Investigation of Contributing Factors of Wrong-Way Driving Crashes on Partially/ Uncontrolled-Access Divided Highways

by

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ABSTRACT

Wrong-way driving (WWD) crashes are more likely to pose fatal and serious injuries than other types of highway accidents. This study focuses on differentiating the confounding factors that contribute to WWD crashes from other type of crashes on Alabama divided highways by performing statistical analysis. Crash data from 2009 to 2013, including 112 verified WWD crashes, are compared with 49,599 other type of crashes on the same class of roads during the same period. A simple descriptive data analysis was conducted to identify different explanatory variables contributing to WWD crashes. The results illustrate characteristics of WWD crashes, including temporal distribution, driver characteristics, vehicle characteristics, and environmental conditions. Also, the study provides a comparison of characteristics of WWD crashes between Alabama divided highways and freeways. The Firth's penalized-likelihood logistic regression model was used to identify the statistically significant contributing factors. Odds ratios (OR) of different variables were calculated to measure how each factor affected WWD crashes when compared with other types of crashes. The results show that wrong-way (WW) drivers are more likely to be older and driving under influence (DUI) than other types of crashes on Alabama divided highways. Furthermore, WWD crashes were found to be more prevalent in urban areas and dark road conditions. Dark roadways with no lighting conditions were found to have the largest OR. Additionally, 18 crash entry points are confirmed according to the narratives on crash reports. Among these 18 WWD crashes with known entry points, eight of them occurred at median openings, and six WW drivers entered from parking lots of gas stations or other business area. To complement the analysis, the contributing factors of the fatal WWD crashes were also investigated. Finally, to mitigate WWD activities, countermeasures of three different groups, education, enforcement, and engineering were discussed based on the data analysis results.

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LIST OF ABBREVIATIONS

WWD	Wrong-way Driving
WW	Wrong-way
OR	Odds Ratios
DUI	Driving Under Influence
ALDOT	Alabama Department of Transportation
Caltrans	California Department of Transportation
MLE	Maximum Likelihood Estimation
ITS	Intelligent Transportation System
CARE	Critical Analysis Reporting Environment
CU	Causal Unit
BAC	Blood Alcohol Concentration
NHTSA	National Highway Traffic Safety Administration
MUTCD	Manual on Uniform Traffic Control Devices
TCD	Traffic Control Device
DNE	Do Not Enter
CV	Connected Vehicle

CHAPTER 1

INTRODUCTION

1.1 DEFINITION OF WWD CRASHES ON DIVIDED HIGHWAYS

Wrong-way driving (WWD) is known as vehicular movement along a travel lane in a direction opposing the legal flow of traffic on highways. This study focuses on crashes on partially/uncontrolled-access divided highways (divided highways hereinafter) maintained by Alabama Department of Transportation (ALDOT). For this thesis, a divided highway is considered as a highway with physical separation, and the side streets are its access points. In other words, the difference between this kind of facility and controlled-access highways is the type of access (ramps versus side streets). It has to mention that WWD in this study does not include wrong-way (WW) movements that result from median crossover encroachments.

1.2 GENERAL CHARACTERISTICS OF WWD CRASHES

WWD crashes are relatively infrequent, but they are more likely to cause serious head-on crashes and fatalities compared with other types of crashes. According to a Highway Special Investigation Report from the National Transportation Safety Board (NTSB), an average of 261 fatal WWD crashes occurred per year on U.S. controlled-access highways in which 357 people perished, resulting in almost 1.37 fatalities per WWD fatal crash (NTSB, 2012). A study from 2009 to 2014 on Alabama freeways found that freeway WWD crashes resulted in 18 fatalities in 14 fatal crashes (1.29 fatalities per fatal crashes), while the number for all freeway fatal crashes was 1.13, which translates to 16 more fatalities per 100 fatal crashes than all freeway fatal crashes. Also, from 2009 through 2013, the annual economic costs of WWD crashes on Alabama freeways ranged from $10.7 million to $32.0 million and fatalities account for 86% of total costs imposed by WWD crashes (Pour-Rouholamin et al., 2016 a). Thus, reducing the number of WWD fatal crashes can reduce societal costs considerably.

WWD had raised the attention of transportation agencies for more than 40 years. Previous studies around the United States and other countries show that a significant portion of WWD crashes was caused by driving under the influence (DUI) of alcohol or drugs. Young drivers and older drivers are overrepresented in the WWD crashes. Scaramuzza and Caveg (2007) report that young drivers who performed risky maneuvers after drinking alcohols are especially at risks, while Kemel (2015) in France by using descriptive statistics found it is 15 times possibility for drivers over 65 to be involved in a WWD crashes as drivers under 25. The overwhelming majority of WWD crashes involved are male drivers. Most WWD crashes happened over weekends at nighttime with poor light conditions. Zhou et al. (2012) report that the wrong-way crashes are more frequent during non-daylight hours. That study also finds that the weather and light conditions are considered part of the temporal distribution since both are highly related to the crash time. Additionally, more WWD crashes happened in urban areas than rural areas, and the study also shows that infrastructure characteristics will impact the frequency of WWD crashes. However, few past studies were found to identify contributing factors on divided highways. This study will focus on more comprehensive characteristics of WWD crashes on Alabama divided highways.

1.3 OBJECTIVE OF THE STUDY

The focus of the study is to identify WWD crashes on Alabama divided highways, then to investigate their characteristics and compounding contributing factors by using advanced statistical analysis. Finally, the study will provide a complete set of countermeasures for reducing WWD crashes on divided highways.

In order to have a better understanding of WWD crashes, the author will compare the different contributing factors between WWD crashes and non-WWD crashes on Alabama divided highways. Specifically, five-year crash data will be studied by using logistic data analysis method. A variety of explanatory variables will be applied to the statistical model to check their significance. Additionally, the contributing factors of fatal crashes will also be further investigated and discussed in the study.

The study also aims to identify reliable and low-cost countermeasures to mitigate the WWD crash frequency and severity on divided highways. The countermeasures are generated based on the statistical analysis results and the field review of the high-frequency crash locations in Alabama. The results and findings of this study can help the ALDOT to develop effective interventions to reduce WWD crashes on Alabama divided highways.

1.4 OUTLINE OF THE CHAPTERS

The rest of this thesis is structured as follows. Chapter Two presents a comprehensive review of past and ongoing studies of WWD crashes, including crash data collection and analysis methods. Different countermeasures of WWD crashes, mostly for freeways, are also summarized in this chapter. In Chapter Three, the data-collection procedures, including WWD crash identification and verification, are presented. Two data analysis methods, descriptive statistical analysis and Firth’s penalized-likelihood logistic regression analysis, are introduced. Then, Chapter Four shows the analysis procedure and results, including descriptive statistical analysis results and the Firth’s model outputs. The corresponding odds ratios (OR) are calculated to show the difference among different contributing variables. The additional contributing factors for the fatal WWD crashes are also analyzed in this chapter. Chapter Five summarizes all the findings and countermeasures to reduce WWD crashes based on the final results.

CHAPTER 2

LITERATURE REVIEW

2.1 WWD CRASHES

Previous studies showed that a very small ratio of traffic crashes were caused by WWD, however, WWD crashes are far deadlier than non-WWD crashes. WWD crashes are generally high-speed and opposing-direction accident. The divided highways impose a unidirectional traffic flow, which might be prone to severe head-on collisions. A recent study also shows that the high number of fatalities have been consistent even though total traffic fatalities declined by 4% over the eight-year period from 2004 through 2011（Zhou, et al., 2012）.

A study (Vaswani, 1977) in Virginia found the fatality rate for WW collisions on freeways to be 27 times that of other types of crashes. The California Department of Transportation (Caltrans) found a fatality rate 12 times greater compared to all other accidents on controlled-access highways (Caltrans, 2014). Additionally, WWD crashes can kill drivers and passengers on both right-way and wrong-way. According to a study of New Mexico interstate highway system, 49 fatal WWD crashes happened between 1990 to 2004. Thirty-five drivers and 11 passengers in the wrong-way vehicles were killed among the crashes, 18 drivers and 15 passengers in vehicles traveling in the correct direction were killed as well (Lathrop, 2010). WWD crashes are particularly hazardous and are more possible than other kinds of crashes to result in fatal or incapacitating injuries.

2.2 SCARCE STUDIES OF WWD ON DIVIDED HIGHWAYS

According to the literature, the majority of previous studies of WWD crashes focused on controlled-access highways (freeways) (e.g., see Pour-Rouholamin et al., 2016 a and 2016 b; Zhou et al., 2012, 2014 and 2015; Cooner and Ranft, 2008) instead of partially/ uncontrolled-access highways (divided highways). For the national wide study of WWD, the highway special investigation report of NTSB also only focused on study WWD crashes on the U.S controlled-access highways. Only three states in the U.S. conducted WWD studies focusing on divided highways, and most of the studies were conducted in the 1970s and thus are outdated.

Vaswani (1977) studied how to alleviate WWD crashes on Virginia four-lane divided highways, including interstate routes. Twenty-five months of crash data on 2000 miles of divided highways with 471 identified crashes were collected, and the study investigated the physical aspects of the incident sites from 1970 through 1972. However, the study was mainly about the countermeasures for reducing WWD crashes. Only simple descriptive statistics were used to analyze the causal factors of WWD crashes, such as combination of drunkenness and darkness and WWD entry point. Scifres (1974) studied WWD movement on divided highways in Indiana. Ninety-six WWD crashes were identified from 1970 to 1972. He studied both the characteristics and countermeasures of WWD crashes. The study pointed out that adverse environmental factors (darkness, weather) and external driver stimuli (age, alcohol, fatigue) were the leading causes of drivers' incorrect decision. The Arizona Department of Transportation (2015) recently studied the feasibility of a pilot deployment of a WWD detection and warning system on divided highways. 245 WWD crashes were collected from 2004 to 2014. The study showed simple descriptive characteristics of the crashes. It was found that most of WWD crashes happened during early morning from 12 a.m. to 2 a.m. WWD crashes were more common on weekends, and more than 60% of WW drivers were male. Also, 53% of WWD crashes happened in urban areas.

2.3 MORE EMPIRICALLY ANALYSIS THAN STATISTICALLY ANALYSIS

Kemel (2015) in a study in France indicated that descriptive statistics are informative but cannot always identify predictors. All the previous studies in the United States only use the simple descriptive data to analyze characteristics and contributing factors of WWD crashes on divided highways more empirically than statistically. A more scientific statistical method can be applied to further test the significant contributing factors. Logistic analysis is commonly used in safety analysis to identify the explanatory factors of crashes (e.g., see Poulsen, 2014; Qin, 2013; De Lapparent, 2008), and several WWD studies in the U.S also applied logistic regression models to other road facilities but did not focus on divided highways as in this study.

Lathrop et al. (2010) studied the casual factors of fatal WWD crashes on New Mexico’s interstates by using logistic analysis. They analyzed 875 fatal non-WWD crashes and 49 fatal WWD crashes from 1990 to 2004. Driver alcohol consumption was an affecting factor as well as darkness at 99% significance level. It was also identified that drivers not wearing seatbelts would intensify the crash severity. Ponnaluri (2016) evaluated one million crash records from 2003 to 2010 in Florida, including all kinds of roadway facilities, in order to identify the factors that cause WWD crashes and fatalities. He first conducted a user survey and then developed binomial logistic models for computing the ORs of each variable for WWD crashes and fatal WWD crashes. He found that driver’s age, gender, blood alcohol concentration, driving license state (a proxy to residence), physical defect, and seatbelt use, the purpose for which vehicle was used, facility type, roadway lighting, area of crash, day and time of crash, traffic volume, and other geometric characteristics will affect WWD crash and fatal incidence. Pour-Rouholamin et al. (2016 a) studied 93 WWD crashes on Alabama freeways from 2009 to 2013. The authors mainly compared two logistic regression models, standard binary logistic regression model and Firth's penalized-likelihood logistic regression model to examine the influence of the explanatory variable on the dichotomous dependent variable (WWD versus non-WWD). It was found that a penalized-likelihood model provides more reliable results when the sample size is small, as the model can reduce the small-sample bias (0.16% of Interstate crashes were due to WWD in their model) of the maximum likelihood estimation (MLE) in the logistic regression model.

Only one previous study in France did a detailed logistic statistical study on all the divided roadways, including partially/uncontrolled-access highways and controlled-access highways. Kemel (2015) identified the factors that delineate between 266 wrong-way driving crashes and 22,120 other crashes from 2008 to 2012 on French divided roads. WWD crash characteristics (related to timing, location, vehicle and driver) were compared with 22,120 other crashes that occurred on the same roads over the same period by using a binary logistic regression model. The results showed that WWD crashes were more likely to occur during night hours and on non-freeway roads than other crashes. Also, WW drivers are older, more likely to be intoxicated, to be locals, and to drive older vehicles, which are mainly passenger cars without passengers. However, the database only shows around 1.2% of events (266 WWD versus 22,120 non-WWD crashes). The small sample size may cause bias to the results of the binary model.

2.4 COUNTERMEASURES WITH UNKNOWN IMPACT

Although many engineering countermeausres, including highway design, marking, and signing improvements, have been applied to mitigate WWD on the interstate system since 1950s, the problem of WWD still exists in the United States. Table 1 summarizes various implemented engineering countermeasures by different agencies to reduce WWD crashes， including traffic signs, pavement marking, geometric improvements and ITS technologies. Road design and conventional highway traffic control devices (TCDs) such as pavement arrow markings and signs remain the most implemented safety measures to prevent the WWD crashes (Zhou, 2014; Xing, 2014). ITS devices consist of patrols or electronic devices that can detect WW drivers, like radio or dynamic-sign messages to inform the violator and/or regular users of the risk (Cooner and Ranft, 2008; Scaramuzza and Cavegn, 2007; Vicedo, 2006).

It was summarized that the general countermeasures for WWD include engineering (TCDs, roadway geometry, and ITS), education, and enforcement (emergency response, confinement, and radio messages) (Braam, 2006; Pour-Rouholamin et al., 2014) These countermeasures, especially the ITS countermeasures are often expensive and their impacts have not been proved (Carnis and Kemel, 2014). It is essential to find the contributing factors of WWD crashes in order to select correspondent effective countermeasures.

TABLE 1 Implemented WWD Engineering Countermeasures of Different Agencies

Sign	Pavement Marking	Geometric Improvement	ITS Technology
Implementing standard WW sign package and improved static signs; Lowering sign height; Using oversized signs; Mounting multiple signs on the same post; Applying red retro-reflective strip to the vertical posts	Stop line; WW arrow; Turn/through lane only arrow; Red raised pavement markers; Short dashed lane delineation through turns	Raised curb median; Increasing the elevation of the crossroads; Longitudinal channelizers; Changes in Geometrics: - Obtuse angle - Sharp corner radii	LED illuminated Signs; Dynamic signs – warn other drivers; Use existing GPS; Navigation technologies to provide WW movement alerts; Provide consistent messages or alerts that are intuitive to the driver

CHAPTER 3

DATA COLLECTION AND METHODOLOGY

This chapter provides detailed information of data collection and two analysis methodologies. Section One explains the data obtaining procedures, which include WWD crash identification and crash verification. Section Two contains two data analysis methodologies. The first method is descriptive statistics, used to compare the difference between WWD crashes and non-WWD crashes based on four categories of crash contributing variables. The second is Firth's penalized-likelihood logistic regression model. The author explains why using Firth's logistic model rather than the standard binary logistic model, and gives a brief introduction of Firth's logistic model.

3.1 DATA COLLECTION

3.1.1 Crash Database

Crash data from 2009 to 2013 on Alabama divided highways were collected from Critical Analysis Reporting Environment (CARE) software (2015). CARE is the main software used to gather Alabama crash records. Also, hard copies of the crash reports were requested from ALDOT. The data of crash narrative, diagram, and location are used for further investigation. Two steps, crash identification and crash verification, were taken to find the actual WWD crashes.

