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Evaluation of the Monroe Expressway Wrong Way Vehicle Detection Program

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16. Abstract

In North Carolina, wrong way driving (WWD) crashes are one of the most severe traffic crashes that often result in a fatality or serious injury since they involve head-on or opposite direction sideswipe crashes at high speeds. To minimize the occurrence of WWD crashes, the North Carolina Turnpike Authority (NCTA), which is a unit of the North Carolina Department of Transportation (NCDOT), deployed a wrong way vehicle detection system along the Monroe Expressway in 2018. The system can automatically detect wrong way vehicles at mainline stations and inform traffic management center operators.

This project evaluated the effectiveness of wrong-way traffic control devices installed at the ramp and mainline locations along the Monroe Expressway. A comprehensive literature search was conducted to summarize the state-of-the-practice of WWD crash modeling, detection, and prevention. Real-world traffic data including traffic volume, traffic control devices present, geometry and configuration of interchanges were employed for identifying the relationship between the frequencies of wrong way incidents and facility characteristics. During the study period of approximately 1.5 years of data collection, there were 13 actual WWD events, of which five wrong way movements originated from the roundabout parclo interchanges on the Monroe Expressway. In addition, this project collected statewide data on partial cloverleaf interchanges to assess the risk for wrong way movements. It was found that the partial cloverleaf interchange configuration was associated with the highest number of WWD activities, and factors that affect the risk of WWD mainly include: entrance and exit ramp traffic volume and control type, divided or undivided exit ramp, median cut turn access, left-turn perpendicular turning distance, skew angle, and distance between ramp terminals.

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Executive Summary

In North Carolina, wrong way driving (WWD) crashes made up only 0.2% of all freeway crashes; however, they accounted for 5.6% of fatalities across the state. In addition, approximately 60% of WWD freeway crashes resulted in a fatality or serious injury. In current practice, NCDOT has been developing strategies to address this issue with multiple solutions including upgrading interchange geometry, lighting and traffic control devices, and employing Intelligent Transportation System (ITS) based WWD detection and warning technologies.

In November 2018, the North Carolina Turnpike Authority (NCTA), which is a unit of the NCDOT, opened the Monroe Expressway. As part of the Monroe Expressway project, wrong way vehicle detection technology was installed at the toll zone locations. This technology, which was state-of-the-art at the time of installation, could automatically detect vehicles at toll zones travelling in the wrong direction along the Expressway and notify operators at the NCTA traffic management center.

This research aimed to provide an assessment of the effectiveness of the Monroe Expressway wrong way vehicle detection and warning systems, as well as to further understand the relationship between the frequencies of wrong way incidents and facility characteristics, such as interchange design and traffic volumes. Additionally, this project collected statewide data on partial cloverleaf interchanges to assess the risk for wrong way movements based on a risk model developed in a previous study found in the literature.

The statewide analysis found that the highest expected risk of wrong way movements occurred at predominantly lower demand partial cloverleaf interchanges with arterials or access roads nearby. Median separation of the arterial and tighter turning radii were correlated with lower risk of wrong way movements.

Analysis of the Monroe Expressway wrong way vehicle detection system found that the quality of data collected improved significantly over the analysis period. The two primary datasets included the operators logs and the detection system vendor logs which were cross-referenced in order to identify valid wrong way movements. From November 2018 – May 2020, a total of 13 confirmed wrong way movements were identified, with a statistically significant portion originating at the two roundabout partial cloverleaf interchanges. Additionally, recommendations on the collection and monitoring of the data were provided to improve data reliability and support future benefit cost analysis.

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Table of Contents

List of Tables

List of Figures

1. Introduction

In North Carolina, wrong way driving (WWD) crashes made up only 0.2% of all freeway crashes; however, they accounted for 5.6% of fatalities in the state. In addition, approximately 60% of WWD freeway crashes resulted in a fatality or serious injury. Based on these findings, the prevention of WWD crashes has been considered by the North Carolina Department of Transportation (NCDOT) as a high priority task that has recently garnered more attention. To date, the NCDOT has implemented multiple solutions to address this issue including upgrading interchange geometry, lighting and traffic control devices, and employing Intelligent Transportation System (ITS) based WWD detection and warning technologies. Previous NCDOT research identified potential entry points for wrong way crashes on freeways and developed a toolbox of treatments which can improve interchanges or ramps with wrong way movements.

In November 2018, the North Carolina Turnpike Authority (NCTA) opened the Monroe Expressway, which is a nearly 20-mile-long toll road in Monroe. It serves as an alternative route to the existing U.S. 74 corridor located southeast of Charlotte, extending from Stallings to Marshville in Union County, North Carolina. As part of the Monroe Expressway project, wrong way vehicle detection technology was installed at toll zone locations. This state-of-the-art technology could automatically detect vehicles at the toll zones travelling in the wrong direction on the Expressway, alert wrong way drivers in real time through electronic signing, and notify operators at the NCTA traffic management center.

This research effort aimed at providing an assessment of the effectiveness of the Monroe Expressway wrong way vehicle detection and warning systems, as well as to further understand the relationship between the frequencies of wrong way incidents and facility characteristics such as interchange design and traffic volumes. In practice, due to the relatively low frequency of wrong way driving incidents, this research employed both naturalistic and experimental WWD events at the controlled-access Monroe Expressway. Moreover, traffic flow data such as traffic volume and average speed were collected at each detector location. It is expected that the results of this research will enable NCTA and NCDOT to consider ITS, traffic control, and geometric improvements to reduce wrong way incidents at freeway interchanges statewide.

This report includes a literature review chapter summarizing the findings of previous research, a chapter on the statewide parclo inventory and results, a chapter on the Monroe Expressway WWD system data and results, a chapter of conclusions and recommendations as well as a chapter of references from the report. In addition, the parclo inventory is provided as a separate Excel file as well as a metadata file describing the Monroe Expressway WWD system datasets.

2. Literature Review

This literature review summarizes previous studies related to WWD crash and entries on access-controlled freeways. It is divided into three sub-sections: (1) statistical modeling of WWD events, (2) traffic control devices (TCDs) and other engineering treatments to prevent WWD events, and (3) ITS-based WWD detection.

2.1. *Statistical Modeling of WWD Events*

In this section, different analytical techniques and data types adopted by past studies for investigating WWD events are discussed. Next, the WWD event data (e.g., crash, citation, and 911 calls) used by those studies are described followed by the predictor variables used when modeling WWD events are listed. Last, a summary of the review of past studies related to WWD modeling WWD events is presented.

2.1.1. Analysis Techniques

Most studies related to WWD events focused on estimating the WWD frequency or probability as a function of the driver, vehicle, location, traffic, and environment-related characteristics. Until 2015, most studies related to WWD events used descriptive statistics of crash data (*1–3*). As cited by Das et. al., Braam et. al. *(1)* used the statewide crash database of North Carolina to describe the nature of the factors associated with WWD crashes *(4)*. Another study *(2)* used crash data and radio messages related to WWD events to identify contributing factors for WWD events on Switzerland's roads, whereas Morena and Leix *(5)* used the descriptive statistics of crash data. These studies revealed that driver characteristics, location of the WWD accident, and interchange type associated with the WW entry-ramp are most likely to influence the likelihood and severity of WWD accidents. They also showed that it is crucial to implement treatment strategies both at the crossroad-ramp junction and along the ramp so that drivers can correct the wrong way entry even after wrongfully entering an off-ramp.

Zhou et al. *(3)* developed a metric called WWD crash rate (CR) with an objective to rank each interchange type within the state of Illinois. The major challenge of this effort that researchers faced was assigning a reported WWD crash to an interchange. In tackling this problem, Zhou et al. assigned a relative weight to an interchange for each WWD crash depending on its distance from the police-reported crash location. If a police report does not mention the entry point of the WW vehicle associated with a crash, then two types of weight were assigned to the nearby interchanges for each crash. An interchange gets a weight of 0.7 if it is the closest and 0.3 if it is the second closest from the crash location. If a police report mentions the WWD's entry point associated with a crash, that interchange gets a weight of 1.0 for that crash. After assigning these weights, the WWD crash rate, CR_{int}, (i.e., the total number of weighted wrong-way entries per 100 interchanges per year) for each interchange type is estimated using Equation 1.

$$CR_{int} = 100 * \frac{1 * E_{1,int} + 0.7 * E_{0.7,int} + 0.3 * E_{0.3,int}}{N_{int} * T} \quad \text{Equation 1}$$

where,

int = interchange type, e.g., diamond, parclo, etc.;

N_{int} = total number of that particular type of interchange in Illinois; and

$E_{1,int}$ = total number of WWD crashes for that interchange category with ramps mentioned in the police report as the point of entry of the WWD event.

$E_{0.7,int}, E_{0.3,int}$ = total number of WWD crashes for that interchange category that was the closest or second closest from the crash location, respectively.

T = study period (years)

From 2015 onward, several studies used regression techniques to estimate the frequency and probability of WWD events and crashes. Several studies *(6–8)* used binary regression models to estimate the likelihood for an interchange to have a record of WWD crashes within a period. A couple focused only on parclo interchanges specifically *(6–7)*, while one only focused on diamond interchanges (*8*). One common challenge these studies faced was that the number of interchanges with at least one WWD crash was significantly lower than that with no history of WWD crash. Two of these studies used a special regression technique called the *Firth's logistic regression* to account for this imbalance in data *(6,8)*.

Another study utilized a binomial regression model for estimating the frequency of WWD events *(9)*. They considered both WWD crashes, 911 calls, and citations as events. The researchers regarded a binomial regression model to be more suitable than a Poisson regression model because the observed variance of crash frequency was found to be significantly higher than its observed mean value, which violates the Poisson distribution assumption.

Two similar studies estimated the frequency of WWD crashes using generalized linear regression models *(10–11)*. Unlike Kayes et al. *(9)*, these two studies assumed that WWD crash occurrences follow a Poisson distribution. The model proposed by Sandt et al. (*11*) for WWD crash frequency at freeway segments is shown in Equation 2.

$Y = exp(-3.82 - 0.484p + 0.783 * log\ (q) - 0.534r + 1.201s - 0.926t + 0.661 * log\ log\ (x)$	Equation 2

where,

Y = *WWD crash frequency for four years;*

p = citation (binary);

q = 911 call frequency;

r = partial diamond interchange (binary);

s = trumpet interchange (binary);

t = major directional interchange (binary); and

x = crossing AADT

Sandt et al. (*11*) extended their research to include the duration of WWD events which are often critical from a traffic operation perspective. This study ranked various freeway routes and segments of Central Florida based on the reported durations of WWD crashes by traffic management centers.

Unlike most of the studies discussed above, several studies focused on identifying patterns of different factors associated with WWD crashes using data mining tools *(4,12,13)*. Das et al. *(4)* estimated the association of different geometric and driver characteristics concerning WW crashes using multiple correspondence analyses (MCA). The MCA technique is primarily used to estimate the association among the values of different categorical variables associated with a WWD crash. For instance, upon mining several years of WWD crash data, the researchers revealed that fatal WWD crashes corresponded highly to locations with a posted speed limit between 60 to 70 mph located in open rural areas. Such associations may provide essential insights to transportation agencies for preventing WWD crash occurrences and applying treatments. Other notable associations the research team found are:

i) WWD crashes with poor lighting conditions being associated with a) area type = rural, b) access control = full, c) road type = two-way with a median barrier and

ii) WWD crashes with driver severity being associated with crossroad AADT > 40,000.

Despite being able to recommend control strategies based on these findings, these rules cannot conclude causality among these variables. Das et al. (*12*) attempted to address this gap by applying a machine learning-based algorithm called frequent pattern mining (FPM) to five years of WWD crash data. Two important parameters related to this FPM technique are the *support* and *confidence* of the observed pattern. These two parameters are estimated based on the observed frequency and rate of a pattern from the characteristics of WWD crashes. The FPM method revealed the association of several geometric and driver-related factors associated with WWD crashes, including the median type on two-lane roadways, impaired driving, improper and inadequate pavement marking, and insufficient road signs.

2.1.2. WWD Event Data

Most studies used police-reported WWD crash data to describe and model WWD events. Ponnaluri (*13*) employed the reported crashes on the Florida freeway system between the years 2003 and 2010 to estimate the likelihood of WWD crashes and their fatalities. Pour-Rouholamin (*6*) used police-reported crashes along access-controlled highways in Alabama between 2009 and 2013 and Illinois between the years 2004 and 2013 to estimate the likelihood for different parclo interchanges to have a WWD crash history. All 65 WWD crashes were found to be associated with 54 parclo interchanges within these two states. Atiquzzaman and Zhou (*8*) also used the same crash data as Pour-Rouholamin (*6*); however, they focused on diamond interchanges to estimate the likelihood for an interchange to have a WWD.

