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16. ABSTRACT

This report details a research study that aimed to investigate the cognitive abilities of severely intoxicated drivers and evaluate the efficacy of engineering countermeasures in preventing wrong-way entry onto freeways through exit ramps. The study involved 30 human subjects who participated in a driving simulator experiment, which depicted various scenarios involving both traditional and novel wrong-way-related traffic control devices such as signs and pavement markings. Each participant underwent three simulator sessions, which included an initial training session, a sober session, and an intoxicated session with a target blood alcohol level of 0.12. The researchers recorded all the participants' inputs in the driving simulator and tracked their eye movements through eye-tracking devices. The analysis of the data allowed for the identification of the most effective wrong-way warning methods based on the observed virtual driving behavior.

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Report NO. XXX

Identify Communication Methods for Severely Intoxicated Drivers to Develop Effective Engineering Countermeasures for Wrong-Way Driving

Submitted to

California Department of Transportation

Division of Research, Innovation and System Information

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CHAPTER 1 INTRODUCTION

1.1 Background

Wrong-way driving (WWD) crashes occur when a driver drives in the opposite direction of traffic flow and collides with a right-way vehicle. Although WWD crashes are infrequent compared with other types of crashes, they usually have a high likelihood of fatal or severe injuries. According to an overview of WWD crashes in the United States by Baratian-Ghorghi et al. in 2014, WWD crashes have not declined over the years compared with the overall trends of fatal traffic crashes. Though WWD crashes are rare and random, past research consistently indicated that these crashes were related to alcohol. Copelan reported that impaired drivers on California freeways accounted for almost 60 percent of all WWD crashes and nearly 77 percent of fatal WWD crashes (*Copelan, 1989*). Researchers in Indiana determined that out of 77 WWD crashes, 42 involved driving under the influence (DUI) (*Scifres et al., 1974*). A Washington State Department of Transportation (WSDOT) study found that 50 percent of the 30 WWD crashes on the I-82 Yakima-to-Tri-Cities corridor study were alcohol- or drug-related (*Moler, 2002*). Based on a study (*Zhou et al., 2016*) investigating contributing factors for WWD on high-speed divided highways, a driver who is DUI is almost four times more likely to be involved in WWD crashes than sober drivers.

WWD engineering countermeasures by the California Department of Transportation (Caltrans) focused on improving signage, pavement markings, and geometric design elements. Early research results indicated that low-mounted DO NOT ENTER (DNE) signs paired with WRONG WAY (WW) signs were an effective countermeasure. The WWD crash rate was significantly reduced in California after implementing these research recommendations in the 1970s and 1980s. An early Caltrans study recommended using oversized DNE signs for locations with a history of WWD problems (*Copelan, 1989*). The Manual on Uniform Traffic Control Devices (MUTCD) also recommends using large DNE and WW signs at multi-lane exit ramps or on one-way streets. A study by Texas Transportation Institute (TTI) developed guidelines for potential countermeasures to reduce the frequency and severity of WWD crashes in Texas (*Cooner et al., 2004a, 2004b*). Recent studies by Zhou et al. (*2012, 2014a, and 2016*) developed guidelines for emerging engineering countermeasures and logistic models to predict the likelihood of WWD crashes based on factors of driver condition, geometric features, traffic control devices (TCDs), and environmental variables. In 2013, the first National WWD Summit provided insights into candidate countermeasures and their effectiveness based on case studies (*Zhou et al., 2014b*).

Recently, a study (*Yang et al., 2019*) developed a new pavement marking called directional rumble strips (DRS). Researchers believe that directional rumble strips (DRS) may be the only countermeasure capable of directly alerting severely intoxicated wrong-way (WW) drivers with sounds and vibrations. Field implementation results have shown that some DRS patterns can significantly reduce the frequency of WW driving incidents and improve self-correction rates. In addition to DRS, many state DOTs have recently implemented WW signs with LED border lights or Rectangular Rapid Flashing Beacons (RRFB), which have shown promise in improving self-correction rates and are favored by drivers according to focus group surveys. However, there is a lack of research on the effectiveness of these emerging countermeasures on severely intoxicated WW drivers.

Driving simulator-based studies offer several advantages over other methods of investigating the effectiveness of WW-related countermeasures on alcohol-impaired drivers. They allow for the manipulation of countermeasures while holding all other factors constant, providing a better understanding of their effectiveness. Additionally, they are relatively low-cost compared to other methods, and participants are exposed to a lower risk level. Allen et al. (*1975*) conducted a pilot study using a driving simulator to test the effect of alcohol on driving performance. The study included eighteen drivers aged 21-65 at BAC of 0, 0.06, and 0.11., and the results showed that alcohol caused more extensive lane and heading deviations, resulting in increased detection and reaction times on discrete tasks. A study (*Boot et al., 2015*) explored several potentially more sensitive metrics to detect driver confusion at interchange decision points in the driving simulator. It was discovered that the effectiveness of countermeasures at interchange decision points can be improved by increasing their salience and number. This can help to reduce confusion among drivers and ensure they enter the correct highway entry point.