3.1.2 WWD Crash Identification

The process of crash identification has two parts: identifying crashes that happened on divided highways and nominating possible WWD crashes for further investigation. To identify crashes on divided highways, a filter in CARE was created to extract crashes on non-controlled-access federal and state highways in which the opposing lane separation variable takes one of the following values: paved surface, unpaved surface, concrete barrier, or metal guardrail. Following this attempt, another filter in CARE was defined on the extracted crashes to identify possible WWD crashes on these facilities. The filter includes these variables, contributing circumstances, vehicle maneuvers, and citations issued for the causal unit and the second vehicle. Two values were considered for all these variables, and they are “traveling wrong way/wrong side” and “wrong side of road”. Initial crash identification found 1,321 possible WWD crashes on divided highways based on contributing circumstances.

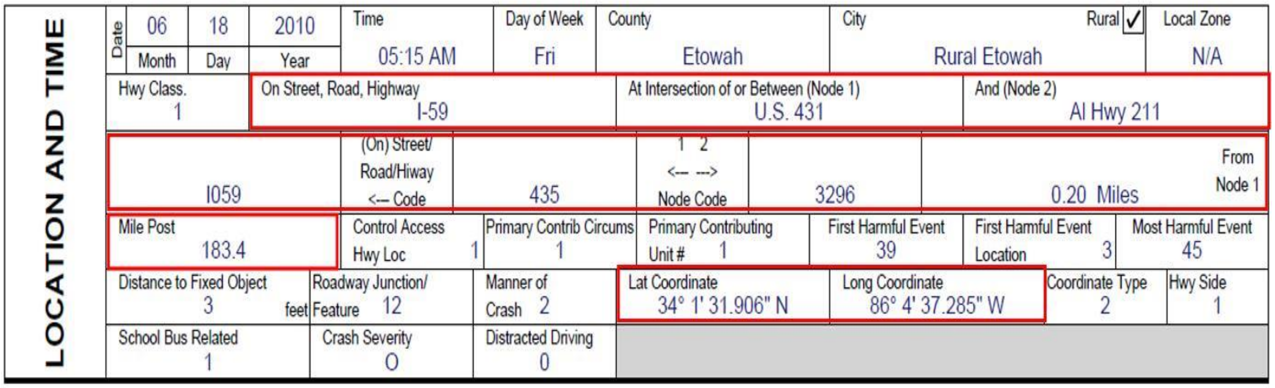
3.1.3 WWD Crash Verification

The process of crash verification also has two parts, verifying those 1,321 possible crashes that happened on divided highways and confirming true WWD crashes. In this study, WWD does not include WWD movements that result from median crossover encroachments on divided highways. Altogether, 112 crashes were validated as actual WWD crashes on divided highways.

To verify the actual WWD crashes on divided highways, crash diagrams in crash report were located on Google Maps due to inaccuracy of the original diagrams on crash reports. Figure 1 shows a Google satellite image as an example to verify the possible WWD crash. A highway with a visible physical median can be considered as divided highway. Crash locations can be identified using several variables under the “Location and Time” section in the crash reports.

These variables include facility name and description, node codes, and coordinates. Figure 1 depicts an example of the "Location and Time" portion of a crash report. As can be seen in Figure 2, other information, such as the mile post and distance from nodes, can be used to correctly pinpoint the crash on Google Maps in case that sometimes the coordinates are not available.

FIGURE 1 An Example to Verify the Location of Possible WWD Crash (Google Earth)



LOCATION AND TIME	Date	06 Month	18 Day	2010 Year	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 Hamful 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 Location and Time Portion of Crash Report (ALDOT)

The second part was to review the narrative description in crash reports to confirm that each crash was 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 “traveling on the wrong side of roadway.”

Finally, the data of 112 actual WWD crashes, and 49,599 non-WWD crashes on the same roads were collected on Alabama divided highways from 2009 to 2013. Table 2 shows the number of crashes under different categories in Alabama.

TABLE 2 Number of Crashes Under Different Categories in Alabama (2009–2013)

Year	2009	2010	2011	2012	2013	Total
Total crashes	123,999	129,608	128,583	128,420	126,634	513,245
Divided Highway Crashes	7,401	10,368	10,643	10,692	10,607	49,711
Possible WWD crashes	465	246	207	209	197	1,321
Actual WWD crashes	28	33	18	18	15	112

3.1.4 Crash Data Cleansing

Data cleansing is an important step before applying the data to create statistical model. It is an assessment of data to determine quality failures (inaccuracy, incompleteness, etc.) and then to improve the quality by correcting as possible any errors found.

A spreadsheet of the 112 “true” WWD crash data with rows representing each crash record and columns representing each attribute extracted from CARE database was created. The attributes for the database entries of each WWD crash were double-checked against the original crash hardcopy report for accuracy. At the same time, all the same attributes of non-WWD crashes on Alabama divided highways were also extracted and stored in a spreadsheet. 49,599 non-WWD crash data with complete attributes were applied in the model. The following shows the inaccuracy and incompleteness of the data from CARE software and they were improved during this step.

1) Some variables were miscoded, such as lighting condition, airbag deployment, seatbelt use, type of crash and Causal Unit (CU) model year;

2) CU driver condition was checked and revised based on the narratives. It was found that the variable BAC (Blood Alcohol Concentration) for some crashes was miscoded as showing “Apparently Normal” or “Other/ Unknown” when the narratives indicated that the driver had positive alcohol/drug test results above the allowed levels. Alcohol test column was also revised based on the hardcopies as a number of test results were not mentioned in the electronic version.

3) The information for the type of injury along with the number of persons injured could not be found in the electronic data file. So, the researchers reviewed all the hardcopy reports one-by-one to include this information in the final dataset.

4) The variable for “Manner of Crash” for some crashes was recorded from the report manually.

5）For the non-WWD crashes, the total number of non-WWD crash happened on Alabama divided highways from 2009 to 2013 is 226,638. However, 177,039 crashes were removed during the data cleansing step due to the incompleteness of the original data. Many attributes of those delated crash data show ‘null value’. Finally, 49,599 non-WWD crash data with complete attributes were kept for further study.

3.2 METHODOLOGY

The purpose of the data analysis is to differentiate between the contributing factors of WWD crashes and other crashes on Alabama divided highways. The comparison relies on descriptive statistical analysis, complemented by a Firth's logistic regression model.

3.2.1 DESCRIPTIVE STATISTICS

In this part of the analysis, the distribution of variables between WWD crashes and non-WWD crashes on divided highways were compared. The data were presented in percentage, in a descriptive perspective. Tables 3 shows different studied attributes of WWD crashes on Alabama divided highways. Five main categories of crash contributing variables were considered: 1) crash severity; 2) temporal distribution; 3) responsible driver characteristics; 4) vehicle characteristics; and 5) environmental condition. Additionally, the study also studied the affecting variables of fatal and non-fatal WWD crashes based on these categories of variables.

TABLE 3 Studied Attributes of WWD Crashes on Alabama Divided Highways

	Variable	Category		Variable	Category
Crash Severity	Crash Type	Fatal Crash	**Temporal Distribution**	Month	January
		Incapacitating			February
		Non-Incapacitating			March
		Possible Injury			April
		PDO			May
	Number of Persons	One			June
		Two			July
		Three and More			August
	Number of Vehicles	One			September
		Two			October
		Three and More			November
Responsible Driver Characteristics	Driver Age	Less than 24			December
		25 to 34 years		Day	Monday
		35 to 44 years			Tuesday
		45 to 54 years			Wednesday
		55 to 64 years			Thursday

		65 years or over
	Driver Gender	Male
		Female
	Driver Race	White/Caucasian
		African American
		Hispanic
		Asian/Pacific Islander
		American Indian
	Driver Condition	Apparently Normal
		DUI
		Asleep/Fainted/Fatigued
		Illness
		Emotional
	Driver Residency Distance	Less than 25 Miles
		Greater than 25 Miles
	CU Driver Seatbelt Use	Belt Used
		Belt Not Used
Environmental Condition	Setting	Rural
		Urban
	Lighting Condition	Daylight
		Dark, Road Lit
		Dark, Road Not Lit
		Dawn/Dusk
	Weather Condition	Clear/Cloudy
		Fog/Mist
		Precipitation
	Roadway Condition	Dry
		Wet

		Friday
		Saturday
		Sunday
	Time	Morning (6-12)
		Afternoon (12-18)
		Evening (18-24)
		Night (0-6)
Vehicle Information	Causal Unit (CU) Type	Passenger Car
		Truck
		SUV
		Van
	Vehicle Age	Less than 5 years
		5 to 15 years
		More than 15 years
		Unknown
	CU Vehicle Damage	Minor/None Visible
		Major Not Disabled
		Major and Disabled
	Vehicle Towed?	No
		Yes
	CU Driver Airbag Status	Not Deployed
		Deployed

3.2.2 FIRTH'S PENALIZED-LIKELIHOOD LOGISTIC REGRESSION MODEL

Logistic Regression Model

Because the type of dependent variable in this study (WWD versus non-WWD crashes) is dichotomous, a binary logistic regression model can be considered. Binary responses are commonplace in studies in the medical, behavioral and social sciences. For example, a practitioner may be interested in determining whether or not a patient contracts a disease or complication based on a measureable set of predictors, e.g., age, sex, or environmental exposure factors. The logistic regression model is the most commonly used model for predicting a binary outcome from a set of measurable covariates. For independent observations, maximum likelihood is the method of choice for estimating the logistic regression model parameters (Rader, 2015).

It is important to note that this study applies the logistic regression differently than it is originally intended, as it breaks two important underlying assumptions. First, is does not support the idea that the independent variables of the regression influence a choice of dependent variables. In other words, the logistic regression is intended to predict, once a crash occurs, if each independent variable influences whether that crash is likely to become more or less wrong-way or moving in the correct direction. While this is not a logical order of operations, the author assumes that this is true in order to understand which factors are more associated with each type of crash. The author acknowledges that crash characteristics cannot change the direction of the crash. Second, many crashes occur in locations where it is physically impossible for it to be a wrong-way crash, meaning that both alternatives are not feasible. This breaks the assumption of the logistic regression that each alternative is possible for each crash. With these assumptions violated, the results are carefully interpreted in this thesis to only imply that each crash characteristic may potentially be associated with wrong-way crashes, but the full relationship with factors and difference between wrong-way and regular crashes needs to be explored further.

However, the standard binary logistic regression is well-known to suffer from small-sample bias. The degree of bias is strongly dependent on the number of cases in the less frequent of the two categories. So even with a sample size of 100,000, if there are only 20 events in the sample, substantial bias may occur (Allison, 2012). For example, Xu et al. (2012) analyzed a sample size of 67 patients with just 28 who patients developed hypertension, which is pretty small sample size for MLE method. In another study by Mulla and et al. (2012), they analyzed a sample of 138 patients with only 16 (11.6%) having preeclampsia, the low number of observations in one of the catogories may cause computational problems when being analyzed with MLE methods.

King and Zeng (2011) proposed an alternative estimation method to reduce the bias, a penalized likelihood regression model. Penalized likelihood is a general approach to reducing small-sample bias in MLE. The model is also known as Firth's logistic regression model. Pour-Rouholamin et al compared two logistic models (2016 a), standard binary logistic regression model and Firth's logistic regression model based on Alabama freeway WWD crash database. The study shows that Firth's model outperforms the standard binary logistic model and provides more reliable results when the sample size is very small.

In this study only 0.23% of divided highway crashes are due to WWD, and several explanatory variables of WWD crashes have very low frequency. Firth's model can handle the bias in the calculations and provide more accurate results than binary logistic regression model when the sample size and the event size were small, so Firth's model will be developed in this study.

Firth’s logistic regression model is a generalization of the MLE models. The basic idea of Firth’s model is to introduce a more effective score function by adding a term that counteracts the first-order term from the asymptotic expansion of the bias of the maximum MLE—and the term will go to zero as the sample size increases (Firth, 1993; Heinze, 2002). This model is more widely available in commercial software.

As is known, in the binary model, the log-likelihood can be formulated as an exponential family model as follows

$$l(\beta_n) = t\beta_n - K(\beta_n), n = 1, \dots, k \tag{1}$$

where

t = vector of observed sufficient statistics;

βn= regression parameter (to be estimated);

k = number of parameters estimated.

However, the score function, which is derivative of the log-likelihood, will be used to calculate the MLE of the parameter βn as follows:

$$\mathrm{U}(\beta n) = l'(\beta n) = t - \mathrm{K}(\beta n), n = 1, \dots, k \tag{2}$$

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

$$\mathrm{U}(\beta n)^* = \mathrm{U}(\beta n) + \alpha_n, n = 1, \dots, k \tag{3}$$

where α_n has the n^{th} entry and is formulated as

$$\alpha_n = \frac{1}{2} tr[I\beta^{-1} \frac{\partial \mathrm{I}(\beta)}{\beta_n}], n = 1, \dots, k \tag{4}$$

where

tr = trace function;

(β) = Fisher’s information matrix.

Statistical analysis software can be used to simplify the logistic regression analysis procedure. For example, both the package ‘logistf’ in R software and package ‘firthlogit’ in STATA software can provide comprehensive tool to facilitate the application of Firth’s modified score procedure in logistic regression analysis. In this study, the author applied the package ‘firthlogit’ in STATA software to create the Firth’s model. Before creating the Firth’s model in STATA, crash data were coded into dummy variables, 0 and 1. 0 means non-WWD crash, and 1 is WWD crash. All the attributes of the data were also coded into binary mode for further analysis.

Odds Ratio

After calculating parameter estimates for statistically significant variables, the odds ratio (OR) as a relative measure of effect and the corresponding confidence interval 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.

Odds ratios are used to compare the relative odds of the occurrence of the outcome of interest (e.g. disease or disorder), given exposure to the variable of interest (e.g. health characteristic, aspect of medical history). The odds ratio can also be used to determine whether a particular exposure is a risk factor for a particular outcome, and to compare the magnitude of various risk factors for that outcome (Scotia, 2010). The following shows the explanation of OR.

The calculation of OR is simple. The OR can be computed by raising e to the power of the logistic coefficient. Below shows the formula of it.

$$OR = e^{\beta} \quad (5)$$

Where

β = the logistic coefficient**.**

In this study, if the logistic coefficient is zero, it means that that parameter has no effect on the probability of the outcome, therefore the resulting OR would 1. When OR is greater than one, WWD crash is more likely to have the specific characteristic (defined in the category) than the unexposed category. Similarly, when OR is less than one, WWD is less likely to have the specific characteristic (defined in the category) than the unexposed category.

CHAPTER 4

ANALYSIS AND RESULTS

Chapter four presents key results from the analysis, and summarizes the significance of the results. With a large amount of data collected, tables and figures were created to show different characteristics of WWD crash and non-WWD crashes. The results start with the descriptive statistical analysis results, move onto Firth's model analysis results, analysis of contributing factors of fatal crash, comparison of WWD crashes between divided highways and freeways, and finish with WWD entry points analysis, which includes field review results of WW entry points.

4.1 DESCRIPTIVE STATISTICAL ANALYSIS RESULTS

All the result tables in this section present the explanatory variables used in this study for both WWD and non-WWD crashes on Alabama divided highways. When looking at these tables, a few points are worth mentioning. The variables with no difference between WWD crashes and other crashes are not shown. The categories showing conspicuous difference (here a difference of more than 10% is considered conspicuous) of the distribution between WWD crashes and other crashes in these tables will be colored in red and italic. Also, the missing values are treated as unknown, and they are not shown in the tables that represent the results.

4.1.1 Crash Severity

Table 4 shows the crash severity of the WWD crashes compared to non-WWD crashes on divided highways in terms of crash severity level and the involvement number of persons and vehicles. According to Table 4, the percentage of severe injuries (fatal and incapacitating crashes) is 30.4%, while this number for all crashes on divided highways in Alabama within the same time period is only 7.0%. About 94.7% of WWD crashes involved more than one person in the crash, while only 86.5% of non-WWD crashes involved more than one persons. Similarly, more WWD crashes involved more than one vehicle than non-WWD crashes.