Wang (*7*) estimated the odd-ratio for a parclo interchange to have a WWD crash record using crash data from 44 parclo interchanges located along Illinois' access-controlled highway network. Morena and Leix (*5*) identified the contribution of different driver, vehicle, traffic, and geometric characteristics of interchanges to WWD crash rate based on the crash records of Michigan’s freeway network between 2005 and 2009. Rogers et al. (*10*) and Sandt et al. (*11*) used WWD crash data aggregated over route-level and segment-level to rank the routes and segments of the South and Central Florida freeway network, respectively, in terms of WWD crash occurrences.

Das et al. (*4*) used five years (2010–2014) of WWD crashes in Louisiana to determine the key associations between various driver, traffic, and geometric factors that may contribute to WWD crashes. Another effort (*12*) used the same crash data to determine the interactions between different factors (e.g., absence of proper signs and markings, mainline AADT, and lighting conditions) leading to WWD crashes.

Utilizing police-reported crash data for analyzing WWD events is advantageous because such data sources include detailed information about driver impairment and demographics. However, relying solely on crash data to estimate WWD probability has some limitations. First, WWD events are rare, and even more infrequent are the WWD crashes. Consequently, studies that relied on WWD crashes had to collect crash data over a very long period and cover a large area. A few studies addressed the issue of limited samples of WWD crashes by supplementing crash data with the records of 911 calls and citation reports. Rogers et al. (*10*) used WWD crashes, citations, and 911 call reports and showed that WWD crash frequency is correlated with the number of citations and 911 call reports. Kayes et al. (*9*) combined WWD crash data collected over five years (2011-2015) with WWD related citation and 911 call reports of eight years (2011-2018) to model the overall WWD events at 1157 exit ramps located along Florida's access-controlled freeways. While other studies (*10*–*11*) used WWD related citations and 911 calls as predictors, Kayes team claimed to be the first one to use those data to supplement the small sample size of WWD crashes.

The second issue associated with using WWD crash data is that if the focus of research is identifying the site-specific characteristics that may contribute to WWD events, it must locate the WW vehicle's entrance location associated with each WWD crash. This task is often challenging and needs to be done based on an educated guess using police-reported crash data. Zhou et al. (*3*) focused on this task exclusively since their objective was to rank the interchanges of Illinois in terms of WWD crashes. Of the WWD crash reports they analyzed, only 22% reported both the crash and the entry ramp location for the WW vehicle. The cumulative distribution of the distance between these two locations for those 22% of crashes is shown in Figure 1 with the red line. The remaining 78% of police reports contained only the location of the crashes. For these remaining crashes, the distances to the first and second nearest interchanges downstream of each reported crash locations were estimated. Their cumulative distributions are shown by the dashed blue and the dotted yellow lines, respectively. This plot shows that for most crashes, the second closest interchange is several kilometers away from the nearest interchange to the event. Also, the distribution for the nearest interchange distance matches closely with the red line, which was derived from the police reports. Based on this observation, the researchers selected different weights for the nearest and second nearest interchange for each WWD crash when ranking interchanges based on an estimated crash rate (see Eq. 1).

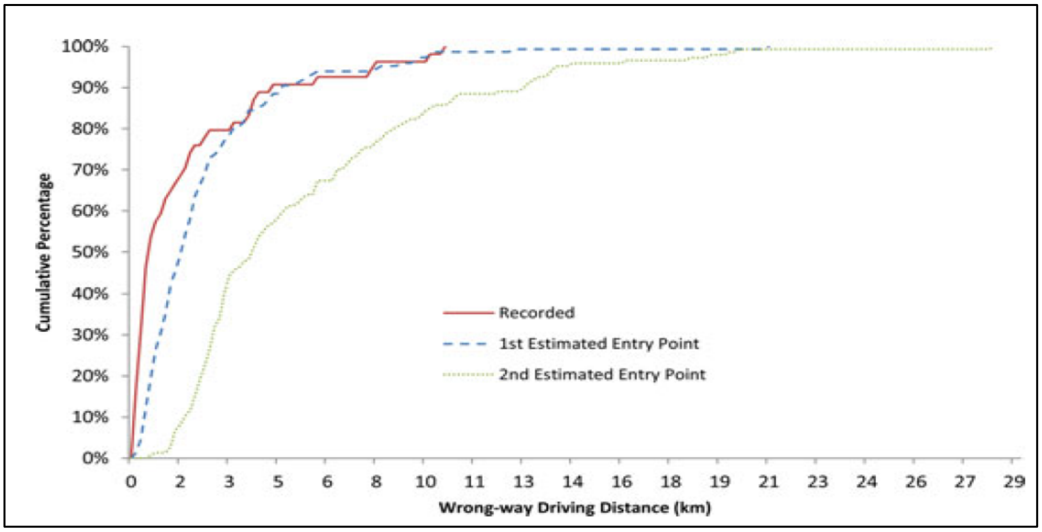


Figure 1. Cumulative distribution of distances between WWD crash locations and entry points estimated based on either the closest interchange locations or police reports of crashes (3)

2.1.3. Contributing Factors

The previous sections showed that most prior studies related to WWD events focused on estimating or finding associations of different factors with WWD probability or frequency. This section discusses the predictor variables those studies found as statistically significant in their models or considered important to analyze the descriptive statistics of WWD crashes. Several studies targeted the planning level aspects of modeling WWD crashes (*6*–*9*). Hence, they used geometric characteristics, land-area type, and long-term traffic demand data. These researchers avoided including operational data, such as lighting conditions, weather, driver, and vehicle characteristics associated with each WWD crash. The geometric features that were considered by these studies are described in Figure 2. Pour-Rouholamin (*6*), while investigating the WWD crash risk for parclo interchanges, found that WWD crash risk is high for partial cloverleaf interchanges where adjacent entry and exit ramps are co-located (esp. near a driveway entrance) and a large corner radius with a traversable median from the crossroad is present. Figure 2 shows that at the intersection of a crossroad and a two-way ramp, a higher value of the corner radius from the crossroad may lead the left-turning traffic from the crossroad to enter the ramp the wrong way. The high chance of WWD events associated with a traversable median and a nearby driveway is intuitive, although those are not shown in Figure 2. In addition to these, Wang (*7*) considered another intersection feature, which is the stop-bars relative position for the left-turn movement from the crossroad median of the closely spaced on and off-ramps (Figure 3). The value is expressed as a percentage of the total distance, L_{max}, between the two stop bars on the crossroad. While there is no guideline on the maximum value for this distance in the MUTCD, the Washington State DOT manual suggests this distance be less than 60% (*14*) of the distance between the stop bars on the mainline so that the left-turn movement from the crossroad does not get confused with the entrance of the ramp. No guidance was provided on how to interpret this distance when no stop bars are present. Wang (*7*) also corroborated this guideline as his findings revealed that the higher this distance, the higher the number of WWD events.

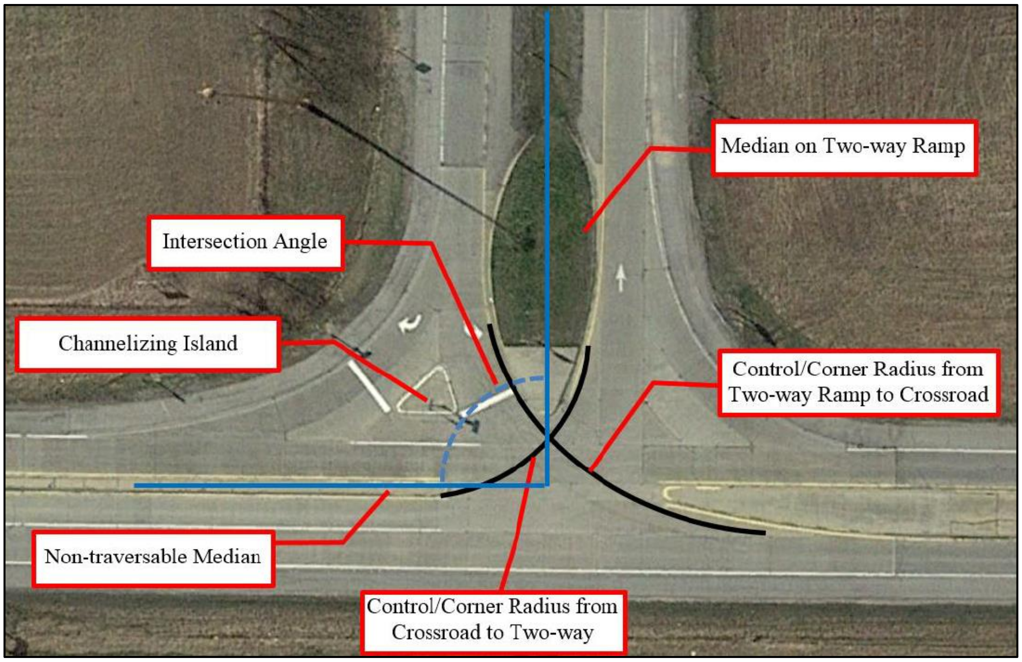


Figure 2. Geometric features of a parclo interchange considered by Pour-Rouholamin (6)

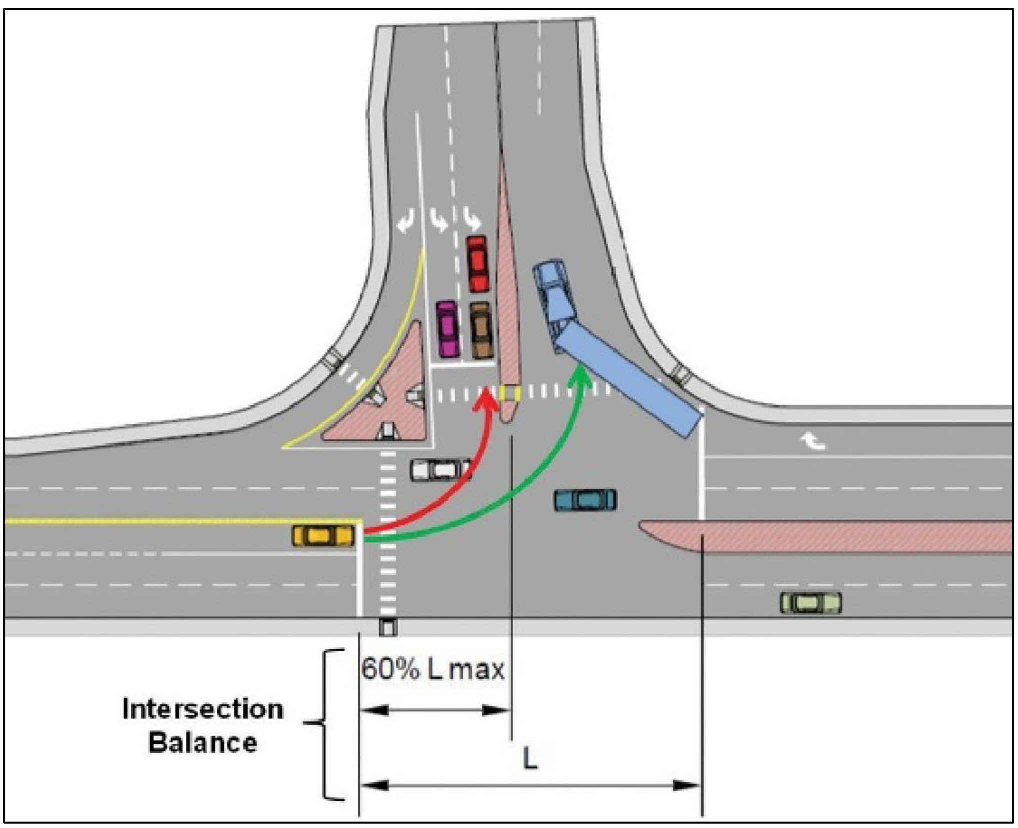


Figure 3. Explanation of intersection balance. Courtesy: Wang (2018)

Atiquzzaman and Zhou (*8*) considered the a) traffic control type at the intersection, b) the presence, number, and distance of Do Not Enter (DNE) signs, and c) the AADT of the crossroad for diamond interchanges. They divided their models into two groups based on the number of lanes on the crossroad —multilane and two-lane (i.e., single lane on each direction) crossroads. An obtuse intersection angle exhibited a lower likelihood of WWD than a right-angle or acute angle intersection. This is contrary to the guidelines of the AASHTO Green Book (*15*), which suggests a right-angle intersection for one-way exit ramps. The odds of WW entry increased by three to five times when the distance between the first WW sign and crossroad is more than 200 ft compared to when the distance is 200 ft or less. This is an interesting finding given that the placement of WW sign varies widely among different state and local transportation agencies. NCDOT provides design standards for the placement of Wrong Way signs on ramps for cloverleaf and diamond interchanges. An intuitive finding reported by Atiquzzaman and Zhou (*8*) was that the AADT on the exit ramp and on the crossroad have different effects on the probability WWD events, with the latter one having a positive correlation with WWD events. This finding is unsurprising because the higher the exit ramp volume, the lower the crossroad driver's chance of getting confused with the ramp's direction of flow. On the contrary, the higher the crossroad volume, the higher the number of WWD events. The usage of DNE signs, channelization of the island, and distance to the nearest access point was found not statistically significant by this study.

