, M. (2015). *Investigation of Contributing Factors Regarding Wrong-Way Driving on Freeways, Phase II*. Illinois Center for Transportation/Illinois Department of Transportation.

Zhou, H., Pour-Rouholamin, M., Zhang, B., Wang, J., & Turochy, R. (2016). *A Study of Wrong-Way Driving Crashes in Alabama*. Alabama Department of Transportation.

Zhou, H., Williams, K. M., & Farah, W. (2008). Methodology to evaluate the effects of access control near freeway interchange areas. *Journal of Transportation Engineering*, *134*(12), 504-511.

Zhou, H., Zhao, J., Fries, R., Gahrooei, M. R., Wang, L., Vaughn, B., ... & Ayyalasomayajula, B. (2012). Investigation of contributing factors regarding wrong-way driving on freeways. *FHWA-ICT-12-010*.

Zhou, H., Zhao, J., Pour-Rouholamin, M., & Tobias, P. A. (2015). Statistical characteristics of wrong-way driving crashes on Illinois freeways. *Traffic Injury Prevention*, 16(6), 760-767.

Appendix A: Survey Questionnaire

A Survey on Wrong-Way Crashes and Countermeasures

Name: ____
Agency: ____
City/State: ____________________________________
Email: ____
Phone Number: (   )   -

This survey is to investigate the current and emerging practices and countermeasures employed by different agencies to mitigate wrong-way driving incidents. The estimated completion time is 15 minutes. Please return the completed questionnaire to Mr. **Mahdi Pour-Rouholamin** at the conference or email it to mahdipn@gmail.com

General Questions

1) Do you believe wrong-way driving is a severe problem in your state?

☐ Yes
☐ No

2) Has your state conducted any studies or implemented any countermeasures to reduce wrong-way driving crashes?

☐ Yes
☐ No

If Yes:

- Which types of countermeasures have been implemented to combat wrong-way driving crashes?

☐ Program and Funding
☐ Engineering
☐ Education
☐ Enforcement
☐ 4 E's Program
☐ Other(s):

- Please briefly describe the program and year the program was put in place.

3) Does your state have a wrong-way driving monitor program to obtain information about the location, severity, time of day, etc. for wrong-way collisions?

☐ Yes
☐ No

4) Does your state have any supplement to the MUTCD 2009 to mitigate wrong-way incidents?

☐ Yes
☐ No

5) Does your state have any supplement to the AASHTO Green Book 2011 to mitigate wrong-way incidents?

☐ Yes
☐ No

6) Does your state use extra lighting at locations susceptible to wrong-way maneuvers to reduce the visibility problem during nighttime conditions?

☐ Yes
☐ No

Wrong-Way Related Signage

7) Which of the following traditional signs are being used in your state to mitigate wrong-way issues?

Sign / Location		
Exit Ramp		
Frontage Road		
Divided Highway (along non-ramp sections)		

8) Which of the following (combination of) static signs are being used in your state to mitigate wrong-way issues?

Sign / Location				
Exit Ramp				
Frontage Road				
Divided Highway (along non-ramp sections)				

Other(s)? Please specify/sketch.

9) What methods has your state used to enhance the conspicuity of wrong-way signs? Check all that apply.

☐ Increasing the size of signs
☐ Doubling-up of signs
☐ Adding a second identical sign on the left-hand side of the roadway
☐ Adding one or more red or orange flags
☐ Adding a red or yellow flashing beacon
☐ Adding a strip of retroreflective material to the sign support
☐ Augmenting warning signing with audio alerts or sirens
☐ Making signs internally illuminated
☐ Using border illuminated signs
☐ Other(s)? Please specify:

10) What mounting height does your state use for wrong-way related signs (if different signs are mounted differently, please specify separately in front of each choice below)?

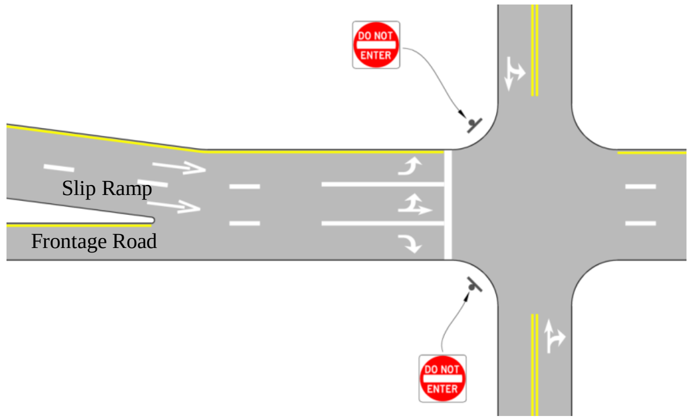
☐ Standard height (7 ft urban/5 ft rural):
☐ Low height:
☐ Overhead:

11) What sizes and where (<u>exit ramps</u>, <u>frontage roads</u>, <u>divided highways</u>) does your state use the following signs to mitigate wrong-way driving issues? Please specify the location in front of each size.