TABLE 4 Crash Severity of WWD and Other Divided Highway Crashes

Variable	Category	WWD Crashes (n=112)		Other Crashes (n=49599)	
		Frequency	Percentage	Frequency	Percentage
Crash Severity Level	*Fatal Crash*	*14*	*12.5*	*291*	*0.6*
	Incapacitating	*20*	*17.9*	*3,174*	*6.4*
	Non-Incapacitating	17	15.2	4,020	8.1
	Possible Injury	7	6.3	4,235	8.5
	PDO	*52*	*46.4*	*37,315*	*75.2*
Involvement Number of Persons	*One*	*6*	*5.4*	*6,657*	*13.4*
	Two	57	50.9	20,608	41.5
	Three and More	49	43.8	22,334	45.0
Involvement Number of Vehicles	*One*	*7*	*6.3*	*9,112*	*18.4*
	Two	*98*	*87.5*	*36,786*	*74.2*
	Three and More	7	6.3	3,701	7.5

Table 5 gives a summarization of the frequency and percentage of WWD crashes by severity on divided highways each year from 2009 to 2013. In 2012, there are 6 fatal crashes, and the crash frequency is the highest among all the five years.

TABLE 5 Frequency and Percentage of WWD Crashes by Severity Per Year

Crash Severity	Total		2009		2010		2011		2012		2013	
Fatal Crash	14	12.5%	4	14.3%	3	9.1%	1	5.6%	6	33.3%	0	0.0%
Incapacitating Crash	20	17.9%	8	28.6%	7	21.2%	2	11.1%	0	0.0%	3	20.0%
Non-Incapacitating Crash	17	15.2%	2	7.1%	5	15.2%	3	16.7%	3	16.7%	4	26.7%
Possible Injury	7	6.3%	1	3.6%	4	12.1%	1	5.6%	1	5.6%	0	0.0%
No Injuries	52	46.4%	13	46.4%	14	42.4%	10	55.6%	7	38.9%	8	53.3%

4.1.2 Temporal Distribution

In temporal distribution analysis, three kinds of variables: month, day, and hour of the day are analyzed. Table 6 lists the frequency and percentage distribution of WWD crashes and other divided highway crashes by the day and hour of the day that they occurred.

The following conclusions can be ascertained from the table. The percentage of WWD crashes that happened on weekends is nearly twice as high as the percentage of other divided highway crashes that happened on weekends (35.7% vs. 20.1%). The hourly distribution is also varied within the entire day, but evening and night have the highest frequency of WWD crashes. Accordingly, the hours of 6:00 p.m. to 12:00 a.m. has the highest frequency of the WWD crashes. About 45.5% of WWD crashes happened during this time period, which is much higher than other crashes. This is because the frequency of DUI driving crash is much higher at this time period, and the lighting condition is poor. Figure 3 shows the time distribution of DUI drivers and non-DUI drivers. It is obviously to find that more than half of the DUI caused WWD crashes (15 out of 26) happened from 6:00 p.m. to 12:00 a.m. Also, according to the data, about 65% (33 out of 51) of the roads were under no lighting condition during this time period. The distribution of WWD crashes by month is similar to that of other divided highway crashes.

TABLE 6 Temporal Distribution of WWD and Other Divided Highway Crashes

Variable	Category	WWD Crashes (*n*=112)		Other Crashes (*n*=49,599)	
		Frequency	Percentage	Frequency	Percentage
Day	Monday	16	14.3	7,480	15.1
	Tuesday	12	10.7	7,608	15.3
	Wednesday	15	13.4	7,523	15.2
	Thursday	9	8.0	7,778	15.7
	Friday	20	17.9	9,219	18.6
	Saturday	23	20.5	5,918	11.9
	Sunday	17	15.2	4,073	8.2
Time	Morning (6-12)	11	9.8	13,657	27.5
	Afternoon (12-18)	27	24.1	24,656	49.7
	Evening (18-24)	*51*	*45.5*	*8,678*	*17.5*
	Night (0-6)	*22*	*19.6*	*2,599*	*5.2*

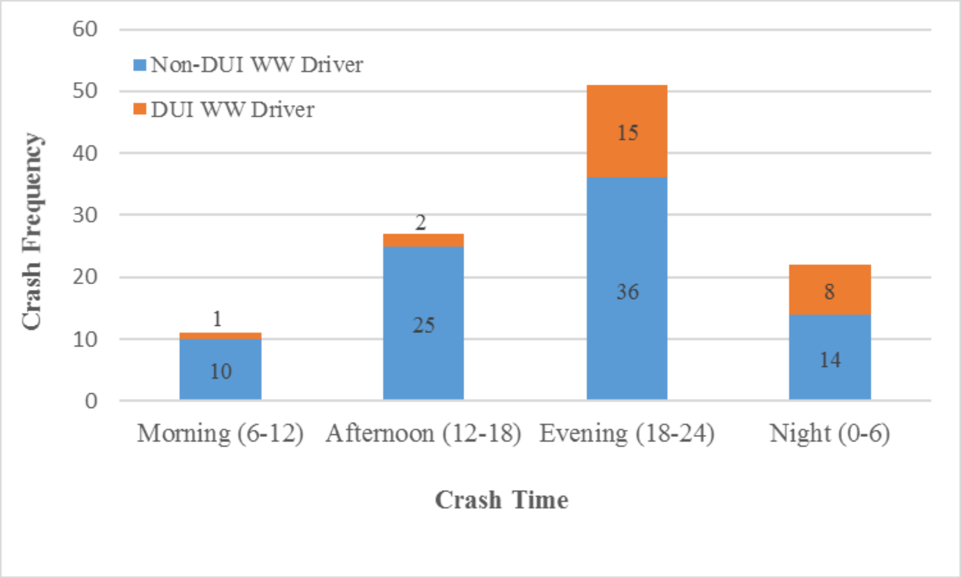


FIGURE 3 Time Distribution of DUI Drivers and Non-DUI Drivers

4.1.3 Driver Characteristics

Driver characteristics analysis includes the driver's age, gender (male or female), race, and condition, CU driver seatbelt behavior as well as the variable if the driver's dwelling place was within 25 miles of the crash location. Table 7 lists the frequency and percent distribution of CU driver’s age, CU driver’s condition, and CU driver seatbelt behavior. The key findings are as follows.

Young and older drivers are proportionally over-represented in WWD crashes. According to the National Highway Traffic Safety Administration (NHTSA) criteria of classification of different age groups, drivers under age 25 are young drivers and those 65 years and above are older drivers.

About 23.2% of WWD drivers were DUI, whereas less than 3% of drivers in non-WWD crashes are intoxicated. For those DUI drivers involved in WWD crashes, 77% were caused by alcohol and nearly 23% by other drugs. Blood Alcohol Concentration (BAC) test result, and driver’s condition were analyzed to investigate the possible impact of DUI on WWD crashes. The illegal BAC limits in Alabama are 0.02% for school bus drivers and drivers under the age of 21, 0.04% for commercial driver’s license holders, and 0.08% for drivers aged 21 and over.

Most of the WWD crashes caused airbag deployment (45.5%), which is much higher than other non-WWD crashes (13.4%). Also, WWD crashes have a similar percent distribution among male and female and different races, as other divided highway crashes. About 63% of the WWD driver’s dwelling place was within 25 miles of the crash location, which is similar to other crashes on divided highways

TABLE 7 CU Driver Characteristics of WWD and Other Divided Highway Crashes

Variable	Category	WWD Crashes (*n*=112)		Other Crashes (*n*=49,599)	
		Frequency	Percentage	Frequency	Percentage
Driver Age	Less than 24	18	16.1	13,973	28.2
	25 to 34 years	18	16.1	9,896	20.0
	35 to 44 years	16	14.3	7,360	14.8
	45 to 54 years	10	8.9	6,698	13.5
	55 to 64 years	14	12.5	4,973	10.0
	65 years or over	*30*	*26.8*	*5,350*	*10.8*
Driver Condition	Apparently Normal	51	45.5	44,718	90.2
	DUI	*26*	*23.2*	*1,508*	*3.0*
	Asleep/Fainted/Fatigued	1	0.9	757	1.5
	Illness	2	1.8	228	0.5
	Emotional	2	1.8	0	0.0
CU Driver Seatbelt Use	*Belt Used*	*79*	*70.5*	*46,024*	*92.8*
	Belt Not Used	*14*	*12.5*	*1,310*	*2.6*

4.1.4 Vehicle Characteristics

The vehicle characteristics reflect type of vehicle, vehicle age, type/extent of damage, towing information, and CU driver airbag status. Table 8 lists a comparison between vehicle information for WWD crashes and other divided highway crashes. According to this table, about 68.8% of the WWD vehicles become disabled after the crash, while this percentage for other divided highway crashes is only 37%, resulting in more vehicles being towed after WWD crashes (73.2% of WWD vehicles versus 40.8% of other vehicles). Approximately 70.5% of WW drivers used their seat belts, which is much lower than the 92.8% of other divided highway drivers that were belted. Also, most of the WWD vehicles are passenger cars (60.7%) and WWD vehicle ages are five to 15 years (65.2%), which are similar to other crashes on divided highways.

TABLE 8 Vehicle Characteristics of WWD and Other Divided Highway Crashes

Variable	**Category**	**WWD Crashes (*n*=112)**		**Other Crashes (*n*=49,599)**	
		Frequency	**Percentage**	**Frequency**	**Percentage**
CU Vehicle Damage	Minor/None Visible	16	14.3	20,711	41.8
	Major Not Disabled	12	10.7	9,408	19.0
	Major and Disabled	*77*	*68.8*	*18,334*	*37.0*
Vehicle Towed?	No	29	25.6	28,510	57.5
	Yes	*82*	*73.2*	*20,240*	*40.8*
CU Driver Airbag Status	Not Deployed	42	37.5	37,290	75.2
	Deployed	*51*	*45.5*	*6,646*	*13.4*

4.1.5 Environmental Condition

The environmental condition refers to area type, lighting, weather, and roadway condition. Table 9 lists a comparison of environmental conditions between WWD crashes and other divided highway crashes. Here are some key findings: WWD crashes have a similar percentage distribution between rural and urban areas as other divided highway crashes, and most of the crashes happened on urban areas. The percentage of WWD crashes during dark conditions (whether roadway is lit or not) is much higher than other divided highway crashes (71.1% versus 21.3%). The percentage of WWD crashes happened on days with precipitation is almost five times larger than other crashes. About 16.3% of WWD crashes happened on precipitation days, while only other crashes have 3%. Most of WWD crashes occurred under clear weather conditions and on dry roadway surfaces, which is similar as other divided highway crashes.

TABLE 9 Environmental Condition of WWD and Other Divided Highway Crashes

Variable	**Category**	**WWD Crashes (*n*=112)**		**Other Crashes (*n*=49,599)**	
		Frequency	**Percentage**	**Frequency**	**Percentage**
Lighting Condition	Daylight	33	29.7	37,152	74.9
	Dark, road Lit	*30*	*27.0*	*5,577*	*11.2*
	Dark, road Not Lit	*49*	*44.1*	*5033*	*10.1*
	Dawn/Dusk	0	0.0	1,742	3.5
Weather Condition	Clear/Cloudy	94	84.7	42,088	84.9
	Fog/Mist	0	0	6,031	12.2
	Precipitation	*18*	*16.2*	*1,480*	*3.0*

4.2 FIRTH'S MODEL ANALYSIS RESULTS

Following the descriptive analysis, the same variable groups, except crash severity were analyzed to create Firth's model. First, all possible contributing factors were applied in a model. Then, a backward elimination procedure based on the penalized-likelihood ratio was employed to produce the final model. The final model is composed of the variables that are significant at 95% confidence interval. All the other insignificant variables will not be kept in the final model. Table 10 summarizes the final analysis results of the Firth's model. The reference factor of each variable is in the first row, and the final analysis results include parameter estimated coefficient along with their corresponding standard errors and odds ratio (OR).

TABLE 10 Final Firth's Penalized-Likelihood Regression Model for WWD Crashes

Variable	**Category**	**Est. Coef.**	**Std. Err.**	***P*-value**	**OR**
Intercept	–	-8.46	0.29		–
Driver Age	Less than 25 years	–	–		Reference
	55 to 64 years	0.85	0.29	0.004	2.33
	65 years or over	1.82	0.23	<0.001	6.19
Driver Condition	Apparently Normal	–	–		Reference
	DUI	1.39	0.26	<0.001	4.02
CU Driver Seatbelt Use	Use	–	–		Reference
	Not Use	0.75	0.31	0.02	2.12
Setting	Rural	–	–		Reference
	Urban	0.67	0.23	0.003	1.96
CU Driver Airbag Status	Not Deployed	–	–		Reference
	Deployed	1.30	0.20	<0.001	3.68
Lighting Condition	Daylight	–	–		Reference
	Dark, road lit	1.65	0.26	<0.001	5.19
	Dark, road not lit	2.53	0.25	<0.001	12.51
Penalized Likelihood Ratio Test: χ^2=-648.61141 on 9 d.f., *p*-value<0.05 **Wald Test = 278.76.83 on 9 d.f., *p*-value<0.05** **AIC= 1313.223**					

According to the final Firth's model in Table 10, the penalized-likelihood ratio test statistic of -648.61141 with corresponding *p*-value of less than 0.05 (with 9 degrees of freedom) indicates that the alternative hypothesis (i.e., "the current model is true") is accepted. It can conclude that the factors of older drivers, driving under influence of alcohol or drugs, drivers who do not use their seatbelt, and driving during dark roadway conditions are significantly differentiated between WWD and non-WWD crashes.

To measure the effectiveness of the contributing variables, ORs were computed. ORs show the magnitude of the change in the dependent variable when one unit change in a specific explanatory variable is made. According to OR results from the Firth’s model, when comparing WWD with non-WWD crashes, drivers who are 55 to 64 years old are 2.33 times more likely to be involved in WWD crashes than a younger driver (less than 25 years), and 65 and older drivers are 6.19 times more likely to cause WWD. This higher crash rate also applies to drivers who are under the influence of alcohol and drugs at 4.02 times more than normal drivers. Urban areas are 1.96 times more likely to have WWD crashes than rural areas. Drivers who do not use their seatbelts are 2.12 times more possible to have WWD crashes. Both dark with lighting conditions and dark without lighting conditions will cause higher WWD crash rate than a daylight condition, their ORs are 5.12 and 12.51, respectively. Moreover, WWD crashes can be characterized by airbag deployment, and the OR of airbag deployment is 3.68.

4.3 ANALYSIS OF CONTRIBUTING FACTORS OF FATAL CRASHES

Table 11 presents the data of fatal crashes percentage on divided highways that were caused by WWD in Alabama from 2009 to 2013 extracted from CARE. Fatal crashes due to WWD made up about 5% of all the fatal crashes on Alabama divided highways, even though WWD crashes only comprised around 0.23% of all divided highway crashes. Also, severe crashes (fatal crash and injury crash) account for more than 30% of all WWD crashes on Alabama divided highways in those five years. WWD crashes are rare but have a high fatal rate, so in this section the contributing factors of fatal WWD crashes will be investigated to complete the study.

Table 11 also shows that WWD crashes on Alabama divided highways resulted in 18 fatalities from 14 fatal crashes (1.29 fatalities per fatal crashes) from 2009 to 2013. For all fatal crashes on Alabama divided highways, there were 328 fatalities in 291 fatal crashes (1.13 fatalities per fatal crashes), which translates to 16 more fatalities per 100 fatal crashes. Additionally, the fatality rate is the same on Alabama freeways based on the same year's crash data. All in all, WWD crashes are rare but severe, and it is vital to know the contributing factors of fatal crashes before implementing countermeasures.

TABLE 11 Percentage of WWD Fatal Crashes on Divided Highways

Year	2009	2010	2011	2012	2013	Total
Divided Highway Fatal Crashes	44	68	63	64	52	291
WWD Fatal Crashes (fatalities)	4(5)	3(4)	1(1)	6(8)	0(0)	14(18)
WWD Fatal Crash Percentage	9.1%	4.4%	1.6%	9.4%	0.0%	4.8%

4.3.1 Descriptive Characteristics of Fatal Crash

To find the contributing factors of fatal crashes, first Firth's logistic regression analysis was applied. Four types of possible contributing variables (the same as the possible variables in the previous Firth's model for WWD crashes) were tried in the model. After the backward elimination procedure, only three factors of a fatal crash remained that are significant at 95% confidence interval: in September, urban areas, and airbag deployment. The results from Firth's logistic model only showed three contributing factors with large standard errors, so the very limited sample size (14 fatal crash versus 98 non-fatal crash) may cause inaccurate results.