Kayes et al. (*9*) also considered both geometric characteristics of interchanges and long-term traffic demand in their WWD models. Unlike the studies discussed above in this section, Kayes et al. (*9*) focused on all types of interchanges, and hence, used the interchange type as a predictor variable. This variable showed that directional and trumpet interchanges have a higher probability of WWD occurrences compared to cloverleaves. Note that a few studies considered parclo interchanges as a high-risk to WWD crashes (*5*–*6*). However, the most striking findings reported by Kayes et al. (*9*) were the effect of intersection angle, exit ramp AADT, and crossroad AADT. Their finding on the intersection angle conflicted with those reported by Atiquzzaman and Zhou (*8*), as Kayes et al. showed that an obtuse angle had a higher chance of WWD entries than an acute angle intersection. On the other hand, both reported that a right-angle intersection has a high probability of WWD events. Kayes et al. (*9*) reported that the crossroad and ramp AADTs have, respectively, a negative and a positive correlation with WWD events—another finding that contradicts that of past studies. However, it should be noted that Kayes et al. (*9*) developed their models for all interchange types, unlike Atiquzzaman and Zhou (*8*), which considered only diamond interchanges. Furthermore, the coefficient sign of a predictor in a model largely depends on the data and other predictors used in the model.

In addition to these geometric characteristics and long-term traffic demand levels, several studies included crash-specific predictor variables. Morena and Leix (*5*) included environmental, driver-related, and vehicular characteristics associated with WWD crashes in their analyses. It showed that driver age, impairment, lighting condition, location, and interchange type play a significant role in WWD crash occurrences. It also showed that parclo and trumpet interchange designs are more prone to WWD entries than other types of interchanges. Zhou et al. (*3*), based on the descriptive statistics of crash data, reported that night-time hours, driver impairment, and proximity to urban areas were associated with a high number of WWD crashes. The top five interchange types that this study ranked in terms of WWD crash risk include compressed diamond, single point diamond interchange, freeway feeder, and partial and full cloverleaf interchange.

Several studies that did not focus on predicting WWD crash risk for interchanges also revealed important insights about the influence of geometric and traffic characteristics on WWD crashes. Sandt et al. (*11*) identified WWD hotspots at freeway segments and routes by incorporating the historical presence of WWD citations, frequency of 911 calls, the presence of a particular interchange type, and average mainline and ramp AADT as the predictors. They aggregated the data for a group of neighboring interchanges, which were termed as *segments,* as well as for entire freeway routes. Most predictors exhibited intuitive coefficients, e.g., positive coefficients for 911 call frequency, the presence of a trumpet interchange, and crossroad AADT. Das et al. (*4,12*) found statistically significant associations of several geometric and traffic predictors with WWD crash frequency and severity, including the absence of DNE signs, inadequate pavement marking, open area, high mainline AADT, and poor lighting condition.

2.1.4. Summary

From the above discussion, it is apparent that many studies investigated WWD events at freeways and the resulting crash occurrences. While most of these studies focused on determining the effects of different geometric and traffic characteristics, a few concentrated on determining hotspots, ranking of interchanges, and finding the association among various geometric and traffic factors. Police reports of crashes have been the most widely used WWD event data, with a few recent studies incorporating the 911 calls and citation reports of WWD events as well. Descriptive statistics summarized for different factors have been a common form of analysis, but the application of regression models and machine-learning-based algorithms is noticeable in the recent studies. Due to the random nature of WWD events, past studies had to utilize data collected over a long period and from a large number of locations. Most of these studies utilized the statewide crash databases for Alabama, Illinois, North Carolina, Florida, and Michigan.

There are several geometric and traffic characteristics that were considered by multiple past studies for WWD risk modeling. Note that the effect of these characteristics on the estimated WWD risk according to different models' coefficients was different. This is because the coefficient value and sign for a predictor are intertwined with other predictors' presence. Some factors that expectedly were found to contribute to the WWD crash risk are noted below in

Table 1 and are summarized below.

- Ramps and driveways co-locating with the partial cloverleaf interchange ramps *(6)*
- Large corner radius with a traversable median from the crossroad at partial cloverleaf interchanges (*6*)
- Intersection balance is more than 60% (7, *14*)
- Distance between the first WW sign from a crossroad intersection toward the on-ramp is more than 200 ft (*8*)
- Low exit ramp AADT and high crossroad AADT (*8*)
- Absence of DNE signs, inadequate pavement marking, open area, high mainline AADT, and poor lighting condition (3–5*, 12*)

Table 1. Different predictors used by past studies for modeling WWD events

Characteristics	Properties	Predictor type	References
Geometric properties of interchange	Interchange type	Categorical (e.g., Parclo, Trumpet, Diamond, Cloverleaf, Directional)	*3, 5, 9, 11*
	Median type	Binary (traversable vs. non-traversable)	*6–8*
	Distance to the nearest access point	Categorical (e.g., binned by 300’)	*6–8*
	Channelizing island	Categorical (e.g., traversable, non-traversable)	*6–9*
	Median width between exit and entrance ramp	Categorical (e.g., binned by 10’)	*6–8*
	Intersection balance	Categorical (e.g., binned by 10%)	*6–8*
	Intersection angle	Categorical (e.g., acute, right, obtuse)	*6–9*
	Control/corner radius from x-road	Categorical (e.g., binned by 10’)	*6–8*
	Number of lanes on x-road	Binary (e.g., 2 vs. 4)	*8–9*
Traffic control type, sings, and marking	Control type	Binary (e.g., signalized, unsignalized)	*4, 8, 9, 12, 14*
	DNE sign presence	Binary (yes vs. no)	*4, 8, 12*
	Number of DNE signs	Categorical (e.g., binned by 1)	*4, 8, 12*
	Toll-booth presence	Binary (yes vs. no)	*9*
Area type and traffic volume level	Area type	Binary (urban vs. rural)	*3, 4, 8, 9, 12*
	X-road AADT	Continuous	*8, 9, 11*
	Ramp AADT	Continuous	*8–9*
	Mainline AADT	Continuous	*4, 9, 11, 12*

2.2. *Traffic Control Devices / Treatments to Prevent WWD Events*

2.2.1. Sign Height and Size with Enhanced Pavement Markings

Road-side countermeasures such as Wrong-Way signs and road paints are the most common methods to prevent WW driving. Some studies analyzed the installation location of signs and found that low-mounted signs could significantly reduce the WWD incidents frequency from 50-60 per month to 2-6 per month at some problematic sites *(16)*. Lower mounted signs increase visibility for elder drivers who are one of the major age groups involved in WWD incidents.

The Iowa Department of Transportation tested increasing the size of DO NOT ENTER signs to increase their visibility at multiple exit ramps *(17)* while also repainting the pavement markings to provide additional guidance to drivers at several exit ramp intersections. And as a result, the combination of these two treatments decreased WWD frequency by 40% over the 6-month study period compared to the same time period before the treatment *(17)*.

2.2.2. Visibility Enhanced LED/ Lighted Signs

A study conducted by the Texas Department of Transportation (TxDOT) showed that 80% of WWD incidents occur between the hours of 10:00 pm and 6:00 am, and most (45%) of which happen between 2:00 am and 4:00 am. *(18)*. Therefore, lots of studies focus on enhancing the visibility of wrong way signs. For this reason, the TxDOT installed flash bordered wrong way signs at 29 exit ramps in San Antonio. The initial investigation of this treatment found that the WWD frequencies at these sites have dropped by 30%. Further analysis also found that the treatment is cost effective—the average cost recovery time is only 1.5 years *(19)*. In Arizona, the Arizona Department of Transportation (AZDOT) employed thermal detection cameras to detect wrong-way vehicles on freeway off-ramps along Interstate freeway 17 (I-17) in Phoenix *(23)*. When a WWD vehicle is detected, an internally illuminated wrong-way sign with flashing red lights was triggered to notify the driver of a wrong-way entry.

2.3. *ITS-based WWD Detection*

2.3.1. State-of-the-Art

This section presents an overview of the ITS-based wrong-way driving detection technologies *(21,22)* and compares the advantages and limitations of each technology.

2.3.1.1. Doppler Radar

Doppler radar detectors are non-intrusive devices mounted above-ground on poles and require wiring for power and communications. Doppler radar detectors emit focused, high-frequency signals within a specified frequency band in the GHz region. A vehicle moving into or through the detection area reflects the signals back to the detector. From the Doppler shift between the emitted and received frequency, the direction and speed of a vehicle can be determined. One detector could cover multiple lanes depending upon placement, meaning one radar unit on an exit ramp may be sufficient. Radar devices are sensitive to mounting location, so the manufacturer’s guidelines should be followed to properly select the mounting location. Other factors to consider for radar include nearby structures and freeway noise walls, mounting height, mounting offset, and cable lengths (device to cabinet).

2.3.1.2. Microwave Sensor

Microwave is another type of non-intrusive device that could be used to detect a wrong-way vehicle. Microwave is similar to radar in that it is mounted on a pole near the highway and faces perpendicular to the traffic lanes. The microwave sensor continually transmits a low-power microwave signal of constantly varying frequency in a fixed fan-shaped beam. The beam “paints” a long elliptical “footprint” on the road surface. Any non-background targets reflect the signal back to the sensor where the targets are detected and their range is measured. By processing the characteristics of the energy reflected from a vehicle within the target area, the detector is able to recognize the presence of a vehicle through the detection of motion. Microwave sensors are programmed for the number of lanes and can detect traffic up to 120 feet away from the sensor. Microwave sensors may have an advantage over radar because microwaves can diffract around counters to detect vehicles that are hidden by other vehicles.

2.3.1.3. Video Imaging System

Video detection operates on the principal of a processor evaluating movements in a user-defined zone, within a fixed field of view. This technology uses background imagery in predefined zones and, based on changes in those pixels, uses software to determine if those changes are sufficient enough to warrant an actual detection be sent to a signal controller or other similar device. The software is programmed using predefined or manually coded detectors to recognize wrong-way vehicle movements and trigger the sensors when detected. With video detection, cameras placed in line with the lanes detected with as much height as possible are best as they lessen the effect of video occlusion.

2.3.1.4. Thermal Sensor

Thermal video sensors operate similarly to video imaging sensors which use pixel change against background imagery to make decisions. However, they rely on heat instead of light. This system also uses an imaging processor with sophisticated algorithms to detect vehicles and determine the direction of the vehicles. Actual detector video from the thermal sensors can be transmitted using current communication technologies in the same manner as video.

2.3.1.5. Induction Loop Detector

Inductive loop detectors have been used for decades to detect vehicles at traffic signals and count vehicles on roadways. Loop detectors provide a mature technology and support the traditional "wire in pavement" concept. Loop detectors are called an intrusive technology because they are installed by cutting a slot in the pavement and then coiling wire inside for inductance. Loop detectors require a power source and a means to communicate information back to a controller for processing the data they collect. These are the most accurate detector forms available; however, they require regular maintenance and replacement as loops fail over time.

2.3.1.6. Magnetic Sensor

Magnetic sensors are in-pavement (often wireless) vehicle detectors that transmit real-time data for a variety of traffic applications. The vehicles are detected by measuring the change in the Earth's magnetic field caused by the presence of a vehicle near the sensor. When a change in the magnetic field is detected, the sensors send their data via radio to an access point near the field sensors. The vehicles' signature can be processed for speed, classification, and direction using sophisticated algorithms at the roadside controller. Wireless sensors are convenient; however, they have limited battery life and will need replacement more often.