Example: 36 X 36: frontage road
48 X 48: exit ramp

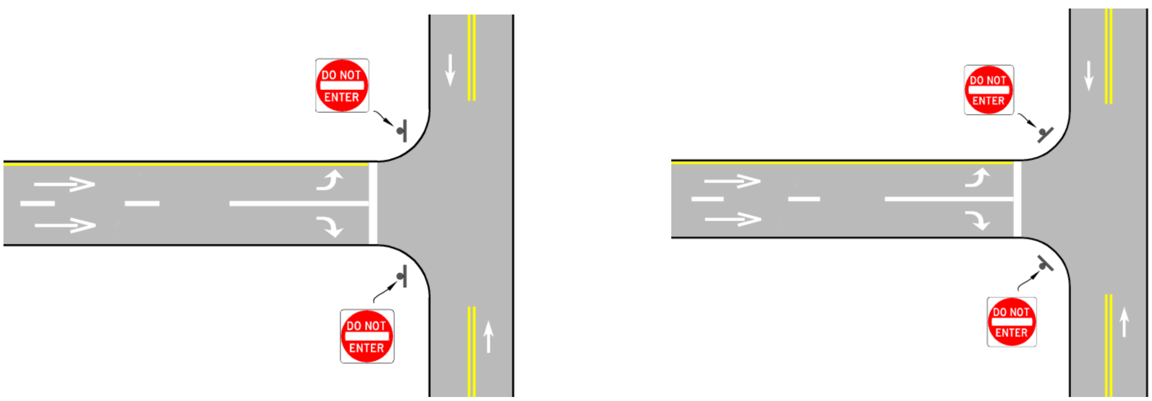
Sign	Size (in)
	30 X 30: 36 X 36: 48 X 48: Other:
	30 X 18: 36 X 24: 42 X 30: Other:
	24 X 24: 36 X 36: 48 X 48: Other:
	36 X 12: 54 X 18: Other:
	18 X 24: 24 X 30: 30 X 36: 36 X 48: 48 X 60: Other:

12) Does your state install DO NOT ENTER signs at the entrance of one-way frontage road connected to slip ramps in order to deter wrong-way maneuvers (figure below)?



☐ Yes
☐ No

13) What is the typical position of the DO NOT ENTER signs in your state (figures below)?



☐ Perpendicular to the roadway

☐ Angled toward the potential wrong-way drivers

Pavement Marking

14) Does your state use wrong-way arrows as described in the MUTCD 2009 on exit ramps (figure below)?

☐ Yes (Please specify the size):
☐ No, other arrows are used (Please specify and/or provide a sketch):

15) Where does your agency place the wrong-way arrows (please check all that apply)?

☐ On the exit ramp near the intersection with crossroad.
☐ At the middle of the exit ramp.
☐ On the exit ramp near the gore point just off the main lane.
☐ On the main lane.

16) Are the pavement markings being used in your state on exit ramps retroreflective (figure below), or is another type of illumination used to make them visible in nighttime conditions?

☐ Retroreflective
☐ Other type of illumination (please specify):

17) Does your state use red-back raised pavement markers (RMPs) on problematic roads (figure below)?

☐ Yes
☐ No

Traffic Signal

18) Does your state use a green arrow as a traffic signal indication at the intersection of exit ramps and crossroads instead of a green ball to provide a better understanding to drivers about the correct movement direction?

☐ Yes
☐ No

Geometric Modification

19) Please rank (using numbers) the following geometric elements that are given special attention when it comes to wrong-way issues, based on your state's policy.

- ___ Medians
- ___ Channelizing islands
- ___ Frontage roads (their continuity, outer separation, etc.)
- ___ Control radius at ramp/crossroad intersection
- ___ Exit ramps (their angle with crossroad, their shape such as button-hook or J-shaped, etc.)
- ___ Type of interchange
- ___ Other(s) (please specify):

ITS Technologies

20) Has your state utilized any ITS technologies to detect and warn drivers?

☐ Yes
☐ No

If yes, which of the following methods are used?

Detection	☐ Radar Detectors ☐ CCTV Camera ☐ Inductive Loop Detectors ☐ Other (please specify):
Caution	☐ In-Pavement Warning Lights (IPWL) ☐ Flashing Wrong Way Signs ☐ Warning Lights ☐ Dynamic Message Signs (DMS) ☐ Other (please specify):
Action	☐ Patrol Units ☐ Spike Strips ☐ Other (please specify):

21) Does your state use dynamic message signs to warn both wrong-way and other drivers if wrong-way driving is detected?

☐ Yes
☐ No

If yes, what message(s) is displayed separately?

- To wrong-way driver:
- To other drivers:

Closing Question

22) Would you recommend elements of the wrong-way driving program to other states? If so, which aspects?

23) Are there any specific items you think should be included in a wrong-way driving mitigation guide?