Because Firth's model does not work well here since almost all the parameters were insignificant, only the descriptive statistical analysis results are shown in Table 12. Table 12 compares the affecting variables of fatal and unfatal WWD crashes. Only the variables from

Table 10 are considered because they significantly contribute to WWD crashes. From the table, it is easy to see that drivers older than 55 years (57.1%), drivers who do not wear seatbelt (35.7%), crashes happened in rural areas (57.1%), and dark roadway with no lights (71.4%) are overrepresented in a fatal crash; 92.9% of vehicles deployed their airbags in fatal WWD crashes.

TABLE 12 Affecting Variables of Fatal and Unfatal WWD Crashes

Variable	**Category**	**Fatal Crashes (*n*=14)**		**Unfatal Crashes (*n*=98)**	
		Frequency	**Percentage**	**Frequency**	**Percentage**
Driver Age	Less than 24	2	14.3	16	16.3
	25 to 34 years	1	7.1	17	17.4
	35 to 44 years	3	21.4	13	13.3
	45 to 54 years	0	0.0	10	10.2
	55 to 64 years	*3*	*21.4*	*11*	*11.2*
	65 years or over	*5*	*35.7*	*25*	*25.5*
Driver Condition	Apparently Normal	4	28.6	47	48.0
	DUI	4	28.6	23	23.5
	Asleep/Fainted/Fatigued	0	0.0	1	1.0
	Illness	1	0. 0	2	2.0
	Emotional	0	0.0	2	2.0
CU Driver Seatbelt Use	Use	7	50.0	72	73.5
	Not Use	*5*	*35.7*	*9*	*9.2*
Setting	*Rural*	*8*	*57.1*	*29*	*29.6*
	Urban	6	42.9	69	70.4
CU Driver Airbag Status	Not Deployed	1	7.1	41	41.8
	Deployed	*13*	*92.9*	*38*	*38.8*
Lighting Condition	Daylight	2	14.3	33	33.7
	Dark, road lit	2	14.3	30	30.6
	Dark, road not lit	*10*	*71.4*	*49*	*50.0*
	Dawn/Dusk	0	0.0	0	0.0

4.3.2 Correlation Analysis of Fatal Crash

Furthermore, a correlation analysis was conducted between affecting variables of fatal crashes (old drivers, DUI, not using belt use, rural condition, and poor lighting condition) and fatal crashes. The analysis assists investigators in connecting WWD contributing factors to fatal crashes. The closer the results are to a value of one, the more relation the two factors share and the stronger the correlation. If the results indicate a negative relation, one factor increases as the other decreases.

The correlation analyses results are presented in Table 13. Significant correlations have been found between variables ‘DUI driver’ and ‘Old drivers’ (-0.356), ‘DUI driver’ and ‘Seatbelt Not Use’ (0.304), ‘Rural area’ and ‘Seatbelt Not Used’ (0.251), ‘Rural area’ and ‘DUI driver’ (0.304), ‘Poor lighting’ and ‘DUI driver’ (0.309), ‘Poor lighting’ and ‘Rural area’ (0.204), ‘Fatal crash’ and ‘Seatbelt Not Used’ (0.265), ‘Fatal crash’ and ‘Rural area’ (0.194). Results show that drivers who are driving under influence are more likely not to use seatbelt. Once among WWD crashes happened in rural areas, the drivers are more likely to be DUI drivers and not wear seatbelt. The rural areas are more likely to have poor lighting conditions. Fatal crashes are more likely to happen when drivers do not wear seatbelts and drive in rural areas.

TABLE 13 Correlation Analysis between Contributing Factors and Fatal Crashes

	% Older Driver	% DUI	% Seatbelt Not	% Rural Area	% Poor Lighting	% Fatal Crash
% Older Driver	1					
% DUI Driver	-0.356**	1				
% Seatbelt Not Use	-0.083	0.304**	1			
% Rural Area	-0.021	0.304**	0.251**	1		
% Poor Lighting	-0.362**	0.309**	0.126	0.204*	1	
% Fatal Crash	0.138	-0.08	.265**	0.194*	0.126	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

In addition, by reviewing hard copies of crash reports and checking Google Maps to look at aerials of locations for fatal crashes, some other characteristics could be found. 13 out of 14 of the fatal crashes happened on divided highways with wide medians (larger than 30 feet). The wide median may block drivers' view of the cross lane especially during dark conditions with no lightings. Also, few traffic signs related to WWD, such as Do Not Enter (DNE) signs, WW signs and One Way signs, existed on these roads, so WW drivers may be unware of their WW behavior until they see the oncoming vehicles. The WWD distance varies, and the range was from about 0.2 mile to 5.1 miles.

4.4 COMPARISON OF WWD CRASHES BETWEEN DIVIDED HIGHWAYS AND FREEWAYS

This section provides a comparison of descriptive statistical analysis results and the final Firth's logistic regression model of WWD crashes between divided highways and freeways. The spatiotemporal distribution comparisons include crash severity, responsible driver characteristics, temporal information, vehicle information, and environmental condition. The distribution of variables showing no conspicuous difference (a difference of more than 10% is considered conspicuous) between the two types of facilities is not presented in the following tables. None of the variables of environmental condition have conspicuous differences, so a comparison of environmental conditions between divided highways and freeways is not presented below.

4.4.1 Descriptive Statistical Analysis Comparison

Table 14 shows crash severity of WWD crashes on divided highways and freeways. The number of persons and vehicles involved in WWD crashes is different between these two facility types, and more persons and vehicles are involved in WWD on divided highways. It can be seen in Table 14 that the crash level distribution on divided highways and freeways is similar, about 30% WWD crashes are severe crashes and about 40% are PDO crashes. The frequency of WWD crashes involving one person on divided highways is smaller than that on freeways (5.4% vs. 16.1%). The frequency of two vehicles being involved in WWD crashes on divided highways is much higher than on freeways (87.5% vs 71.0%).

TABLE 14 Crash Severity of WWD Crashes on Divided Highways and Freeways

Variable	Category	Divided Highways (n=112)		Freeways (n=93)	
		Frequency	Percentage	Frequency	Percentage
Crash Level	Fatal Crash	14	12.5	14	15.1
	Incapacitating	20	17.9	25	26.9
	Non-Incapacitating	17	15.2	11	11.8
	Possible Injury	7	6.3	4	4.3
	PDO	52	46.4	37	39.8
Number of Persons	*One*	*6*	*5.4*	*15*	*16.1*
	Two	57	50.9	43	46.2
	Three and More	49	43.8	35	37.6
Number of Vehicles	One	7	6.3	12	12.9
	Two	*98*	*87.5*	*66*	*71*
	Three and More	7	6.3	15	16.1

Responsible driver characteristics including driver's age, race, and condition are compared in Table 15. There is a higher percentage of WW drivers aged 55 to 64 years on divided highways than on freeways (12.5% vs 4.3%), while the percentage of WW drivers who are African-American is higher on freeways (13.4% vs 36.6%). A higher percentage of WW drivers on freeways are DUI (46.2%), while a higher percentage of WW drivers on divided highways are apparently normal (45.5%）.

TABLE 15 Responsible Driver Characteristics of WWD Crashes on Divided Highways and Freeways

Variable	Category	Divided Highways (n=112)		Freeways (n=93)	
		Frequency	Percentage	Frequency	Percentage
Driver Age	Less than 24	18	16.1	17	18.3
	25 to 34 years	18	16.1	21	22.6
	35 to 44 years	16	14.3	14	15.1
	45 to 54 years	10	8.9	8	8.6
	55 to 64 years	14	12.5	4	4.3
	65 years or over	30	26.8	24	25.8
	Other/Unknown	6	5.4	5	5.4
Driver Race	White/Caucasian	75	67.0	44	47.3
	African American	15	13.4	34	36.6
	Hispanic	6	5.4	5	5.4
	Asian/Pacific Islander	4	3.6	0	0
	American Indian	0	0.0	0	0
	Other/Unknown	12	10.7	10	10.8
Driver Condition	Apparently Normal	51	45.5	23	24.7
	DUI	26	23.2	43	46.2
	Physical Impairment	0	0.0	4	4.3
	Asleep/Fainted/Fatigued	1	0.9	1	1.1
	Illness	2	1.8	1	1.1
	Emotional	2	1.8	0	0
	Other/Unknown	30	26.8	21	22.6

Table 16 presents WWD temporal information including month, day and time between divided highways and freeways. The difference in time distributions is conspicuous. WWD crashes on divided highways happened in the afternoon (12 p.m. – 6 p.m.) are three times more than on freeways (24.1% vs 7.5%), while the percentage of WWD crashes on freeways that happened during midnight to early morning (12 a.m. - 6 a.m.) is more than double on divided highways (19.6% vs 40.2%).

TABLE 16 Temporal Information of WWD Crashes on Divided Highways and Freeways

Variable	Category	Divided Highways (n=112)		Freeways (n=93)	
		Frequency	Percentage	Frequency	Percentage
Month	January	13	11.6	4	4.3
	February	14	12.5	8	8.6
	March	11	9.8	13	14
	April	8	7.1	3	3.2
	May	5	4.5	15	16.1
	June	5	4.5	6	6.5
	July	8	7.1	6	6.5
	August	12	10.7	4	4.3
	September	6	5.4	6	6.5
	October	10	8.9	6	6.5
	November	7	6.3	13	14
	December	13	11.6	9	9.7
Day	Monday	16	14.3	15	16.1
	Tuesday	12	10.7	6	6.5
	Wednesday	15	13.4	7	7.5
	Thursday	9	8.0	5	5.4
	Friday	20	17.9	16	17.2
	Saturday	23	20.5	20	21.5
	Sunday	17	15.2	24	25.8
Time	Morning (6-12)	11	9.8	12	12.9
	Afternoon (12-18)	27	24.1	7	7.5
	Evening (18-24)	51	45.5	31	33.3
	Night (0-6)	22	19.6	43	46.2
	Other/Unknown	1	0.9	4	4.3

Table 17 compares the vehicle information of WWD crashes on the two types of roadways; two variables (causal unit type and if the vehicle were towed) show conspicuous differences. More CU are trucks on divided highways, while only few CU are trucks on freeways (18.8% vs 1.1%). More vehicles are towed away after crashes on freeways than on divided highways (25.6% vs 15.1%). Additionally, there are more severe crash (fatal crash and A injury crash) happened on freeways (39.4%) than on divided highways (30.4%), so the higher severity would likely lead to more towing.

TABLE 17 Vehicle Information of WWD Crashes on Divided Highway and Freeways

Variable	Category	Divided Highways (n=112)		Freeways (n=93)	
		Frequency	Percentage	Frequency	Percentage
Causal Unit (CU) Type	*Passenger Car*	*68*	*60.7*	*89*	*95.7*
	Truck	*21*	*18.8*	*1*	*1.1*
	Bus	0	0.0	0	0
	SUV	19	17.0	0	0.0
	Van	3	2.7	0	0.0
	Motorcycle	0	0.0	0	0
	Other/Unknown	1	0.9	3	3.2
Vehicle Towed?	*No*	*29*	*25.6*	*14*	*15.1*
	Yes	82	73.2	76	81.7
	Other/Unknown	1	0.9	3	3.2

4.4.2 Logistic Regression Analysis Comparison

Table 18 compares the final Firth’s penalized likelihood regression models together with ORs results between WWD crashes on divided highways and freeway based on Pour-Rouholamin et al’s (2016 a) WWD study on Alabama freeways. Both models contain the variables of driver age, driver condition, as well as driver airbag status. Most of them have similar ORs, except for the ORs of DUI (3.98 vs 16.09). Additionally, lighting condition, CU driver seatbelt use condition and roadway setting are specific variables of the model on divided highways. Time of the day, driver residency distance, roadway condition and vehicle age are all specially developed for the Firth's model on freeways. It can be seen in the table that the OR of dark, roadway not light condition of divided highway model is large (OR= 12.15), and the OR of the similar variable, crash happened in the night time of freeways is also large (OR=4.45).

TABLE 18 Firth's Model for WWD Crashes on Divided Highways and Freeways

Divided Highway (n=112)			Freeways (n=93)		
Variable	**Category**	**OR**	**Variable**	**Category**	**OR**
Driver Age	Less than 25 years	Reference	**Driver Age**	Less than 25 years	Reference
	25 to 35 years	1.01		25 to 35 years	1.01
	35 to 45 years	1.44		35 to 45 years	1.23
	45 to 55 years	1.03		45 to 55 years	1.05
	55 to 64 years	2.46		55 to 64 years	1.12
	65 years or over	6.43		65 years or over	8.71
Driver Condition	Apparently Normal	Reference	**Driver Condition**	Apparently Normal	Reference
	DUI	*3.98*		*DUI*	*16.09*
	Asleep/Faint/Fatigue	0.55		Asleep/Faint/Fatigue	0.75
	Illness	3.40		Physical Impairment	74.29
CU Driver Airbag Status	Not Deployed	Reference	**CU Driver Airbag Status**	Not Deployed	Reference
	Deployed	3.74		Deployed	3.12
Lighting Condition	Daylight	Reference	**Time of the Day**	Morning (6-12)	Reference
	Dawn/Dusk	0.31		Afternoon (12-18)	0.44
	Dark, roadway light	4.96		Evening (18-24)	2.51
	Dark, roadway not light	12.15		Night (0-6)	4.45
CU Driver	Use	Reference	**Driver**	Less than 25 Miles	Reference

Seatbelt Use	Not Use	2.10	**Residency Distance**	Greater than 25 Miles	0.60
Setting	Rural	Reference	**Roadway Condition**	Dry	Reference
	Urban	1.95		Wet	0.41
–			**Vehicle Age**	Less than 5 years	Reference
				5 to 15 years	1.50
				More than 15 years	1.90

4.5 WRONG-WAY ENTRY ON ALABAMA DIVIDED HIGHWAYS

4.5.1 Wrong-Way Entry Points

Identifying WW entry points is helpful to develop proper countermeasures to reduce wrong way driving at a specific highway access. However, one of the most challenging aspects of studying WWD is to identify where the driver turned into the wrong direction on the roadway because it is usually unavailable from the crash database. Several previous studies used information sources such as police crash reports, surveys, and images from camera surveillance systems to determine where a WWD movement originated. Most entry points for two-thirds of the crashes were unknown because the WW driver usually could not provide information due to intoxicated condition or because drivers died in the crash (Scifres, 1974; Vaswani, 1977). In this study, in order to obtain WW entry points' information, the author paid special attentions to all the narrative description and collision diagrams of the crash report hard copies one by one, and examined the crash locations by using aerial photographs from Google Earth.

Based on previous studies (Scifres, 1974; Vaswani, 1977), the most common WWD scenarios on divided highways occur when drivers: (1) turn left on the nearby directional roadway instead of the far or second directional roadway when joining from a crossroad (See

Figure 4 for an example), (2) enter a roadway going the wrong direction at the median opening, (3) make a U-turn and misunderstand that the next lane will be in the opposite direction, and (4) attempt to get back on the main road after stopping at a service or parking area. Scifres et al.' (1974) study showed that on non-Interstate four-lane divided highways, about 40% of drivers making WWD entries emerged from intersections with crossroads, about 25% originated from business establishments such as gas stations and motels, and about 20% originated from residential areas, crossovers, beginnings of divided sections, and construction sites, or were associated with U-turns and median openings. The origins of the remaining 15% were unknown.