2.3.2. State-of-the-Practice

To date, several transportation agencies in the U.S. have employed ITS technologies to detect wrong-way driving vehicles and develop countermeasures for wrong-way driving.

2.3.2.1. Arizona

The Arizona Department of Transportation (ADOT) conducted a pilot study in 2013 to determine the viability of various existing ITS-based vehicle detection systems to detect the presence of wrong-way vehicles on the state's highway system *(22)*. The evaluated WWD detection technologies include combinations of microwave, doppler radar, video imaging, thermal, and magnetic sensors at six high-risk freeway exit ramp locations. At each of these locations, various wrong-way scenarios were tested to measure the accuracy of these WWD detection systems. Results of this proof-of-concept effort demonstrated that wrong-way vehicles could be detected using easily deployable equipment that are currently available on the market, while the accuracy of each WWD vehicle detection technology depends on the condition the device(s) were installed.

2.3.2.2. California

The California Department of Transportation (Caltrans) used inductive loop detectors that were installed at several high-risk exit ramp locations to detect wrong-way vehicles *(24)*. In addition, in-pavement warning lights were also installed at the exit ramp as WWD countermeasures. Whenever there is an activation from the detector due to a wrong-way vehicle, the WWD detection system triggers the in-pavement warning lights to notify the wrong-way driver. Through a 15-month pilot test on Interstate 15 in the San Diego County, it was found that overall, the reported WWD events reduced by 44% after installing the WWD detection systems *(25)*.

2.3.2.3. Florida

The Florida Department of Transportation (FDOT) tested the capability of existing freeway video-analytic WWD detection systems in terms of detecting real-time wrong-way vehicles and notifying TMC staff *(26)*. Six testing locations along an I-275 freeway section in the Tampa Bay area were selected. These testing locations were assigned to one of the four testing scenarios: 1) normal daily traffic conditions, 2) consecutive WWD in both directions, 3) normal light nighttime traffic conditions, and 4) low light nighttime traffic conditions. To evaluate the performance of the selected video-imaging systems, four performance measures were used: 1) WWD detection accuracy, 2) percentage of false calls, 3) actual WWD detection accuracy, and 4) percentage of missed calls.

2.3.2.4. Texas

The Texas Department of Transportation (TxDOT) conducted a pilot study using radar-based WWD detection systems along with wrong-way LED warning signs at 16 different locations in San Antonio. The results from this 30-month pilot study showed a reduction of 28 percent in the average rate of wrong-way driving events *(27)*. Besides, the Harris County Toll Road Authority (HCTRA) operates a wrong-way driver detection system on a 13.2-mile portion of the West Park Tollway in Houston using the doppler radar vehicle sensor and induction loop system *(28)*. Eighteen detectors are located along Westpark. Whenever a WWD vehicle is detected, the TMC operator is notified and a message is displayed on the roadside electronic signs to warn other drivers. A total of 159 WWD events were detected between 2009 and 2013. Results show that WWD events do occur throughout the day but are not as common as at night. Specifically, WWD events begin to increase at around 10:00 p.m. and peak at 2:00 a.m.

2.3.2.5. Colorado

In 2019, The Colorado Department of Transportation (CDOT) tested a thermal sensor-based WWD detection system in the Denver metro area *(29)*. The technology is being piloted at the reversible express lanes at Interstate 25 and 70th Avenue. Thermal sensors detect wrong-way driving vehicles as they enter the ramp. The sensors activate an electronic wrong-way sign at the end of the ramp, sending a final warning to drivers. At the same time, those sensors are also sending a message to CDOT's Traffic Operation Center 2-3 seconds after a WWD vehicle passes the sensor. Moreover, a camera above the ramp allows CDOT to visually confirm the WWD event. If the driver doesn't stop, CDOT will alert Colorado State Patrol or local law enforcement to the wrong way driver.

2.3.3. Law Enforcement

The National Transportation Safety Board published a special investigation report in 2012. This report revealed that more than 60% of wrong way crashes are caused by drunk drivers *(20)*. According to this report, highly intoxicated drivers are not sufficiently able to receive and process information from traffic control devices. For this reason, law enforcement and education campaigns may be needed to help address wrong-way driving issues were signing and marking interventions may not be enough. In addition, the report suggests popularizing more extreme measures at the state or national level such as the installation of alcohol ignition interlocks for all DUI offenders. In addition, the Driver Alcohol Detection

System for Safety (DADSS) program is working on making an acceptable alcohol detection system for widespread implementation in the US vehicles.

2.3.4. Vehicle Technology

In addition to the aforementioned practice-ready ITS-based WWD vehicle detection technologies, the vehicle manufacturers are also contributing to and enhancing safety by adding wrong way driving system alerts to their vehicles. In 2007, the BMW Research and Technology Group in Germany developed a new driver assistance program that uses the car's navigation system to automatically recognize when a driver is about to join a road in the wrong direction using navigation data *(20)*. The road sections on which the wrong-way driver was moving were highlighted and the system was capable of reporting information such as position, direction, and speed of the wrong-way vehicle in a Heads-up Display (HUD) through a series of audible and visual signals. The program was also capable of warning other motorists within a range of approximately 2000 ft (approximately 610 meters) by using V2V technology.

In 2011 in Japan, Toyota announced an optional wrong way alerting system on vehicles sold in Japan. Toyota vehicles will collect the information from GPS gyro-sensors to identify the direction of the operating vehicle. If a wrong way driving vehicle is detected, an alert will be sent to the driver. The wrong way navigation alert system earned high praise from NTSB in its 2012 report *(30)*.

3. Statewide Analysis of Wrong Way Driving Risk at Parclo Interchanges

3.1. *Statewide Partial Cloverleaf Data Collection*

In light of the contributing factors for wrong way driving identified in the literature, a statewide inventory of 45 partial cloverleaf (parclo) interchanges from I-40 (n=21), I-440 (n=3), I-85 (n=19), and I-87 (n=2) was developed. The data collected may be used for future safety analysis and were formatted for use in existing predictive models of wrong way driving risk. Where possible, roadway features were categorized using the Model Inventory of Roadway Elements (MIRE) to be understandable and transferable. These data were broken down into the individual quadrants of the interchange as the configurations often differ in multiple geometric or control features in each quadrant. The supplemental Excel files provide all data collected as well as notation or example figures for the measurement of each value using the comments feature. A brief summary of the key geometry features of the investigated parclo interchanges is presented in Table 2. Summary of Key Geometry Features of the Investigated Parclo Interchanges.

3.1.1. Interchange Descriptive Data

Sites were inventoried using the major (often freeway) and minor roadways as a naming convention. NCDOT also has a numbering system for bridge structures which was collected. Location data collected include: Municipality, Division, Region and GPS coordinates of the interchange.

3.1.2. Interchange Traffic and Geometry Data

Annual Average Daily Traffic (AADT) is often used for modeling exposure and crash rates. AADT was inventoried for major and minor roads from 2018, which was the latest year that data were available. The presence of an underpass or overpass was also recorded in the event sight distance issues contributed to WWD. The total number of bridge structures was collected as well as the width of bridges.

Access to the major roadway may be available at different quadrants of the interchange depending on the parclo style; therefore, the overall style, as well as the cardinal locations for entrance and exit ramp access, was also recorded. Additionally, closely spaced intersections were noted as they may cause confusion when located near an exit ramp. Minor street posted speeds and skew from the main road were also recorded.

3.1.3. Exit Ramp Geometry

The angle of the ramp intersection was calculated as the angle between the centerline of the exit ramp and the centerline of the minor road to indicate whether a shallow or sharp turn angle is needed to enter the exit ramp the wrong way. The distance between ramp terminals was also identified as a measure of interest in the literature and was measured as the centerline distance at the ramp gores.

In addition to the skewness of the overall exit ramp to the minor road, many parclo interchanges include a “flared” ramp terminus that requires a sharp turn angle to maneuver the wrong way. The median type and width were recorded using MIRE terminology.

3.1.4. Exit Ramp Traffic Control

The type of control (Stop, Yield, Signal, Merge) present on the exit ramps was recorded as well as lane markings and any signage regarding the wrong way movements. Sign designations from the Manual on Uniform Traffic Control Devices were noted including those shown in Figure 4, below.

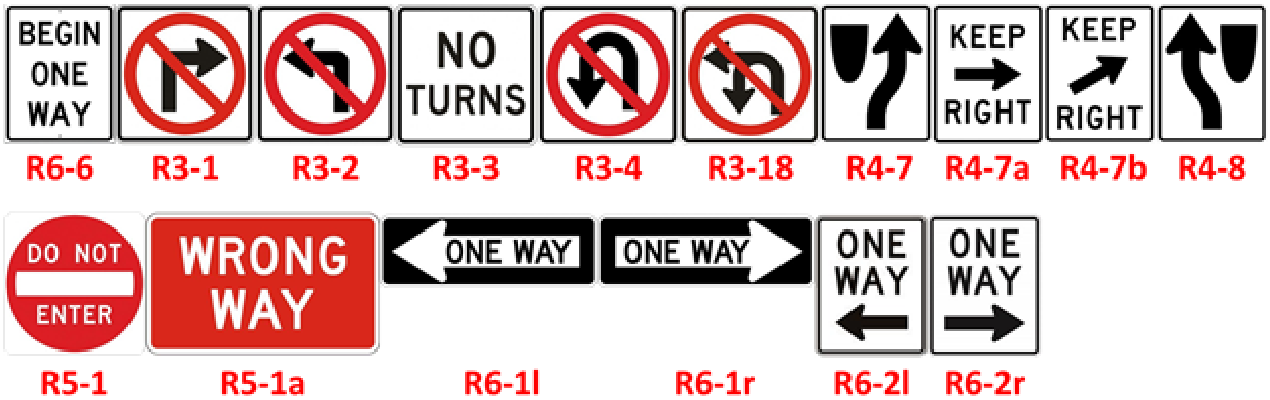


Figure 4. MUTCD Sign Types for Interchange Inventory

Table 2. Summary of Key Geometry Features of the Investigated Parclo Interchanges

Site	Interchange Type	Quadrant	AADT (veh)		Skew Angle	Speed (mph)	On-ramp LT Control	Dividing Line Type	Dist. btw Ramps (ft.)	Median Width (ft.)	LT Turn Angle	Median Cut (LT)
			Major Rd	Minor Rd								
I-440 & Hillsborough	Parclo AB2	N-W	84250	17000	90	35	Signal	Median	38.45	15.3	90	N/A
		N-E							52	13	90	Yes
I-440 & Six Forks	Parclo A4	N-W	147000	54000	130	35	Signal	Median	80	4	90	Yes
		S-E				40			210		0	No
I-440 & New Bern	Parclo B	N	115000	44000	90	35	Yield	Median	340	15	0	No
		S				45			280			
I-87 & New Hope	Parclo AB2	N-E	91000	24000	135	35	Signal	Median	45	8.3	90	Yes
		S-E							49	7.9		
I-87 & Hodge Rd	Parclo AB2	N-W	90000	14000	130	35	Signal	Double Yellow	32.6	N/A	90	N/A
		S-W				45			44			
I-85 & York Rd	Parclo B1	S-W	52750	9750	132	45	Signal	Double Yellow	31		90	N/A
I-85 & Bessemer City Rd	Parclo AB2	W	95000	21000	150	35	Signal	Double Yellow	44	N/A	101	N/A
		S									90	
I-85 & N Chester St	Parclo AB2	N-W	106750	33500	114	35	Signal	Median	41	2	90	Yes
		S-W							46	6		
I-85 & E Ozark Ave	Parclo B2	N	119000	16750	135	35	Yield	Median	44	4	91	Yes
		S				45			85		106	
I-85 & S Main St	Parclo AB2	N-E	129500	15150	90	35	Signal	Double Yellow	79	N/A	90	N/A
		S-E							81			
I-85 & Beatties Ford Rd	Parclo AB2	N-W	126000	30250	101	N/A	Signal	Median	37	N/A	91	N/A
		S-W						Double Yellow	47		90	
I-85 & N Graham St	Parclo AB2	N-E	179000	25250	115	35	Signal	Median	49	6	88	Yes
		S-E							39		90	
I-85 & W Mallard Creek Rd	Parclo A1	N-E	148000	31000	90	45	Yield	Median	71	7	N/A	Yes
I-85 & Dale Earnhardt Blvd	Parclo B1	N	84500	19000	120	35	Signal	Median	32	13	90	Yes
I-85 & Julian Rd	Parclo AB2	W	86750	14500	101	50	Signal	Wide pavement	39	6	91	N/A
		S							44		92	
I-85 & Tributary Way	Parclo B2	N	79250	5300	105	55	Yield	Median/Double Yellow	79	N/A	92	Yes
		S							60			
I-85 & Belmont Rd	Parclo AB2	W	80250	2750	90	55	Yield	Median	46	7	93	Yes
		E							47	6	90	
I-85 & Cotton Grove Rd	Parclo AB2	N-E	59500	23500	104	45	Signal	Median	65	7	89	Yes
		S-E							69	6		
I-85 & Lake Rd	Parclo A1	S-E	58750	6800	96	45	Yield	Double Yellow	54	N/A	89	N/A
I-85 & Hopewell Church Rd	Parclo B2	N	69250	4600	140	45	Yield	Median	34	5	90	Yes
		S							47	11	91	
I-85 & Rock Creek Dairy Rd	Parclo A1	S-E	119500	15000	109	45	Signal	Median / Wide	60	5	93	Yes
I-85 & Redwood Rd	Parclo A2	W	52250	445	123	45	Yield	Double Yellow	26	N/A	97	N/A
		E									94	
I-85 & Poplar Creek Rd	Parclo A1	S-E	41250	2600	99	45	Yield	Double Yellow	39	N/A	87	N/A
-85 & W Andrews Ave	Parclo B1	N-E	34000	9400	102	35	Yield	Double Yellow	60	N/A	86	N/A

Site	Interchange Type	Quadrant	AADT (veh)		Skew Angle	Speed (mph)	On-ramp LT Control	Dividing Line Type	Dist. btw Ramps (ft.)	Median Width (ft.)	LT Turn Angle	Median Cut (LT)
			Major Rd	Minor Rd								
I-40 & Thornburg Dr NE	Parclo B1	S	53750	17000	110	55	Signal	Median	30	4	89	Yes
I-40 & S Stratford Rd	Parclo Ab2	N	84250	36500	109	50	Signal	Double Yellow & Wide pavement	47	N/A	90	N/A
		W							63		89	
I-40 and Peters Creek Pkwy	Parclo B1	S-W	106500	38000	106	35	Signal	Median	45	4	86	Yes
I-40 & NC Highway 68	Parclo B1	S-W	129500	41250	128	35	Signal	Median	44	36	76	Yes
I-40 & Guilford College Rd	Parclo AB2	E	114000	21000	90	35	Signal	Median & Wide	58	6	97	N/A
		S					l	Median & Double yellow	65	8	89	Yes
I-40 & W Wendover Ave	Parclo A1	S	120500	50000	126	35	Signal	Median & Wide	64	6	90	N/A
I-40 & McConnell Rd	Parclo A1	N-W	71750	4200	103	45	Signal	Double Yellow	60	N/A	96	N/A
I-40 & Mt Hope Church Rd	Parclo B1	N	120500	7450	137	45	Signal	Median & Double yellow	57	N/A	102	Yes
I-40 & Rock Creek Dairy Rd	Parclo A1	S-E	119500	15000	108	45	Signal	Median & Wide	65	7	91	Yes
I-40 & Apex Highway	Parclo AB2	N-W	131500	36000	97	45	Signal	Median & Double yellow	78	6	93	Yes
		S-W							65	5	89	
I-40 & Davis Dr	Parclo AB2	N-E	173000	18000	92	55	Signal	Median	42	4	90	Yes
		S-W				45			30	5	96	
I-40 & S Miami Blvd	Parclo AB2	N-E	182000	24250	118	45	Signal	Median	37	7	80	Yes
		S-E							39		90	
I-40 & Page Rd	Parclo AB2	N	200500	12050	113	35	Signal	Double Yellow & Wide	20	N/A	90	N/A
		W						Median	42	17	83	Yes
I-40 & Airport Blvd	Parclo A1	S	156500	27500	111	45	Signal	Median & Double yellow	77	12	N/A	N/A
I-40 & Cary Towne Blvd	Parclo A1	N-E	125500	13800	97	35	Yield	Median & Wide	39	8	102	N/A
I-40 & Rock Quarry Rd	Parclo AB2	S-W	114000	28500	101	35	Signal	Median	51	5	90	Yes
I-40 & Hobbton Hwy	Parclo AB2	N-W	20750	5800	131	55	Yield	Double Yellow	46	N/A	92	N/A
		S-W							67		90	
I-40 & US-117	Parclo AB2	N-W	25000	3850	119	55	Yield	Wide pavement	78	7	96	N/A
		S-W							36		90	
I-40 & US-53	Parclo AB2	E	24500	8100	121	55	Yield	Wide pavement	33	6	88	N/A
		S							21	N/A	95	
I-40 & Holly Shelter Rd	Parclo AB2	S-W	34500	9200	111	45	Yield	Wide pavement & Double Yellow	37	N/A	95	N/A
		S-E						Double Yellow	22	N/A	99	
I-40 & Gordon Rd	Parclo A1	S-W	47250	14300	123	45	Signal	Median	40	5	84	Yes

3.2. ***Statewide Risk of WWD at Partial Cloverleaf Interchanges***

In North Carolina, WW driving crashes appeared to have a low probability of occurrence (0.2%); however, the crashes accounted for a significant portion of freeway related fatalities (5.6%) *(22)*. Looking more closely, when using the KABCO scale, 60% of WW driving crashes on freeways resulted in a fatality (K) or serious injury (A) compared with only 2.5% of all freeway crashes using the same severity type. Due to the significance of this type of crash severity, it is extremely important that NCDOT understands the crash risk as it relates to the features of various interchanges.

A model developed by Pour-Rouholamin, shown in Equation 3 below, is used to evaluate the probability of WWD crash entry for statewide parclo interchanges *(6)*.

$$YLog\left(\frac{p}{1-p}\right) = -1.104 + X_{corner\ radius\ from\ crossroad} + X_{type\ of\ Median\ on\ Crossroad} + X_{median\ between\ exit\ and\ entrance} + X_{distance\ to\ Access\ Point} \qquad \text{Equation 3}$$

where,

p: The wrong way crash risk in percentage.

X: The parameter of the related geometric design variable.

This Firth's penalized-likelihood logistic regression model equates the WWD risk as a probability by considering the geometric design parameters of each interchange. The four variables in this model are: A) control/corner radius from the crossroad, B) type of median on the crossroad, C) median between exit and entrance ramps, and D) distance to nearest access point in the vicinity of the Interchange. Table 3 below illustrates the summary of the parameters of the model where positive parameters indicate an increase in WWD risk related to that condition.

The model was run against all parclo interchanges inventoried in NC as described in the previous section. The results are shown in detail within the supplemental Excel files with a higher output indicating a higher relative risk of wrong way entry. Subsequent to the 2018 data collection effort, multiple interchanges had changes to geometry or markings which may affect wrong way driving risk. As such, interchanges with modifications are highlighted in the inventory. The outputs of the model for interchanges in NC are considered intuitive with the most common design features among those high-risk interchanges being wide control corner radius and no median available on crossroads.

Table 3. Summary of the Firth's Logistic Regression WWD Risk Model

Explanatory Variables	Estimated Parameters	t-stat	Odds Ratio
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	1.15	2.13	3.16
81 to 90 ft	1.499	4.29	4.48
91 to 100 ft	1.138	2.15	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 ft to 20 ft	0.313	2.245	1.37
21 ft to 30 ft	0.43	1.772	1.54
31 to 40 ft	-1.141	-2.47	0.32
41 to 50 ft	-9.576	-1.752	0.56
51 to 60 ft	-1.037	-1.956	0.35
More than 60 ft	-1.598	-2.769	0.2
Distance to Access Point in the vicinity of the Interchange			
300 ft and less	Reference		
301 to 600 ft	0.315	1.97	1.37
601 to 900 ft	-0.516	-2.371	0.6
901 to 1200 ft	-0.415	-1.741	0.66
1201 to 1500 ft	-0.454	-2.026	0.63
More than 1500 ft	-0.327	-1.373	0.72
Constant	-1.104	-1.729	

4. Monroe Expressway Wrong Way Driving Program

The Monroe Expressway serves as an alternate to the US-74 corridor, extending from Stallings to Marshville, North Carolina, as shown in Figure 5 *(31).* It is the state's newest all-electronic toll road which has eight entry and exit points.

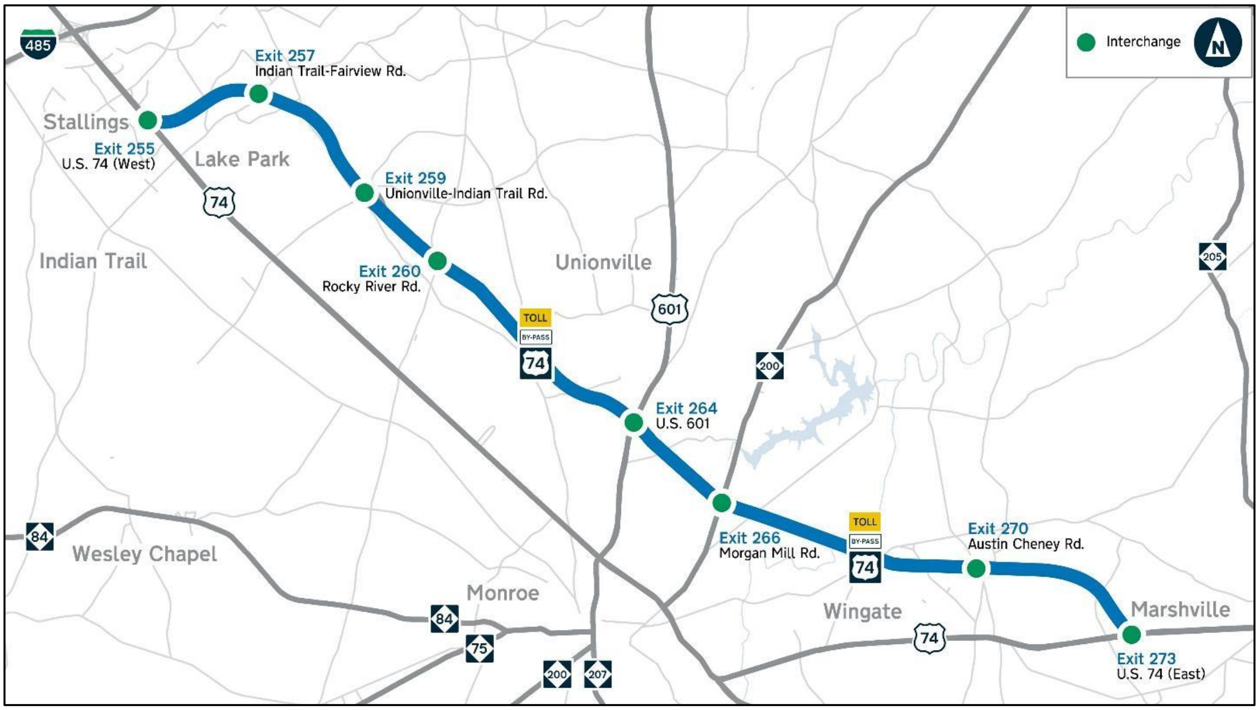


Figure 5. The Monroe Expressway with the exit locations (Courtesy: NC Quick Pass, 2020)

Since past studies showed that WWD events are often influenced by the characteristics of the entry interchange, we present a brief description of the interchanges on the Monroe Expressway in Table 4. Characteristics of the interchanges along the Monroe Expressway before describing the WWD event data. The properties of the interchanges we present in Table 3 were deemed important to predict WWD events as reported by past studies. *Note: Some of these properties do not apply to all interchanges. For instance, the "corner radius from x-road" characteristic is not reported for the connections with US-74 at two ends of the Expressway, diamond interchanges, or round about (RBT) interchanges because either this aspect does not apply to, or likely does not affect, WWD events in the case of these interchanges.*