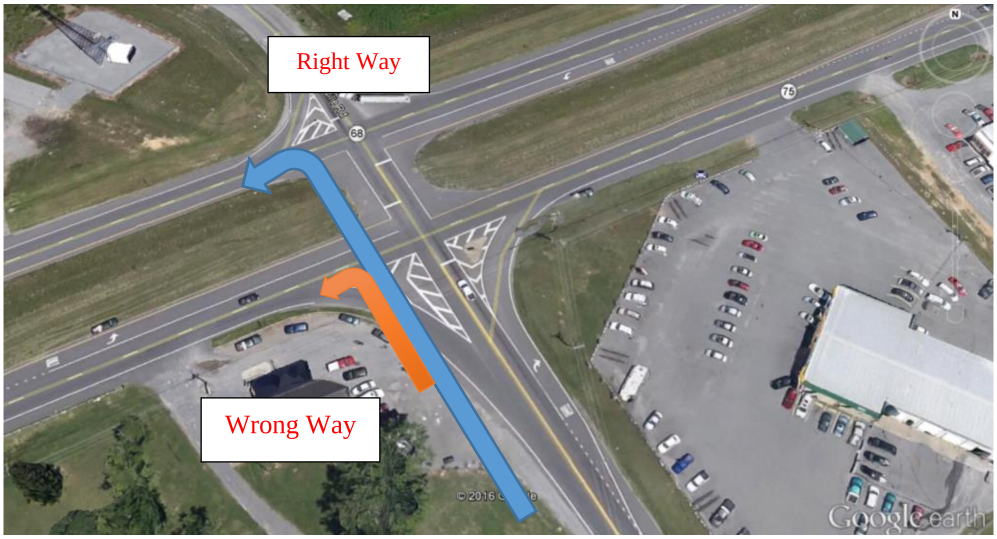


FIGURE 4 Left-turning Movements from Crossroads on Divided Highways (Google Earth)

In this study, the coordinates of the 112 WWD crash locations were extracted. Table 19 shows the distribution of WW crashes with known entry points. Hence, 18 confirmed and 94 possible WWD entry points on multilane divided highways were identified (See Table 19). Among all the WWD crashes with known entry points, the most frequent entry points are median openings and parking lots of gas stations or business areas. They take up 77.8% of all the WWD crashes with known entry points. For the remaining four crashes, three of them entered from signalized intersection and the rest one made an undeliberate lane change due to distraction or DUI driving.

For the 94 WWD crashes with unknown entry points, the estimation is that one of them entered from a nearby interchange because there are 3 interchanges with no median opening nearby the crash location, and in the remaining 93 crashes, the driver entered at median opening or intersection.

TABLE 19 Wrong-Way Entry Points

Category		Number
WWD Crashes with Known Entry Points	Recorded Entry at Median Opening	8
	Recorded Entry at Signalized Intersection	3
	Entry from Parking of Gas Station/ Business Area	6
	Entry by Undeliberate Lane Change *(Distracted and DUI)*	1
WWD Crashes with Unknown Entry Points	Interchange Related (3 Interchanges but No Median Opening Nearby)	1
	Estimated Entry at Median Opening or Intersection	93

4.5.2 Field Review at High-Frequency Wrong-Way Entry Place

Entry at Median Opening

The field review locations of WW entry at median openings were on U.S.280 in Alabama during June, 2015. Figure 4 shows an example of driver's sights at a median opening during night time. Researcher took pictures at the intersections from front, right and left side. The conditions of traffic signs, pavements and geometric design were checked during the procedures of field review, and proper suggestions to reduce WWD crashes of this type of highway access will be put forward.

The followings are some general problems of the conditions at median openings pf traffic control devices and geometric design feature.

1) Traffic control devices. The visibility of some traffic signs and pavements are poor during night time and some locations are some locations are even lacked of WW signs. Also, WW sign and DNE sign are not faced to potential WW drivers, or they are installed very far from the nose of the median opening. Additionally, some pavements, like stop lines are faded and raised pavement markers are broken.

2) Geometric design features. First, usually there is a great difference of the elevation of crossroads and the divided highways at some field review locations. Seconds, the medians of some parts of U.S. 280 are very broad, more than 30 feet. According to MUTCD, if the median is larger than 30 feet, it should be treated as two intersections. Third, there are some existences of turning angles of intersection other than 90 degrees. All these geometric design features will prevent drivers from seeing the roadways across the medians.

The followings are some suggested countermeasures to reduce WWD crashes at median openings based on the problems observed during field reviews.

1) Improve the visibility of the traffic control device. For example, fixing the signs to a proper direction, placing the sign closer to the median opening, adding red retroreflective strips on sign supports, using flashing, internally illuminated signs, adding small LED units along the sign and pavement's orders to catch a wrong-way driver's attention.

2) For roadway geometric designs here are some resolutions, raising the crossroad elevation, treating the broad median openings as one or two separate intersections for traffic control purposes, avoiding skewed intersections.

(a) Front View

(b) Left-Side View (c) Right-Side View

FIGURE 4 Driver's Sights at Median Opening

Entry from Parking of Gas Station/ Business Area

The field review of WW entries from parking lots of gas stations/ business areas was conducted at the intersection of U.S.280 and North College Street in Auburn, Alabama. Figure 5 shows the field review location from Google satellite image. There is a gas station, Chevron, at right side of North College Street. A high frequency of WWD movement was observed by researchers around this intersection and most of the WW drivers are from the parking lot of the gas station. According to the collected WW entry data, parking lot of gas station or business area is one of the high frequency WW entries. Thus, this location was considered to be a good place to conduct field review, and proper suggestions to reduce WWD crashes of this type of highway access also will be developed.

To collect the traffic movements data of this location, a camera was installed facing to the gas station to record the traffic. Figure 6a shows the installation position of the camera, and Figure 6b shows the camera perspective of the gas station. 48 hours of data was collected, from 4:30 p.m., October 27 to 4:30p.m., October 29, 2016.

FIGURE 5 Entry from Parking of Gas Station/ Business Area (Google Earth)

(a) Location of Camera Installation (b) Camera Perspective of the Gas Station

FIGURE 6 Camera Installation and Camera Perspective of the Gas Station

By watching the 48-hours video at the location, a high frequency of WW movements, 15 WW movements were observed. Nine of them happened at daytime, and six of them happened during night or early morning with dark condition. It was found that, most of the WW drivers tried to cut the short to go to the northbound of the U.S.280, so they made the improper left turn at the other side of the gas station entrance. The following are some suggestions to reduce WW movements at this kind of highway access and Figure 7 shows the installation of the countermeasures.

1) Install Right Turn Only sign (R3-5R) and Keep Right Sign (R4-7) at the highway entrance of the gas station, and add a One Way sign (R6-1) on highway median facing to customers leaving the gas station

2) Add WW arrows pavements on the divided highways

3) Add an additional right-in right-out channelization at the highway entrance side of the gas station

4) Add a sign to show XX feet to U-Turn if there is a median opening close to the gas station

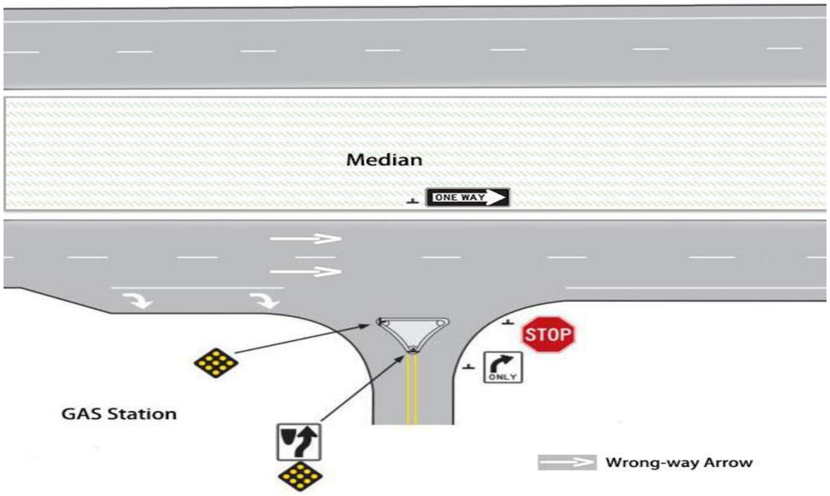


FIGURE 7 Improvements for WW Entry at Gas Station/ Business Area Parking

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This study attempted to differentiate the confounding factors between WWD crashes and other crash types on Alabama federal and state partially/uncontrolled-access divided highways based on crash data from 2009 to 2013. 112 verified WWD crashes and 49,599 other crashes that occurred on these facilities over the same time period were considered. The study started with a descriptive statistical analysis and then applied a logistic regression analysis with Firth's penalized-likelihood logistic regression model, given its capability of handling low event rate and small sample size, which may bias the results of MLE models. To supplement the analysis, contributing factors of fatal crashes were also studied and compared with other non-fatal WWD crashes. The author also compared the contributing factors on Alabama freeways and divided highways. The known WW entry points on Alabama divided highways were also studied as well as the field review of the high frequency WW entry places. The conclusions from this research can be summarized as follows, and suggestions of alleviating WWD crashes are also given in this chapter.

Compared with the simple descriptive analysis results, Firth's model helps to generate more persuasive factors that cause WWD crashes. Furthermore, the ORs, as a measure of relative effect, show a more direct impact of different factors. The study results indicate that WW drivers are more likely to be old drivers, usually 55 to 64 years old (OR= 2.33) and 65 years or over (OR=6.19), to be DUI drivers (OR=4.02), drive in urban areas (OR=1.96), do not wear seatbelt

(OR= 2.12) and in dark road conditions with road lighting (OR= 5.19) and in dark road conditions without road lighting (OR=12.51). The analysis results of fatal crash contributing factors are almost similar to WWD crash contributing factors, except that fatal WWD crashes often happen in rural areas. Based on the obtained ORs, this study found the considerable role of dark roadway conditions to cause WWD crashes as a significant factor.

5.2 RECOMMENDATIONS

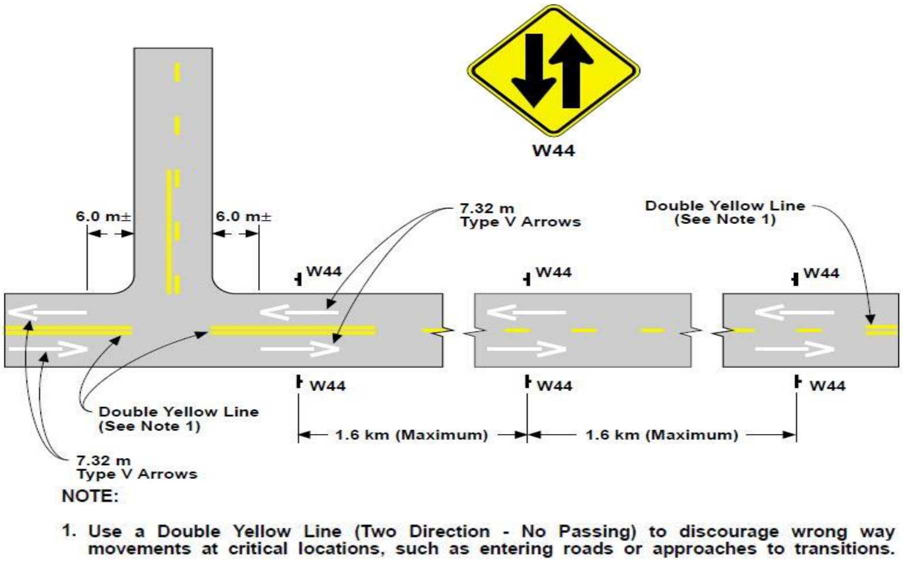
According to the study results, several countermeasures and recommendations to reduce the WWD crashes on Alabama divided highways can be proposed. These countermeasures can be categorized into three groups: engineering, education, and enforcement.

5.2.1 Engineering Countermeasures

The study also identified that both darkness with lighting conditions (OR=5.12) and without lighting conditions (OR=12.51) will significantly increase the possibility of WWD crashes. To address this issue, it is important to improve the visibility of roadway features and traffic control devices (TCDs) during the night. Based on data analysis results and complementary efforts of field review results, the following are some cost-effective countermeasures to reduce WWD crashes in the state of Alabama.

For short-term, low-cost countermeasure, the most important aspect is installing TCDs in high-frequency crash locations, as there are few traffic signs to deter WWD movements in rural areas, and TCDs are important, especially in areas with an overly wide median (more than 30 feet) and high grade differentials in cross sections. There are effective ways to improve the visibility of traffic signs and pavement markings based on the Manual on Uniform Traffic

Control Devices (MUTCD), such as using red retro-reflective strips on traffic sign support, using LED-enhanced traffic signs, adding additional identical signs, and using augmenting warning signing at high-frequency crash locations, ensuring the DNE signs face potential WW drivers, using over-sized DNE signs and WW signs, adding pavement lights such as reflective raised pavement markers, changing the vertical alignment of one of the two directional roadways on divided highways (Pour-Rouholamin et al., 2015). Usually WW arrows are used on ramps because crash analysis showed that some confirmed WW entries were making left turns from driveways, WW arrows (type V arrows) accompanied by warning signs also can be installed on divided highways. It can help WW drivers driving on the wrong side of the road realize that they are running the risk of WWD and effectively can prevent WWD crashes. This countermeasure is now extensively used on California divided highways. Figure below shows WWD treatments, including the WW arrows on divided highways (Caltrans, 1996). For long-term countermeasures, a WWD inspection team can conduct field reviews at high crash locations based on the crash data. Additionally, some intelligent transportation system (ITS) treatments can be applied, such as using radio, vehicle to vehicle (V2V), or vehicle to infrastructure (V2I) to warn right-way drivers of oncoming WW drivers. For example, FDOT is developing a connected vehicle (CV) module in its Sunguide software, which can send real time safety information to CVs (Ponnaluri, 2016).



NOTE:

1. Use a Double Yellow Line (Two Direction - No Passing) to discourage wrong way movements at critical locations, such as entering roads or approaches to transitions.

FIGURE 8 WWD Treatments: WW Arrows on Divided Highways (Caltrans)

5.2.2 Education Countermeasures

Education programs should especially target older drivers and DUI drivers, since 55 to 64 years old drivers (OR=2.33), 65 and older drivers (OR=6.19), and DUI drivers (OR=4.02) are significant contributing factors to WWD crashes.

In educating older drivers, they do not need more information of traffic rules but need to make sure they are able to drive safely. Some other states have provided a self-assignment tool for senior drivers to learn about their abilities to drive (Keskinen, 2014). NHTSA recommends that each state develops a comprehensive highway safety program for older drivers that incorporates elements from their older driver guide, which includes driver licensing and medical review of at-risk drivers, working in collaboration with social services and transportation service providers.

To help prevent DUI caused WWD crashes, the California Highway Patrol (CHP), working with student groups, local individuals, and local organizations such as Mothers Against Drunk Driving, started the Sober Graduation Program in 1985 to reduce drinking and driving among young people. The CHP ran television and radio public service announcements and distributed posters, bumper stickers, decals, key chains, and book covers. The results of this program were rewarding. In May to June 1985 alone, fatal crashes in this age group dropped 25%, and injury crashes decreased 19% (Copelan, 1989). These education countermeasures of reducing DUI drivers can also be applied in the state of Alabama for both old and young drivers.

5.2.3 Enforcement Countermeasures

Related regulation can be set up to regulate drunk drivers and drivers who do not wear seatbelts (OR=2.12). For example, Alabama already started a new law to legislate the use of ignition interlock devices for first-time convicted drunk drivers in 2014 (Pour-Rouholamin et al., 2015; Rauch, 2011). The 2015 WWD crash data can be used to check the effectiveness of this new law.

In addition, for drivers who intentionally make WWD movements from the confirmed WW entries (the gas station as the case study shows), camera can be installed there to monitor WW movements and related penalty tickets can be sent to those WW drivers.

5.3 FUTURE SCOPE OF STUDY

The author will further collect more field data of those confirmed WW entry points to create WWD predictive models, including macroscopic and microscopic models. The macroscopic model can utilize historical WWD crash data as well as incident data to predict the probability and frequency of WWD activities on a corridor or in a specific segment. For microscopic model, geometric design features (e.g., turning radius, intersection balance, median width, median types, sight distance), and traffic control devices (WW-related signage, pavement markings, and traffic signal indications) can be collected to customize this model. The author will quantify the characteristics of high-frequency WW movements areas to put forward widely-used countermeasures to mitigate WWD crashes.

This study has some limitations. For example, the data used to find the fatal crash contributing factors is limited, just five years of data on Alabama divided highways. If the sample size can be bolstered and data can be collected over longer periods and from more states, analysis can produce more comprehensive results.

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APPENDIX FIGURES FOR WRONG-WAY CRASH DATA ANALYSIS

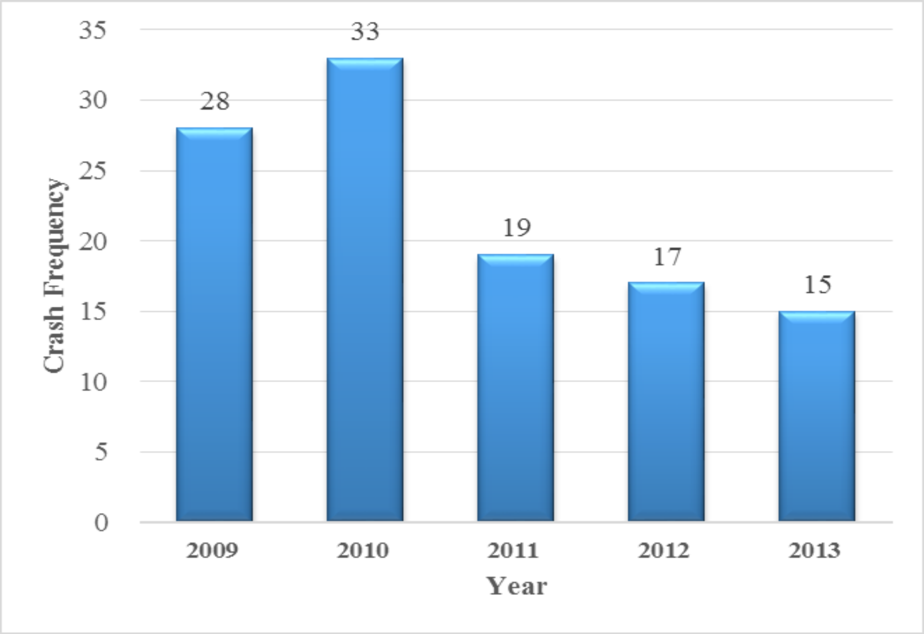

Figure A.1. Annual distribution of wrong-way crashes.

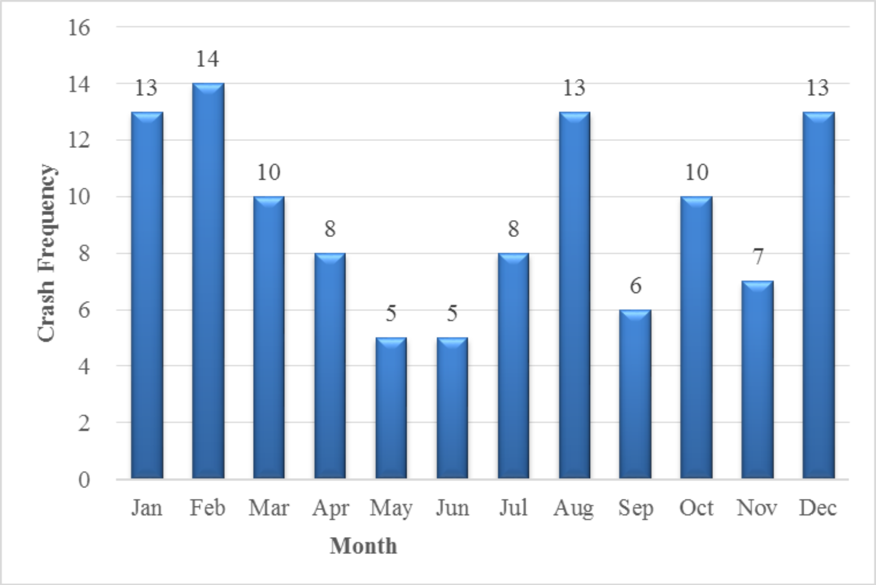

Figure A.2. Monthly distribution of wrong-way crashes.

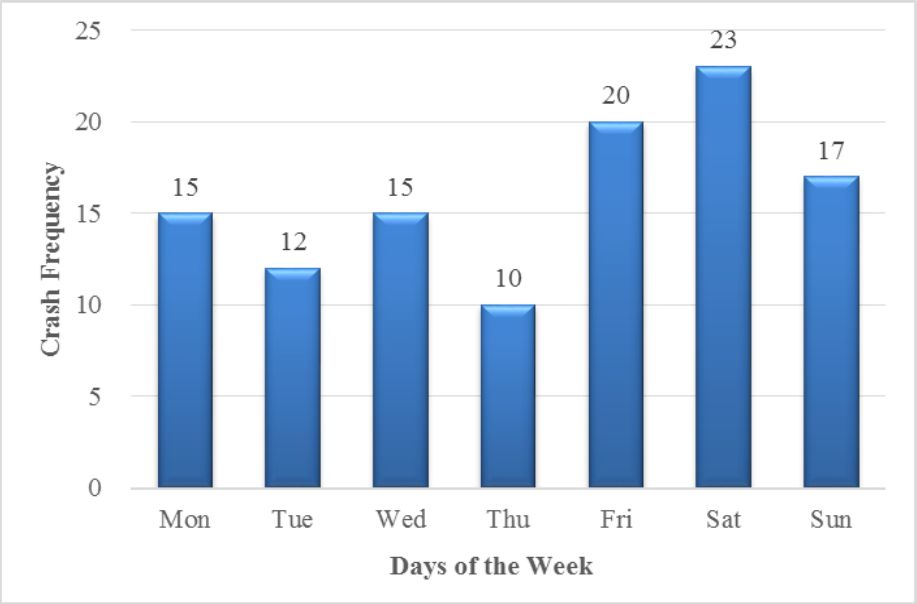

Figure A.3. Weekly distribution of wrong-way crashes.

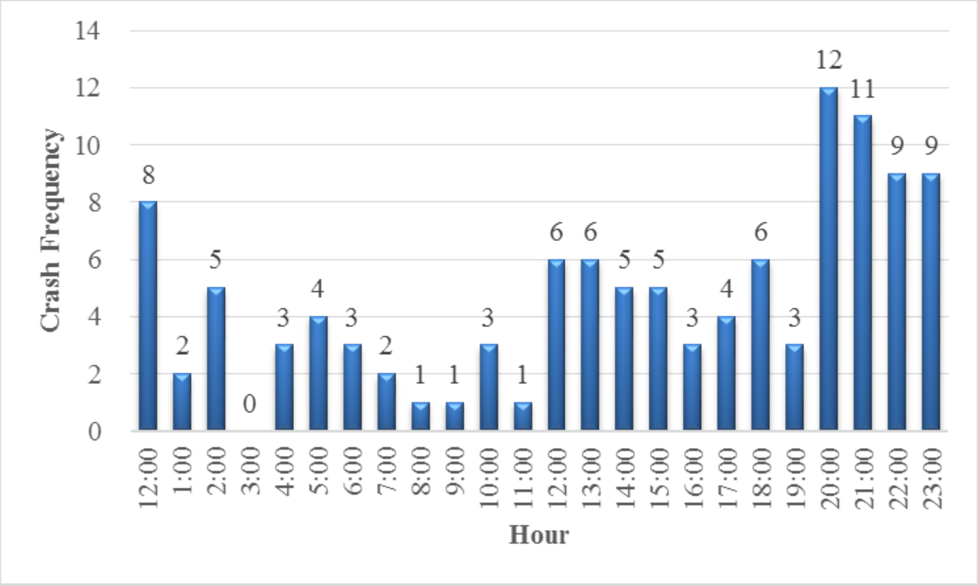

Figure A.4. Hourly distribution of wrong-way crashes.

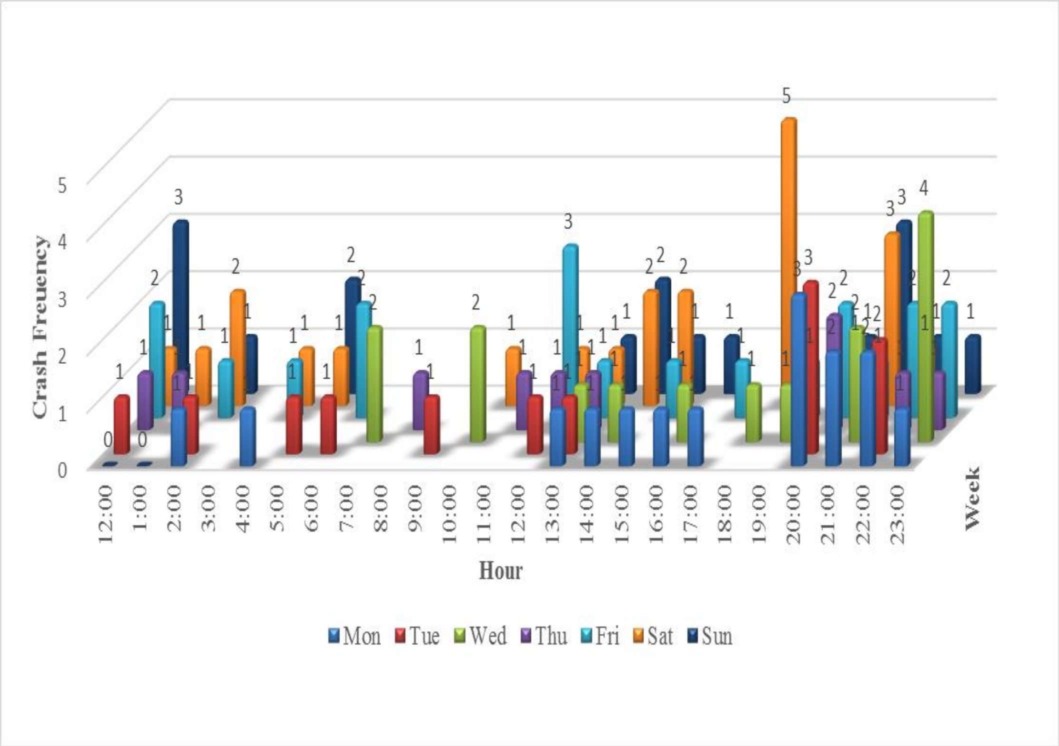

Figure A.5. Temporal distribution of wrong-way crashes.

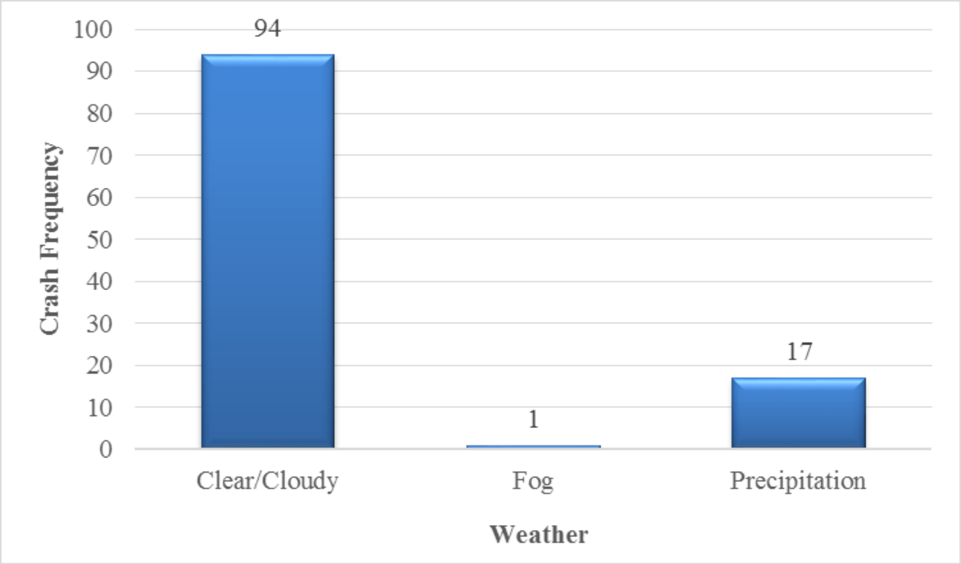

Figure A.6. Weather condition for wrong-way crashes.

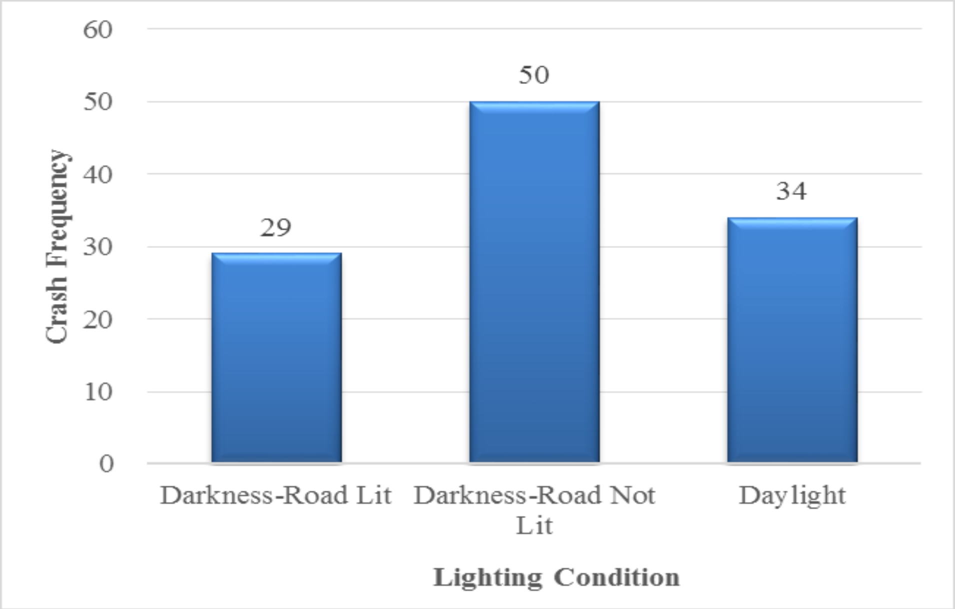

Figure A.7. Lighting condition for wrong-way crashes.

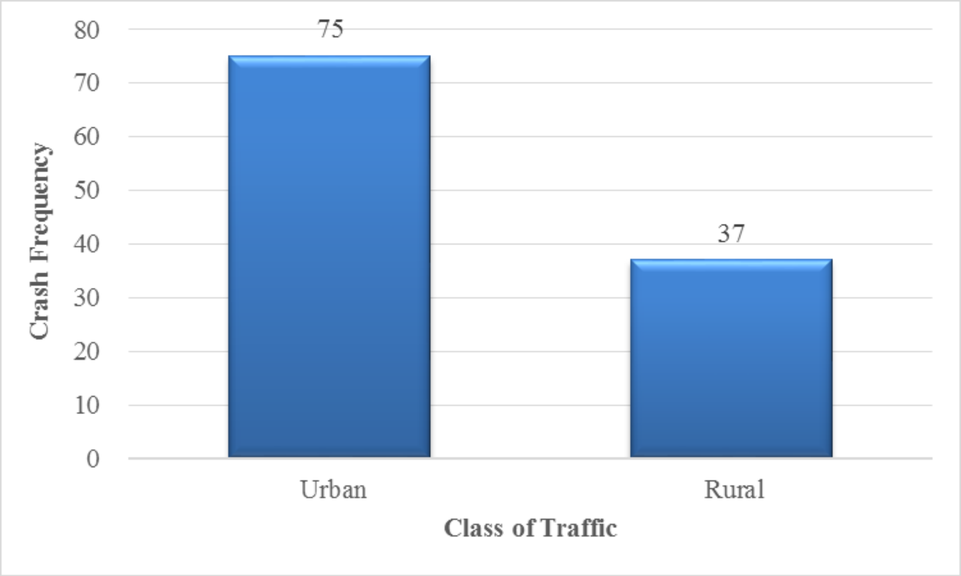

Figure A.8. Class of traffic way for wrong-way crashes.