Table 4. Characteristics of the interchanges along the Monroe Expressway

Exit #	Direction	Configuration	Off-ramp Traffic Control	# of lanes on X-road	# of lanes on off-ramp	Turn Angle (deg)	On-ramp vol. per day	Off-ramp vol. per day	Mainline vol. per day	X-road AADT	Intersection balance	Median width between exit & entrance ramp (ft)	Corner radius from x-road (ft)	Distance to nearest access point (ft)
255	EB	Freeway Connect	Signal	6	NA	90	NA	NA	8,113	10,000	NA	NA	NA	670
	WB		Signal	3	2		NA	569	8,310		NA	NA	NA	400
257	EB	Parclo	Signal	5	2	90	745	763	8,090	11,500	63%	16	60	690
	WB		Signal	5	2	90	517	545	8,290		51%	15	69	660
259	EB	Diamond	Yield	5	2	NA	647	1,022	8,390	11,000	NA	NA	NA	505
	WB		Yield	5	2		1,191	478	8,260		NA	NA	NA	670
260	EB	Parclo (RBT)	Yield	2	2	135	393	599	7,700	7,100	NA	41	NA	685
	WB		Yield	2	1	135	482	415	6,970		NA	32	NA	395
264	EB	Parclo	Signal	6	3	75	430	1,327	7,700	20,000	48%	30	85	380
	WB		Signal	6	2	NA	783	548	6,790		NA	NA	NA	765
266	EB	Parclo	Signal	5	2	90	224	1,401	6,640	9,500	51%	28	67	980
	WB		Yield	5	2	90	1,404	241	5,640		48%	15	71	1,000
270	EB	Parclo (RBT)	Yield	1	1	135	64	959	5,340	2,750	NA	24	NA	450
	WB		Yield	1	1	135	1,002	117	4,770		NA	18	NA	420
273	EB	Freeway Connect	Free flow	NA	NA	NA	NA	NA	4,470	NA	NA	NA	NA	2,960
	WB		Free flow	NA	NA	NA	NA	NA	4,770		NA	NA	NA	2,960

The following points provide a short description for each of the interchange characteristics above. *Note: Aspects related to road signs and markings are not included in this discussion because most interchanges at the study site were found to have consistent signs and markings; however, at the project's inception, there were some updates at Exit 270 interchange which included pavement markings at the roundabouts from 11/2018 to 08/2019 as well as yield markings at Exit 270. These are notated in the text as appropriate.*

Configuration: This property represents the interchange type. Partial cloverleaf (parclo) is the most common type of interchange on the Monroe Expressway. However, a few of these interchanges have a roundabout intersection with the cross-street, which are very different from a typical partial cloverleaf interchange with a signalized intersection.

Off-ramp Traffic Control: These interchanges are either signalized, yield controlled (either roundabout or yield sign on the ramps), or free-flow (at the west connection with US-74) off ramps.

Number of lanes on the crossroad (# of lanes on x-road): The interchanges with roundabouts have the smallest number of lanes on their crossroads (either one or two) as opposed to all other interchanges which have three to six lanes in total.

Number of lanes on the off-ramp: This varies from one to three, with the eastbound off-ramp of exit 264 having the highest number of lanes.

Turn angle: This is either a right angle or an obtuse angle at the off-ramp, except for the eastbound off-ramp at exit 264 which has an acute angle.

On-ramp, off-ramp, mainline, and crossroad volume: The on-ramp, off-ramp, and mainline volumes (per day) were obtained from VDS data. Daily volume data for a year at each of these locations were averaged to estimate the per day volume. The crossroad volume represents the AADT as reported on NCDOT AADT web maps *(32)*. *Note: These data were unavailable (N/A) for some locations.*

Intersection balance: As shown in Figure 3 (Page 7), this value is calculated for parclo interchanges only and represents the stop-bars relative position for the left-turn movement from the crossroad median of the closely spaced on and off-ramps. The value is expressed as a percentage of the total distance, L_{max}, between the two stop bars on the crossroad. For the Monroe Expressway, the value varies between 48%-63% for parclo interchanges.

Median width between exit and entrance ramp: This value is calculated for parclo interchanges only and represents the width between the closely spaced on and off-ramps. On the Monroe Expressway, the value varies from 15 to 41 feet in most cases, except for exit 264 westbound, which has a very wide median. *Note: For some interchanges, the exit and entrance ramps are so far apart that their median width values are not reported in Table 3.*

Corner radius from crossroad: As shown in Figure 2 (Page 7), this value is calculated for parclo interchanges only and represent the radius from the left turn movement on the crossroad to the exit ramp. For the Monroe Expressway, the value varies between 60 to 85 feet for parclo interchanges.

Distance to the nearest access point: An access point can be a driveway or other road connected to the crossroad. If such an access point is located very close to the interchange, drivers (or navigational tools) may confuse an off-ramp with the access point. Distances to the nearest access point range from 380 feet to over one-half mile.

4.1. *Monroe Expressway System and Data Description*

The Monroe Expressway is an expressway near Charlotte with several toll locations along its length. A series of wire loops placed underneath the road have been installed to enforce the speed limit; the time it takes for a vehicle to trigger each loop can be used to determine the vehicle's speed. The triggering of these loops in reverse identifies wrong way movement along the Expressway.

Two datasets of the most importance are the operator logs and vendor datasets. The *operator log* (which may be referred to by the initials RVN), consists of the location, dates, times, notes, and type of wrong way movement along the Expressway. The events are coded into four categories, F, N, U and Y. F events are "False Positive" events, where the alarm was triggered, but no vehicle could have triggered the alarm. N events are "No" events, where the alarm was triggered by a vehicle with the right to move against the flow of traffic, such as a construction vehicle or a police cruiser. U events are "Unknown" events, where the alarm was triggered with no identifiable cause. Y events are "Yes" events, true wrong way movements.

The *vendor dataset* (which may be referred to as WWD dataset) consists of a log of WW movements including the dates, times, locations, and notes about the events. The two datasets agree for the most part, but do contradict in one or two instances. After consulting with the stakeholders, it was determined that the operator log is to be used in instances of contradiction.

Additionally, the stakeholders provided the research team with a map of the Expressway and instructions on how best to determine which lane numbers correspond to the exit ramps. Using the maps, the research team was able to determine the origin point of the wrong way events as well as the particular aspects of the geometry for the individual exits.

The events coded as "U" presented some difficulties for the research team. Little was written about them, and the decision to include them as actual wrong way events or to exclude them would greatly influence the approach taken to draw conclusions from the data. Only around twenty events were recorded as actual true (“Y”) wrong way events. Any model which included events that were not actual wrong way events would produce a model that, in effect, more-often-than-not predicts the occurrence of the sensor going off when a WW event was not occurring instead of a true WW event.

Taking a closer look at the “U” events, the research team noted that many of the events occurred within seconds or minutes of each other at the same location. This is consistent with testing behavior, a vehicle tripping the same sensor multiple times, and is inconsistent with actual wrong way driving, where a vehicle trips the sensor one time and continues on its way. Because of this, it was decided to exclude the “U” events from the actual wrong way events.

As noted earlier, approximately 20 actual (“Y”) WW events existed, and even these would be filtered down further. For instance, two events were removed because they followed on the heels of an ambulance and produced no alarm. Another was removed because the alarm was triggered due to a pedestrian in the shoulder with a shopping cart. And yet another had to be excluded because it involved a construction truck, a misclassified “N” event. More events had to be excluded because they were not origin events – i.e., a sedan entered the Expressway and continued heading in the incorrect direction for several exits. All but the origin event was excluded for “modelling” purposes.

This left 13 actual wrong way events for the study period over approximately one year of data collection. Clearly, such a small sample size precludes the possibility of any rigorous modelling as discussed in the literature review. Only descriptive statistics and other observations can be used to attempt to draw conclusions from the events that do exist.

4.2. *Monroe Expressway WWD Analysis and Findings*

4.2.1. Description of WWD Events at the Monroe Expressway

This section presents a detailed description for each WWD event detected at the Monroe Expressway during the period of this study. In Table 5 through Table 12, we have highlighted the operational condition, geometric characteristics of the possible entry points, and possible entry movements for all 13 WWD events.

Table 5. Description of WWD events possibly associated with Exit# 255 WB off-ramp

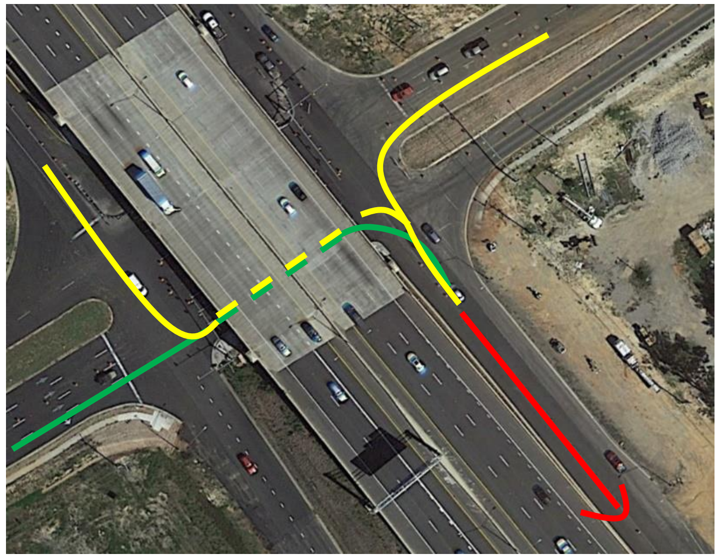
Geometry of Exit# 255 WB: **X-Street**: Stallings Rd. **Interchange type**: Diamond **Traffic Control**: Signal	
<u>Event# 1</u> Date: Thursday 4/2/2020, Time: 0000, Weather: Clear. Note: "Actual. Black sedan traveling at speed in right lane."	
<u>Event# 2</u> Date: Sunday 5/10/2020, Time: 0251, Weather: Clear. Note: "Semi going WB followed by black SUV going EB."	
<u>Event# 3</u> Date: Wednesday 5/27/2020, Time: 1343, Weather: Rain. Note: "Silver Toyota Hatchback reversing in right shoulder in the rain. Self-corrected."	

Table 6. Description of WWD events possibly associated with Exit# 257 EB off-ramp

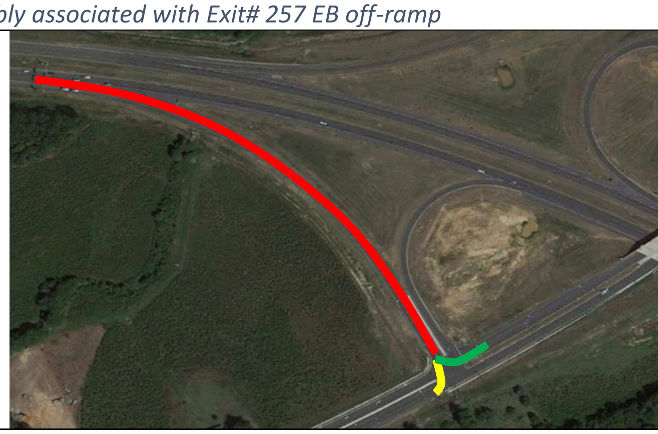
Geometry of Exit# 257 E**B:** **X-Street**: Indian trail-Fairview Rd. **Interchange type**: Parclo **Traffic Control**: Signal	
<u>Event# 1</u> Date: Saturday 5/18/2019, Time: 0520, Weather: Clear. Note: "White sedan traveling WB in the lane. SHP contacted."	
<u>Event# 2</u> Date: Friday 6/21/2019, Time: 1517, Weather: Clear. Note: "Video skipped. Black truck briefly seen heading the wrong direction in the lane."	

Table 7. Description of WWD events possibly associated with Exit# 259 WB off-ramp

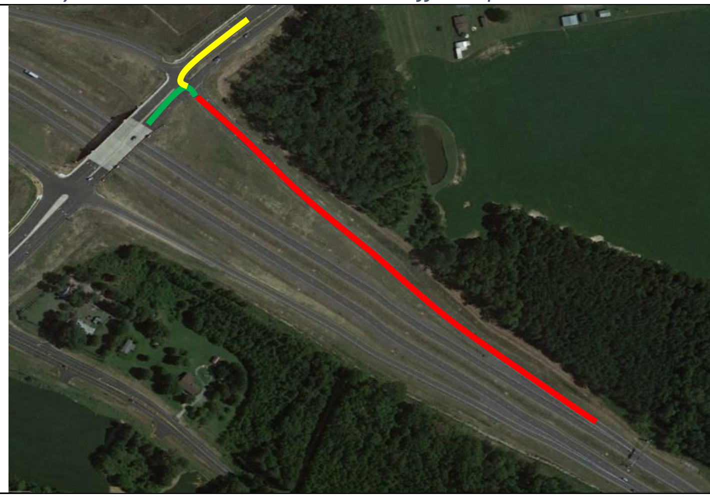
Geometry of Exit# 259 WB: **X-Street**: Unionville-Indian trail Rd. **Interchange type**: Diamond **Traffic Control**: TWSC	
<u>Event# 1</u> Date: Friday 7/19/2019, Time: 22:15, Weather: Rain. Note: "Actual, SHP notified. Unable to identify."	

Table 8. Description of WWD events possibly associated with Exit# 260 EB off-ramp

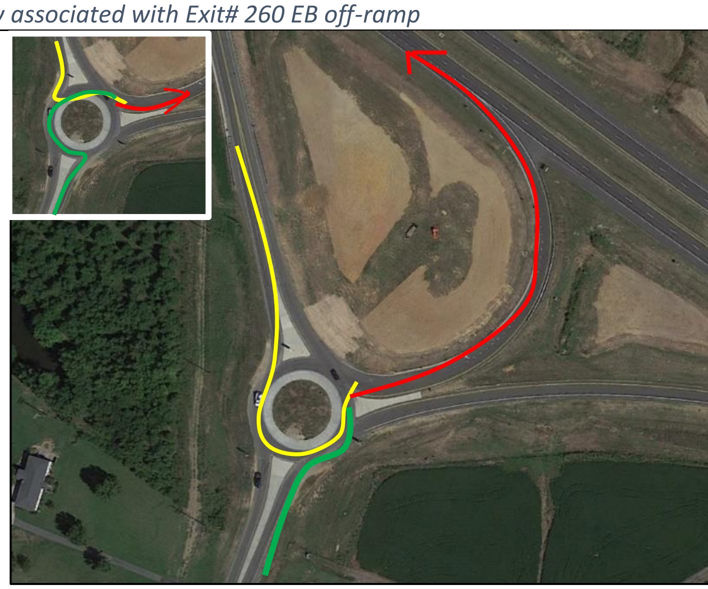
Geometry of Exit# 260 EB: **X-Street**: Rocky River Rd. **Interchange type**: Parclo **Traffic Control**: RBT **Note**: Drivers may enter this ramp wrong way in four possible ways. The main figure shows two such maneuvers if the RBT is circled properly. The inset figure shows two maneuvers if the RBT is circled wrong way.	
<u>Event# 1</u> Date: Sunday 3/28/2020, Time: 0246, Weather: Clear. Note: "Actual, resulted in incident involving a fatality."	

Table 9. Description of WWD events possibly associated with Exit# 260 WB off-ramp

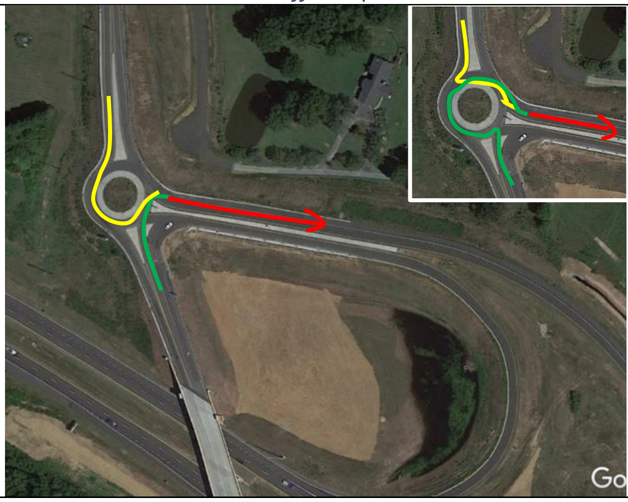
Geometry of Exit# 260 WB: **X-Street**: Rocky River Rd. **Interchange type**: Parclo **Traffic Control**: RBT **Note**: Drivers may enter this ramp wrong way in four possible ways. The main figure shows two such maneuvers if the RBT is circled properly. The inset figure shows two maneuvers if the RBT is circled wrong way.	
<u>Event# 1</u> Date: Monday 5/18/2020, Time: 1133, Weather: Clear. Note: "Pedestrian walking along side of road. White sedan reversing in shoulder alongside pedestrian."	
<u>Event# 2</u> Date: Saturday 5/23/2020, Time: 0244, Weather: Clear. Note: "Black sedan. Actual RVN. SHP contacted"	

Table 10. Description of WWD events possibly associated with Exit# 264 EB off-ramp

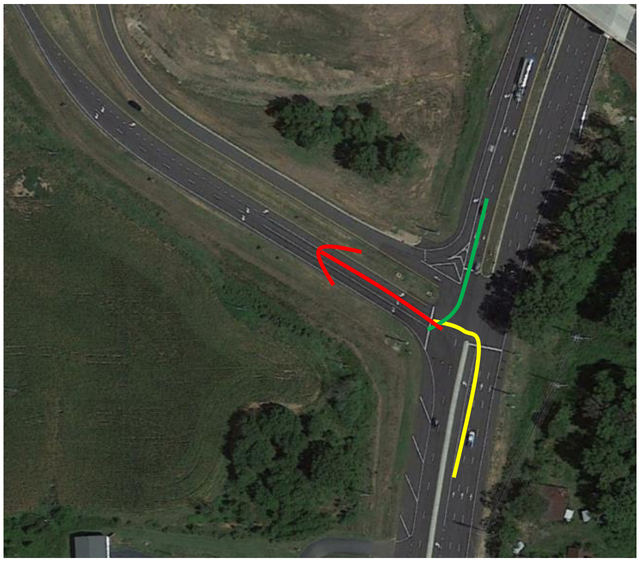
Geometry of Exit# 264 EB: **X-Street**: US 601 **Interchange type**: Parclo **Traffic Control**: Signal	
<u>Event# 1</u> Date: Saturday 5/30/2020, Time: 2010, Weather: Clear. Note: "Red Smith's Wrecker with vehicle in tow reversing in shoulder"	

Table 11. Description of WWD events possibly associated with Exit# 270 WB off-ramp

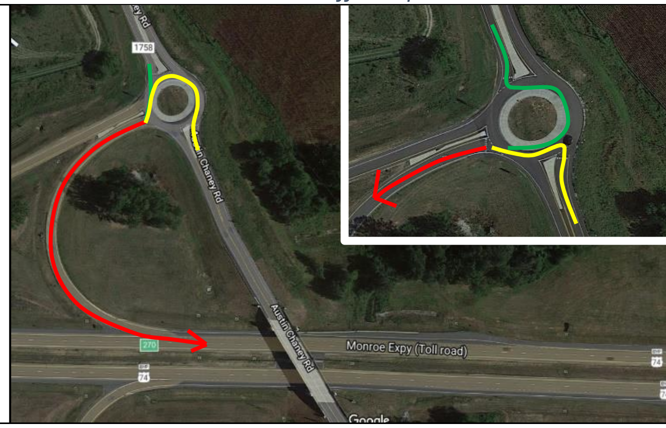
<table>
<tr><td>Geometry of Exit# 270 WB:
X-Street: Austin Chaney Rd.
Interchange type: Parclo
Traffic Control: RBT
Note: Drivers may enter this ramp wrong way in four possible ways. The main figure shows two such maneuvers if the RBT is circled properly. The inset figure shows two maneuvers if the RBT is circled wrong way.</td><td>
</td></tr>
<tr><td colspan="2"><u>Event# 1</u>
Date: Friday 11/30/2018, Time: 0130, Weather: Clear.
Note: “Contacted Troop H, vehicle going EB in WB lane at end of Bypass near Austin. Unable to obtain visual.” This incident took place prior to improvements in pavement markings – namely an elongated arrow on the ramp approach between 11/2018 and 03/2019 and yield lines and updated hashing at the entry approaches between 03/2019 and 8/2019.</td></tr>
<tr><td colspan="2"><u>Event# 2</u>
Date: Friday 07/26/2019, Time: 2222, Weather: Clear.
Note: “Pickup truck going the wrong way in the lane. SHP contacted and responded they had stopped motorist at Marshall Blvd.” This incident likely took place prior to finalized improvements in pavement markings – namely yield lines and updated hashing at the entry approaches between 03/2019 and 8/2019.</td></tr>
</table>

Table 12. Description of WWD events possibly associated with Exit# 273 EB off-ramp

<table>
<tr><td>Geometry of Exit# 273 EB:
X-Street: US-74
Interchange type: Systematic
Traffic Control: None
Note: Since this is a systematic interchange, the possible WW entry points are the nearest intersection and median left-turn openings.</td><td></td></tr>
<tr><td colspan="2"><u>Event# 1</u>
Date: Sunday 3/15/2020, Time: 22:24, Weather: Clear.
Note: “Wrong Way driver, SHP advised via phone”</td></tr>
</table>

4.2.2. Analysis of Wrong Way Driving Rates

Of the 13 events, 5 occurred on the two partial cloverleaf interchanges with roundabouts, including the only fatality during the study period. This is not a wholesale condemnation of roundabouts, as they provide navigable paths for drivers merging into a single traffic stream with reduced conflicts and severity type. When a driver enters the wrong way, however, that system breaks, and the geometry will then navigate the offending driver the wrong way down almost any road they subsequently travel on.

Nonetheless, the two interchanges with roundabouts (four roundabouts total) contributed a significantly higher count of events than other interchanges (p = 0.086) and this significance increased when accounting for volume ($p = 0.046$) by dividing the count of events by the on-ramp volume (vehicles with the opportunity for wrong way travel). *Note: the p in this context represents the probability that the WWD events between the two groups (i.e., interchanges with roundabouts vs. the rest) is in fact the same. Any p less than 0.05 is generally considered to be significant evidence of a difference, while p less than 0.1 is marginally significant.* There were two interchanges with roundabout averaging 2.5 events per interchange (variance of 0.5) during the study period while all the other interchanges averaged 1.3 events (variance of 1.07). The number of events per vehicle (the events divided by the on-ramp volume) for the roundabout interchanges averaged 0.005201 (variance of 1.64×10^{-6}), while all other interchanges the average events per vehicle was 0.001651 (variance of 1.64×10^{-6}). *Note: The sample size of crashes is very limited and decisive conclusions cannot be drawn because pavement markings at these sites were being modified at the time two events took place.*

T-tests assuming unequal variances were used to determine significance. The first test looked at the average of WWD events at non roundabout locations and compared them the average WWD events at the roundabout locations. The two groups' variances were then used to determine whether the difference in the averages meant anything, which it did, as noted above. The second test was much the same as the first, the only difference being that the average WWD events was divided by the on-ramp volume at that particular interchange. On-ramp volume was used as an estimator for the number of vehicles that were attempting to access the Expressway and was easily accessible from the VDS data provided to the research to team.

A T-test was used to evaluate the two groups averages. T-tests must meet the following criteria *(33)*:

1. The data must be numerical.
2. The data comes from a simple random sample.
3. The data follows a normal (bell curve) distribution.
4. The data has equal variances.

The first assumption is satisfied immediately. The second assumption exists to eliminate sample bias. While the data was not sampled with a simple random sample sampling scheme, the study was conducted throughout all four seasons, and drivers were free to choose to drive the correct direction at all times. Data was collected at all times of day during all weather conditions. The largest issue with the sampling is potential sensor error, that a wrong way driving vehicle entered the Expressway and failed to trip the sensor corresponding with its entry point, and instead tripped the next sensor down the line. However, the sensors have been tripped by pedestrians with shopping carts (proving their sensitivity), and very few incidents resulted in the driver tripping multiple sensors. It is far more likely that a sensor error simply results in a lost data point rather than a mis-assigned one. The tests used in this context assumed unequal variances from the outset, which rendered the fourth assumption moot.

The bell curve assumption can be thought of like school test scores. Most students score somewhere in the C range, with slightly fewer scoring in the B and D ranges, and with the fewest scoring in the A and F ranges. The WWD data, however, is less like test scores and more akin to coin flips. A driver may choose to drive the correct way, or they may choose to drive the wrong way, just like a coin may land on heads or tails. T-tests can still be done on coin flips. If a 100 people flip a fair coin once each, they might expect around 50 of those flips to be heads. Slightly fewer would get between 25 to 40 heads or 60 to 75 heads, with the fewest getting less than 24 or more than 76 heads. This scenario now resembles the original school test scenario, and the same principles apply to the WWD data. It may be unknown exactly how many people had the opportunity to drive the wrong way, or what the probability of a WWD event is for any given driver, but the number of events observed will be a function of those two things.