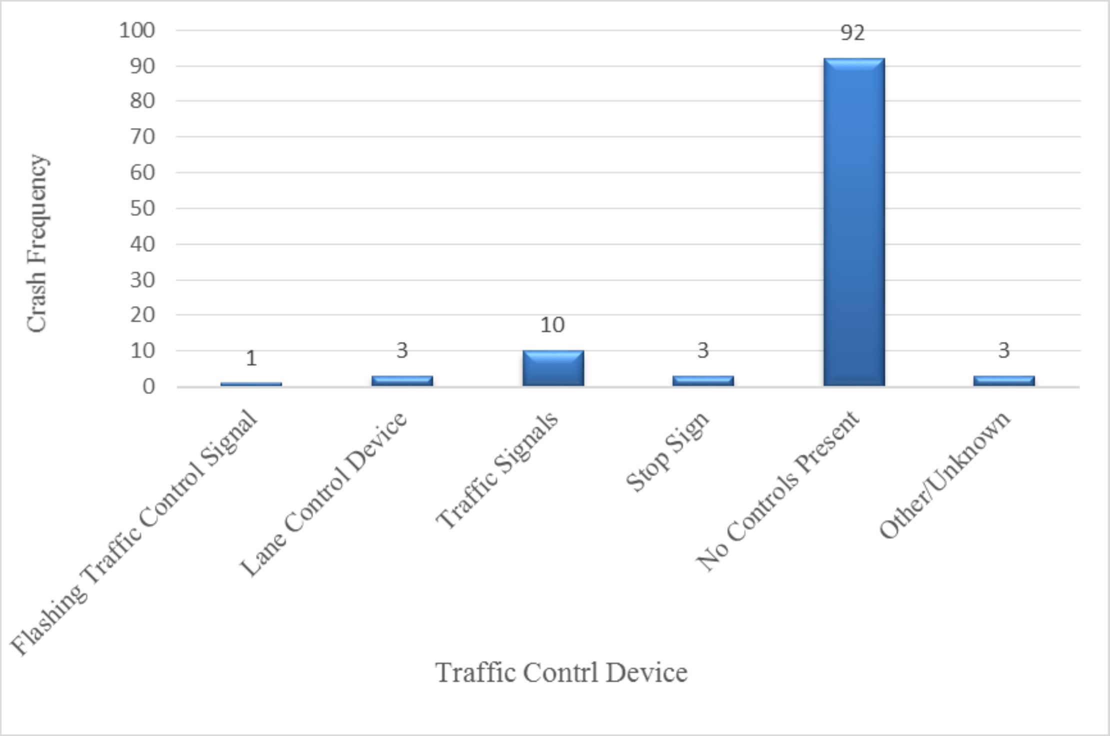

Figure A.9. Traffic control device presence for wrong-way crashes.

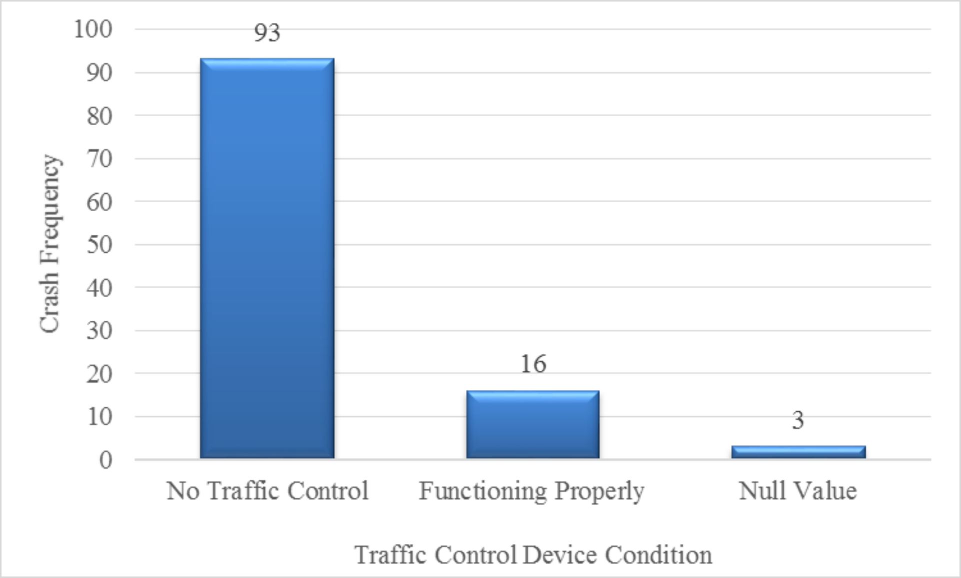

Figure A.10. Traffic control device operating condition for wrong-way crashes.

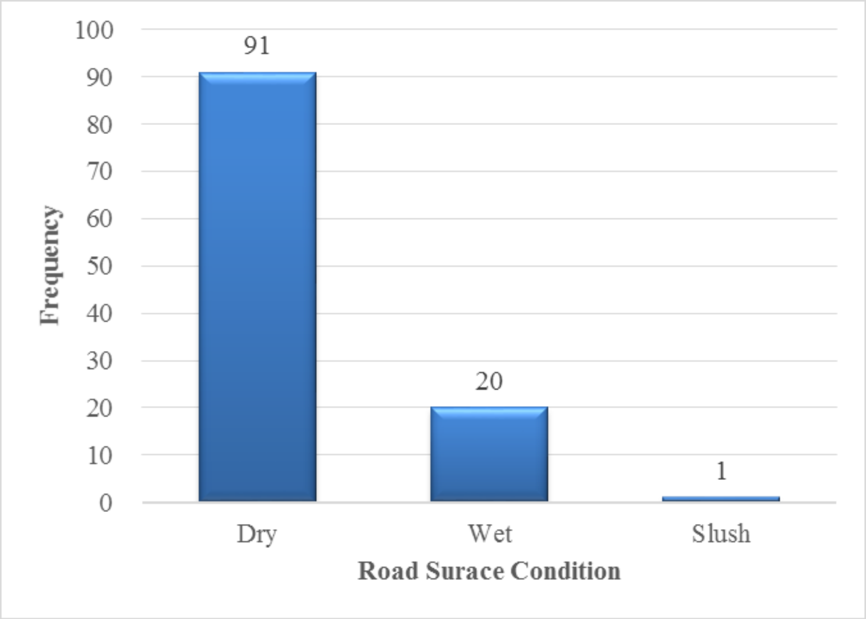

Figure A.11. Road surface condition for wrong-way crashes.

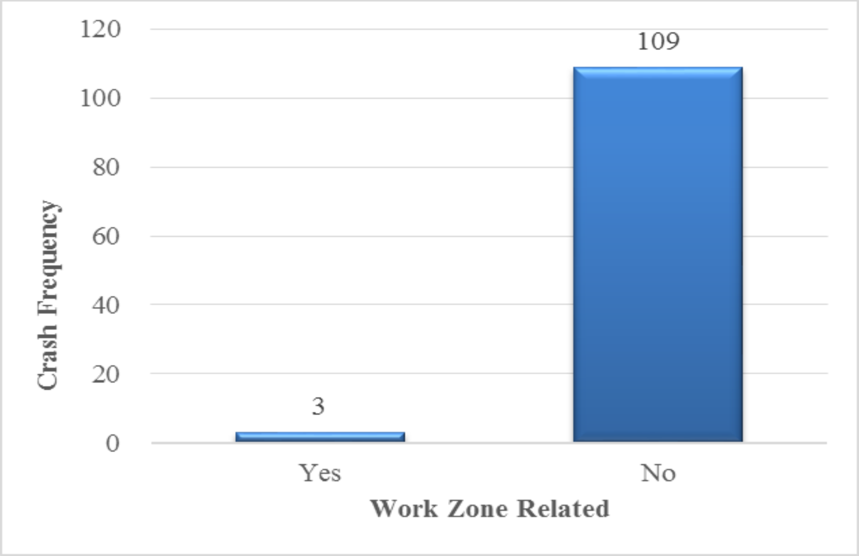

Figure A.12. Work zone–related wrong-way crashes.

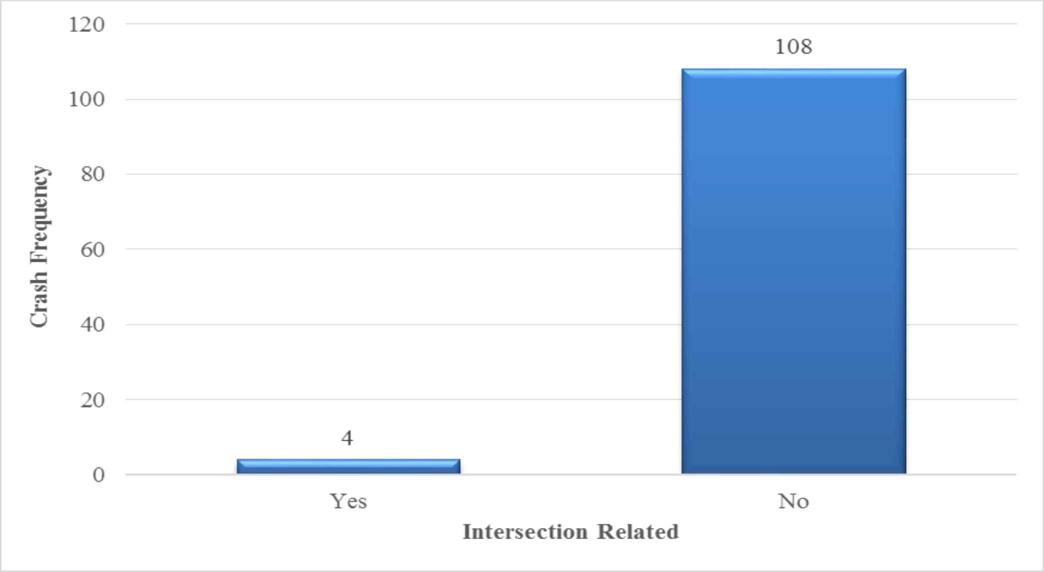

Figure A.13. Relationship between intersections and wrong-way crashes.

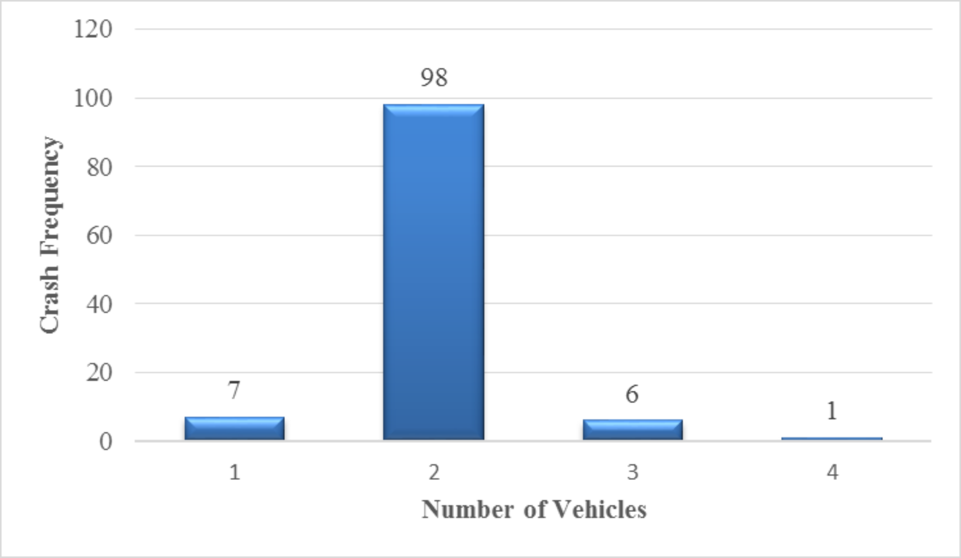

Figure A.14. Number of vehicles involved in wrong-way crashes.

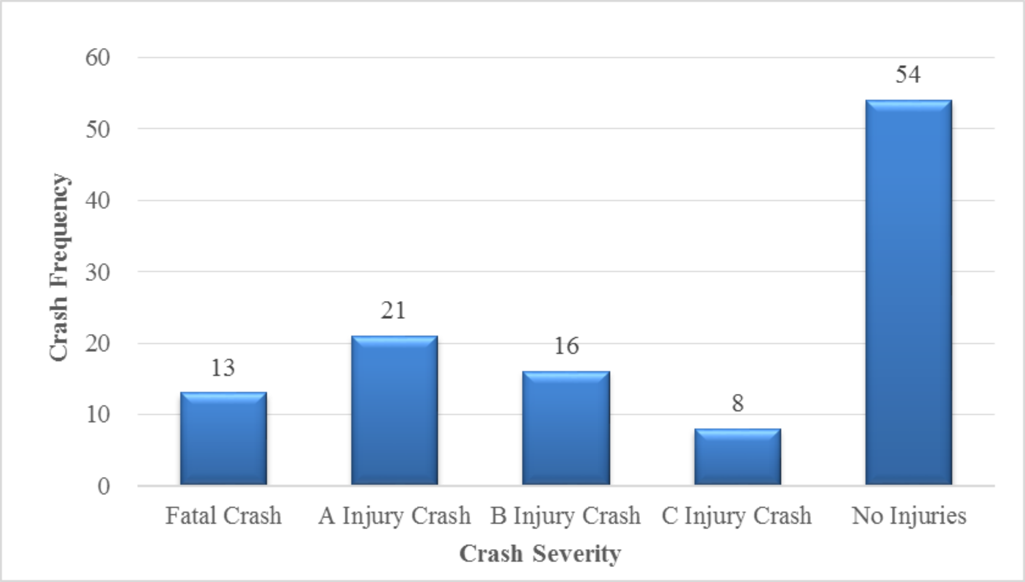

Figure A.15. Wrong-way crash severity.

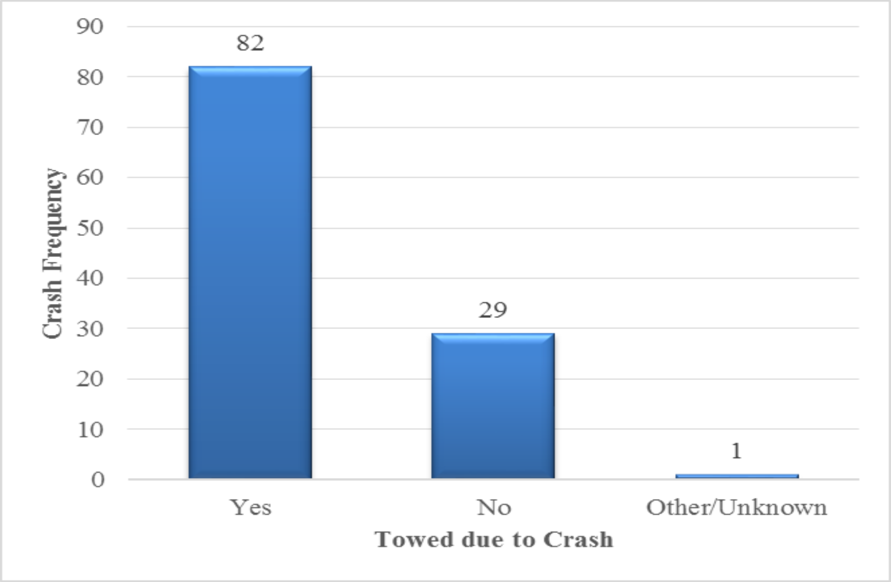

Figure A.16. Towed due to crash for wrong-way crashes.

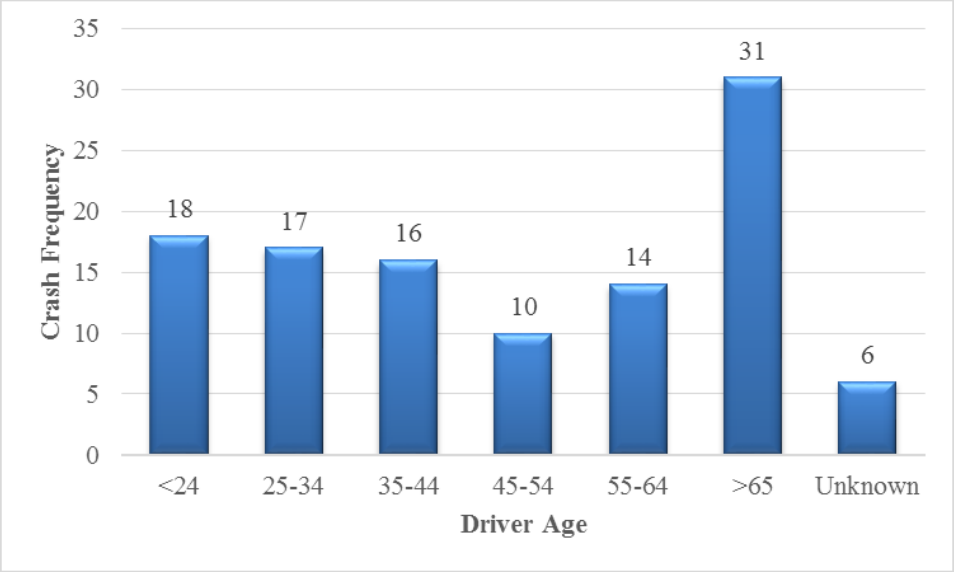

Figure A.17. Wrong-way driver age group.

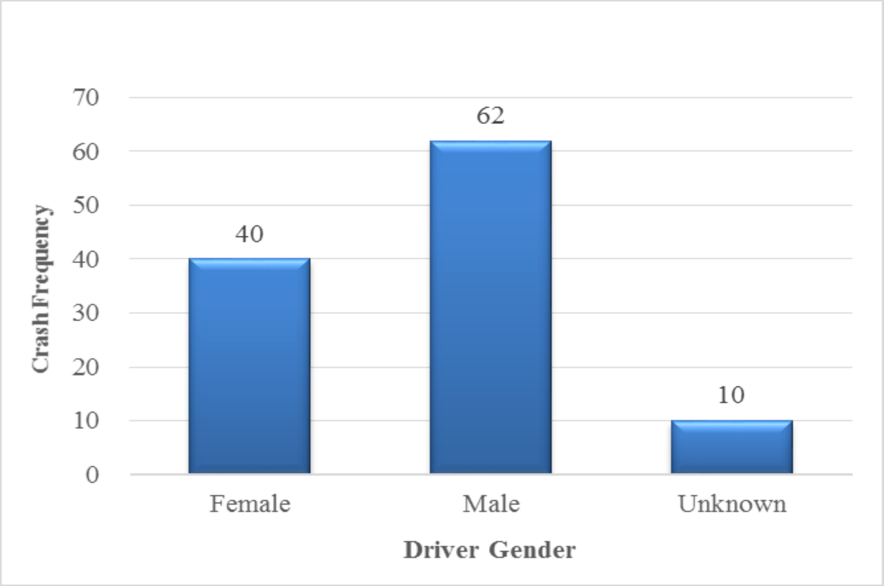

Figure A.18. Wrong-way driver gender distribution.

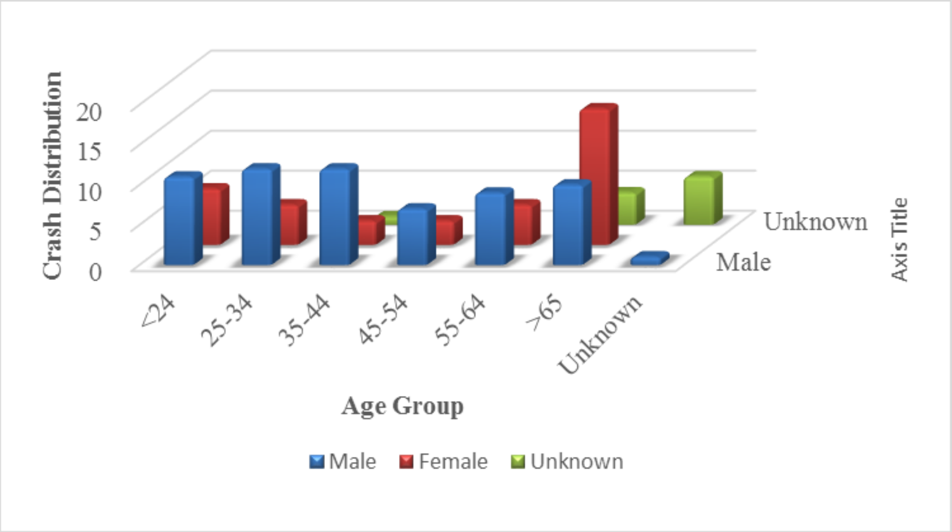

Figure A.19. Relationship between wrong-way driver age group and gender.

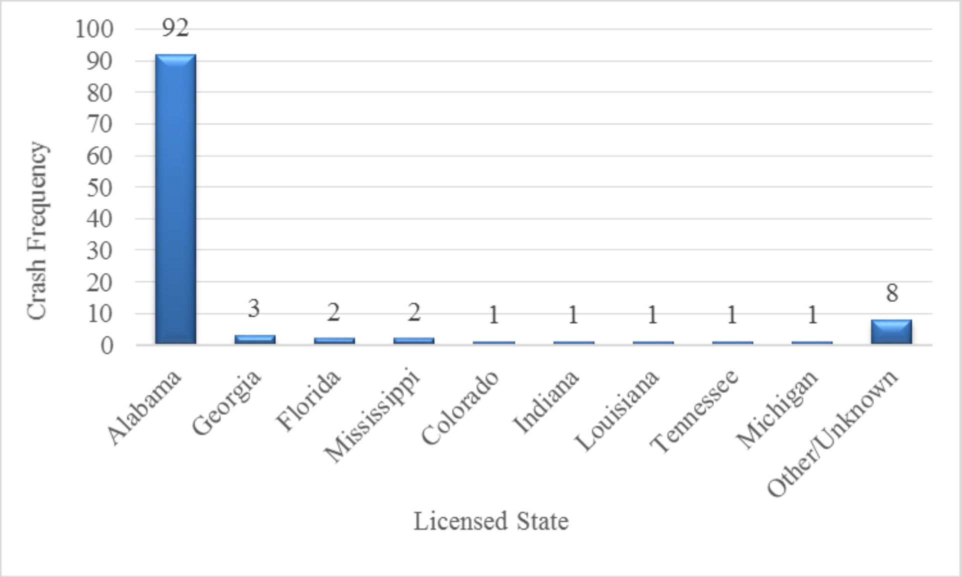

Figure A.20. Licensed state for wrong-way drivers.

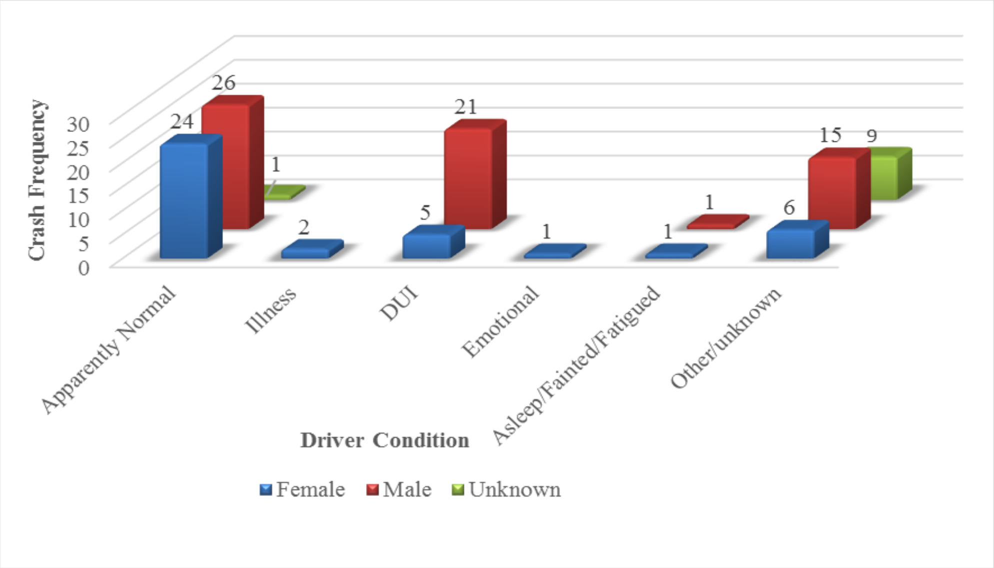

Figure A.21. Relationship between driver gender and condition.

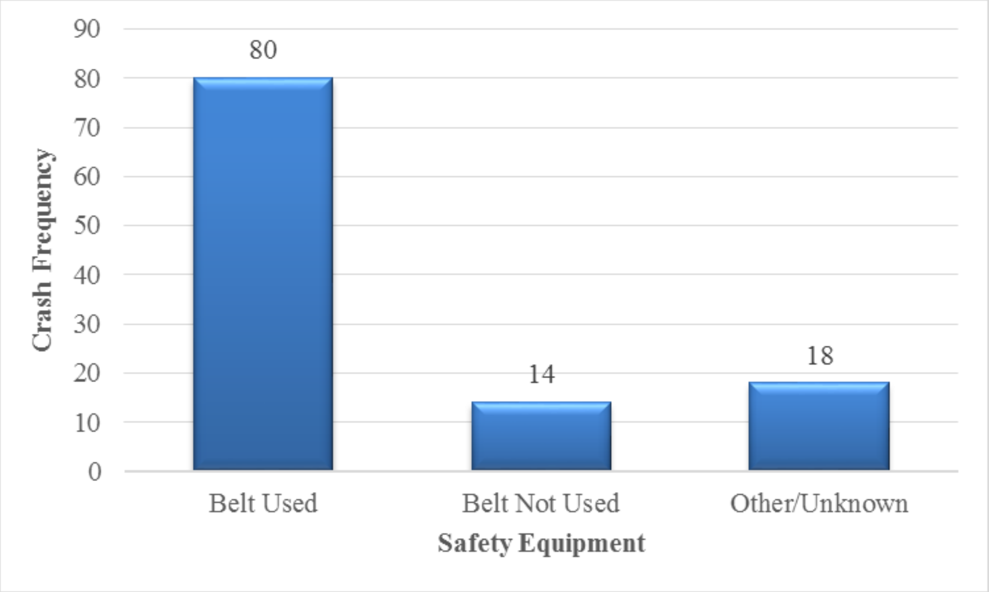

Figure A.22. Safety equipment used by wrong-way drivers.

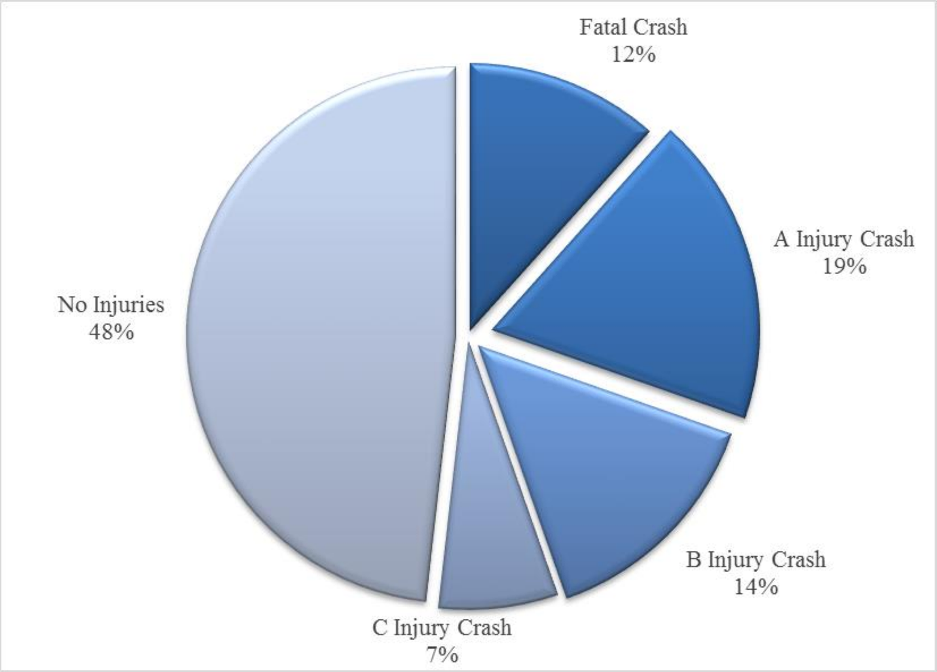

Figure A.23. Injury severity level for wrong-way drivers.

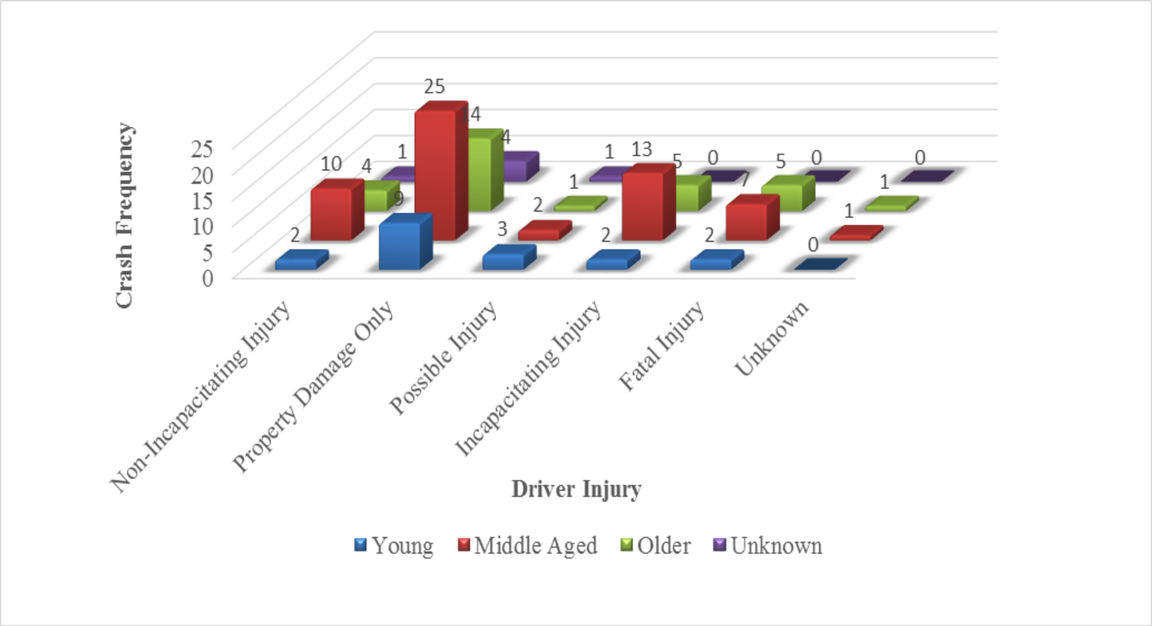

Figure A.24. Relationship between driver injury severity level and driver age group

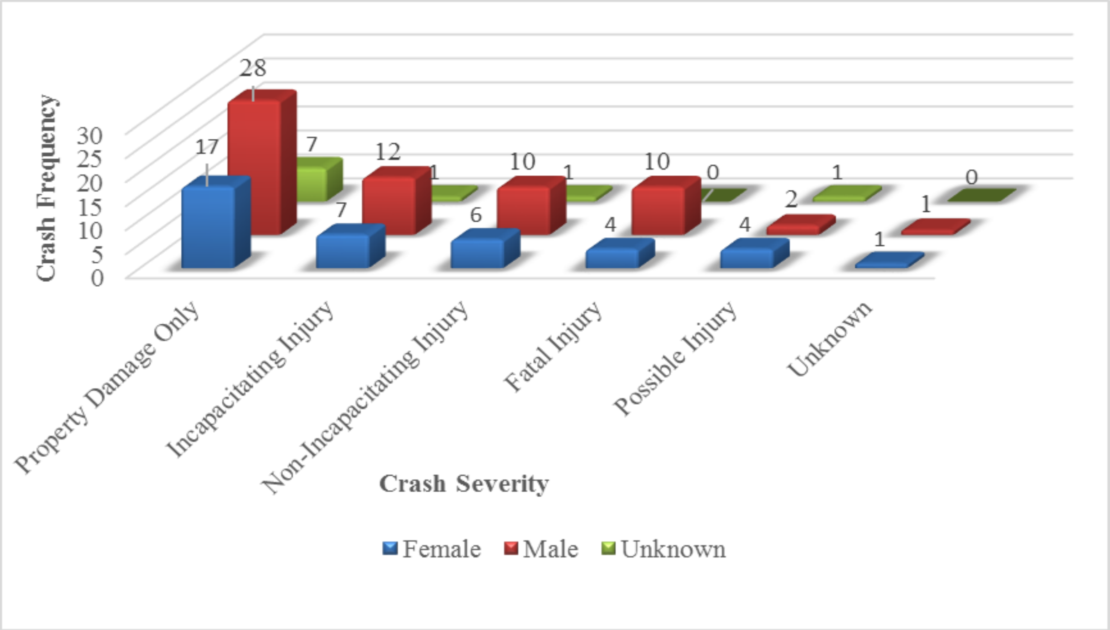

Figure A.25. Relationship between driver injury severity level and driver gender