Besides T-tests with roundabouts, other variables were also carefully examined to determine the potential impact on WW driving along the Expressway. Weather did not seem to impact the study in a meaningful way. Only two of the events occurred during adverse weather and no fog was present during these events. Time-of-day did seem to play a role, as eight of the events occurred at night, a ninth occurred just moments after the sun had set. *Note: We should note that all of the roundabout events happened at night. And one of the night events spawned a journey which tripped several sensors over the course of a few minutes (this event did not originate from a roundabout).*

These results are presented with a caution that the originating interchange was determined from the first point of detection which may be misassigned if earlier detection on the facility was missed. Confirmation of this entry point is recommended through video analysis of the downstream (in the correct flow of traffic) in the period prior to the first detection to confirm that the wrong way vehicle is not observed. This time period to review prior is based on an expected minimum and maximum speed of the wrong way vehicle and the distance to the downstream camera and is calculated by dividing the distance by each speed. This analysis was not possible at the time of the study due to a limited storage period of the video data by NCTA. Based on this limitation, the video review should be conducted each month or every other month if conducted. This review would also provide a chance for quality assurance checks on the operator logs and allow for any unclear events to be reviewed with contractors to determine if events were triggered by testing or maintenance of the system.

In conclusion, while T tests indicated potential differences in wrong way movement frequency at roundabout interchanges, one of the incidents occurred before all markings were complete and that if removed from the sample of 5, the roundabout overrepresentation is no longer significant on the frequency of events. Nine of the thirteen events (including all roundabout events) occurred after the sun had set. Weather did not seem to play a significant role in influencing wrong way driving.

5. Conclusions and Recommendations

5.1. *Interchange Configurations*

Extensive literature has focused on partial cloverleaf interchanges which often have higher likelihood for wrong way movements due to the placement of adjacent on and off ramps. Key features posited to increase this hazard including the offset distance between ramps, traffic control type, turning radius for wrong way movements, and the presence of nearby access points. The project developed an inventory of partial cloverleaf interchanges across the state to understand how these features vary in North Carolina. The interchange inventory includes a total of 52 fields of data which may be utilized by NCDOT to assess or address geometric and traffic features of partial cloverleaf interchanges for further study or upgrade. The inventory is also presented with the estimated risk of wrong way movements based on a regression model adopted from the literature.

In addition, this research project found that 5 of 13 wrong way movements along the Monroe Expressway originated from parclo interchanges utilizing roundabouts, with the single wrong way crash occurring on the Expressway originating from a roundabout interchange. This finding was counterintuitive as the roundabout control at ramp terminals was expected to provide improved directional guidance to drivers. The researchers caution that the methodology used to identify the originating interchange relies on all wrong way movements being fully captured, so if the entry actually occurred further downstream, but was not detected until the roundabout interchange, it would be misidentified as a roundabout entry. Additionally, removal of the event occurring before the completion of roundabout markings results in inconclusive results in the statistical analysis.

5.2. *Wrong Way Driving Prevention*

A number of enforcement, vehicle technology, and infrastructure options are available to minimize the risk of wrong way driving at freeway access points. The literature review covered many ITS options for detecting and informing drivers of wrong way movements, and studies have shown that coordination with enforcement can reduce the risk of high severity wrong way crashes in other states. The NCTA has implemented consistent traffic control device options for indicating wrong way movements on the Monroe Expressway including consistent placement of R-5 and R-5a signs at each exit ramp. However, pavement markings such as an elongated arrow on the off-ramp and yield markings at roundabout approaches at some sites were added after those facilities were open to the public. The NCTA operators notify the local State Highway Patrol Troop of confirmed wrong way detections as appropriate. Statewide, consistent WWD signing and marking is also recommended for upgrades to existing interchanges where NCDOT determines a safety need as this has proven to decrease wrong way driving incidence in states where it has been studied.

5.3. *Innovative WWD Technology*

The NCTA has tested multiple WWD detection systems and advanced signage and marking systems on its facilities in addition to the WWD system on the Monroe Expressway. Different detection systems can be considered based on the efficacy of the detection technology itself as well as the placement and interventions available. Some systems include detection on the off-ramp where activatable signs may notify and correct wrong way movements prior to the driver entering the mainline freeway. Additionally, NCTA has tested directional edge markings and in pavement text which change color to indicate wrong way movements. Continued testing and adoption of these safety technologies will allow NCTA and NCDOT to continue to address this serious safety concern.

5.4. *WWD Data Collection and Review*

The research team was able to document the data format and collection methods for the operator logs and WWD system vendor logs to support a combined analysis. This review identified infrequent inconsistencies in the combined datasets early on in the analysis period, most likely attributable to continued physical and digital testing of the WWD detection equipment and software platform. Based on review of the data collection and analysis with each of the parties, it was found that a review of uncertain logs from the operator could be confirmed with the recorded work schedules of the contractors to discriminate between true positive WWD events and contractor testing which would trigger WWD messages in the software.

In addition to confirming events with the contractors, the research team discovered that video footage is only stored for a short period which prevents review of historic events on just an annual basis. Due to the concern of potential misidentification of wrong way entry points, a review of all video data while still available is recommended to confirm the entry point. Video from the downstream gantry (from the correct direction of traffic) from the wrong way event should be reviewed to identify the presence or absence of the vehicle triggering the wrong way event. The time period to review should be prior to the event recorded using the distance between gantries divided by an estimated maximum and minimum speed of the wrong way vehicle. A review monthly or every other month of wrong way events with the video analysis would provide both quality control benefits as well as support future decisions on WWD system improvements.

Future analysis of wrong way incidents on the Monroe Expressway is recommended once a larger event history can be collected. As with many other safety studies, 3 to 5 years of data is recommended to develop a large enough sample size to draw conclusive findings. Operator logs may be collected and reduced to confirmed events using the methodology mentioned in the previous chapter to assign origination data. Volume data from entry and exit ramps may be used to develop rate-based frequencies for groups of interchanges as described in 4.2.2. Further regression modeling may be possible to estimate the effect of individual geometric or traffic control features however statistical testing of these models should be performed to ensure they do not overfit the wrong way events.

6. References

1. Braam, A.C., 2006. *Wrong-way Crashes: Statewide Study of Wrong-way Crashes on Freeways in North Carolina*. North Carolina Department of Transportation, North Carolina, USA.
2. Scaramuzza, G., Cavegn, M., 2007. *Wrong-way drivers: extent-interventions.* In: The European Transport Conference. Leeuwenhorst Conference Centre, The Netherlands.
3. Zhou, Huaguo, Jiguang Zhao, Mahdi Pour-Rouholamin, and Priscilla A. Tobias. *Statistical characteristics of wrong-way driving crashes on Illinois freeways.* Traffic injury prevention 16, no. 8 (2015): 760-767.
4. Das, Subasish, Raul Avelar, Karen Dixon, and Xiaoduan Sun. *Investigation on the wrong way driving crash patterns using multiple correspondence analysis.* Accident Analysis & Prevention 111 (2018): 43-55.
5. Morena, David A., and Tracie J. Leix. *Where these drivers went wrong.* Public Roads 75, no. 6 (2012).
6. Pour-Rouholamin, Mahdi. *Wrong-Way Driving: Crash Data Analysis and Safety Countermeasures.* (2016).
7. Wang, Jin. *Relationship between Geometric Elements and Wrong-Way Crashes at Partial Cloverleaf Interchange Terminals.* Institute of Transportation Engineers. ITE Journal 88, no. 4 (2018): 45-49.
8. Atiquzzaman, Md, and Huaguo Zhou. *Modeling the risk of wrong-way driving entry at the exit ramp terminals of full diamond interchanges.* Transportation research record 2672, no. 17 (2018): 35-47.
9. Kayes, Md Imrul, Adrian Sandt, Haitham Al-Deek, Nizam Uddin, John H. Rogers Jr, and Grady Carrick. *Modeling wrong-way driving entries at limited access facility exit ramps in Florida.* Transportation research record 2673, no. 8 (2019): 567-576.
10. Rogers Jr, John H., Haitham Al-Deek, Ahmad H. Alomari, Eric Gordin, and Grady Carrick. *Modeling the risk of wrong-way driving on freeways and toll roads.* Transportation Research Record 2554, no. 1 (2016): 166-176.
11. Sandt, Adrian, Haitham Al-Deek, and John H. Rogers Jr. *Identifying wrong-way driving hotspots by modeling crash risk and assessing duration of wrong-way driving events.* Transportation Research Record 2616, no. 1 (2017): 58-68.
12. Das, Subasish, Anandi Dutta, Mohammad Jalayer, Apoorba Bibeka, and Lingtao Wu. *Factors influencing the patterns of wrong-way driving crashes on freeway exit ramps and median crossovers: Exploration using 'Eclat'association rules to promote safety.* International journal of transportation science and technology 7, no. 2 (2018): 114-123.
13. Ponnaluri, R. V. (2016). *The odds of wrong-way crashes and resulting fatalities: a comprehensive analysis*. Accident Analysis & Prevention, 88, 105-116.
14. Washington State Department of Transportation (WSDOT). (2013). *Design Manual.* Olympia, WA.
15. American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets (Green Book)*. AASHTO, Washington, D.C., 2011.
16. Leduc, J. K. (2008). *Wrong-way Driving Countermeasures.* http://www.cga.ct.gov/2008/rpt/2008- r-0491.htm

17. American Traffic Safety Services Association (ATSSA). (2014). *Emerging Safety Countermeasures for Wrong-way Driving.* Fredericksburg, VA, 2014.
18. 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.
19. 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.
20. *Wrong-Way Driver Information: Advance Warning of Drivers Heading in the Wrong Direction.* BMW Group Research and Technology, Media Information, November 2007.
21. Klein, L.A., Mills, M.K., Gibson, D.R.P. Traffic Detector Handbook: Third Edition—Volume I. Report No. FHWA-HRT-06-108, Federal Highway Administration, McLean, VA, 2006.
22. Simpson, S.A. Wrong-Way Vehicle Detection: Proof of Concept. Report No. FHWA-AZ-13-697, Arizona Department of Transportation, Phoenix, AZ, 2013.
23. Simpson, S.A., Bruggeman, D. Detection and Warning Systems for Wrong-Way Driving. Report No. FHWA-AZ-15-741, Arizona Department of Transportation, Phoenix, AZ, 2015.
24. Cooner, S, A., Cothron, A.S., Ranft, S.E. Countermeasures for Wrong-way Movement on Freeways: Overview of Project Activities and Findings. Report No. FHWA/TX-04/4128-1, Texas Department of Transportation, Austin, TX, 2004.
25. Bucko, T.R. Wrong Way Pilot Projects for Prevention of Wrong Way Collisions on Freeways. California Department of Transportation, Sacramento, CA, 2020.
26. Lin, P.S., Chen, C., Ozkul, S. Testing and Evaluation of Freeway Wrong-way Driving Detection Systems. Report No. FDOT BDV25-977-40, Florida Department of Transportation, Tallahahassee, FL, 2018.
27. ITS International. San Antonio pilot program results in up to 30 percent reduction of wrong way (WW) driving incidents. 2014. Available: http://www.itsinternational.com/sections/cost-benefit-analysis/features/texas-moves-to-prevent-wrong-way-drivers/
28. Finley, M.D., Venglar, S.P., Iragavarapu, V., et al. Assessment of the Effectiveness of Wrong Way Driving Countermeasures and Mitigation Methods Report No. FHWA/TX-15/0-6769-1, Texas Department of Transportation, Austin, TX, 2014.
29. Mason, T. CDOT Tests Wrong-Way Detection System to Prevent Crashes. CBS4Denver, 2019. Available: https://denver.cbslocal.com/2019/11/19/cdot-wrong-way-driver-detection-interstate-25-express-lanes/
30. National Transportation Safety Board (NTSB) (2012). *Wrong-Way Driving*, Highway Special Investigation Report NTSB/SIR-12/01, Washington DC.
31. NC Quick Pass. Roads and Rates. 2020. Available: https://www.ncquickpass.com/rates-facilities/Pages/monroe-expressway.aspx
32. NCDOT. Traffic Volume Maps. 2020. Available: https://connect.ncdot.gov/resources/State-Mapping/Pages/Traffic-Volume-Maps.aspx
33. Investopedia. T-Test. 2020. Available: https://www.investopedia.com/terms/t/t-test.asp