1.2 Objectives

The overarching goal of the project is to assess the efficacy of various WW-related countermeasures on severely intoxicated drivers. This research project will be carried out by achieving the following five sub-objectives:

1. Determine which advanced engineering countermeasures hold the potential to discourage severely intoxicated drivers from driving in the wrong direction.

2. Create driving simulator scenarios that incorporate the selected engineering countermeasures.

3. Recruit participants who have a history of driving under the influence of alcohol for driving simulator experiments.

4. Conduct laboratory experiments to quantify the impact of countermeasures on drivers who are sober versus those who are under the influence of alcohol.

5. Develop recommendations for the implementation of countermeasures at locations that have a track record of WWD events involving severely intoxicated drivers.

1.3 Report Organization

This report contains six chapters:

1. Chapter 2 concisely overviews WWD crash statistics, contributing factors, countermeasures, and past driving simulator-based studies.
2. Chapter 3 presents a detailed description of the driving simulator study plan, including participant recruitment, driving simulator scenario development, lab experiment design, and procedures.
3. Chapter 4 describes the methods for collecting and analyzing driving simulators and eye-tracking data.
4. Chapter 5 documents the evaluation results of the effectiveness of TCD(s).
5. Chapter 6 summarizes the key findings and the recommendations.

CHAPTER 2 LITERATURE REVIEW

This chapter presents a comprehensive summary of the literature review conducted, which is divided into four parts. The first part focuses on the characteristics of WWD crashes caused by alcohol-impaired WW drivers, including age group, gender, BAC level, and other relevant factors. The second part covers the various countermeasures that have been proposed to address WWD and the methods used to evaluate their effectiveness. The third part discusses the procedure involved in developing scenarios and tasks for driving simulator-based studies. Finally, the fourth part provides an overview of the laboratory session procedures involving alcohol, which includes participants' recruitment, screening, sampling, administration of alcohol during the sessions, and the cognitive test's administration.

2.1 WWD Crash

Over the past few decades, many national and state studies have explored contributing factors to WWD crashes. **Table 2.1** summarizes the results of the identified contributing factors to WWD crashes by past studies. For instance, Fitzsimmons et al. (*2019*) employed an ordinary logistic model, using 11 years (2005–2015) of crash data to characterize WWD crashes on a divided highway in Kansas. The authors identified factors such as driving under the influence (DUI), lighting conditions, driver age, and the usage of safety equipment as contributing factors to WWD crashes. Jalayer et al. (*2018*) found that driver age, driver condition, roadway surface condition, and lighting condition are significantly associated with the injury severity of the WWD crash using the random parameters ordered probit model. Pour-Rouholamin et al. (*2016b*) found similar results using the ordered logit model, generalized ordered logit model, and partial proportional odds model. Das et al. (*2018*) used the Eclat algorithm to analyze WWD crashes in Louisiana. The results showed that head-on collisions, male drivers, and off-peak hour are over-represented in fatal WWD crashes. Pour-Rouholamin et al. (*2016a*) applied Firth's penalized-likelihood logistic regression to analyze Illinois's five-year WWD crash data. The analysis revealed that driver age, time of day, driver residency, and driver condition could best describe the characteristics of WWD crashes. Ponnaluri et al. (*2016*) conducted a study in Florida to explore significant factors associated with WWD crashes and fatalities. Results of the binomial logistic regression model revealed that driver age, driver condition, lighting condition, facility type, license state, driver seatbelt use, and the number of vehicles involved in the crash are significantly related to fatal WWD crashes. Kemel (*2015)* conducted a logistic regression analysis of WWD crashes on divided roads in France. The results revealed that nighttime conditions, non-freeway roads, older drivers, impaired drivers, passenger cars, and older vehicles are the contributing factors to WWD crashes. Lathrop et al. (*2009*) analyzed WWD fatal crashes in New Mexico between 1990 and 2004. The results indicated that darkness, intoxicated drivers, older drivers, male drivers, non-Hispanic, and Native Americans are more likely to be involved in fatal WWD crashes.

Table 0.1 A Summary of Contributing Factors to WWD Crashes

Federal and State Reports				
State	**Method**	**Study Year**	**Roadway Type**	**Contributing Factors**
Nationwide *(NTSB, 2012)*	Descriptive statistics	2004–2009	Entrance/exit ramps and controlled-access highways	Drunk driver, driving while the intoxicated or impaired, older driver (70 or more), driver license statuses, 6:00 p.m.–6:00 a.m.
Alabama (*Zhou et al., 2017a; Zhou et al., 2017b*)	Haddon matrices, logistic regression model	2009–2013	Freeway	25–34 years old, older driver, male driver, DUI driver, passenger car, corner radius more than 80 ft
	Haddon matrices, logistic regression model	2009–2013	Divided highway	The older driver, male driver, DUI driver, passenger car, darkness
Florida (*Kittelson & Associates, 2015*)	Descriptive statistics	2009–2013	Freeway	Month (January through April, June, and July) weekend, head-on crashes, impaired drivers, darkness, younger drivers
Texas (*Finely et al., 2014*)	Descriptive statistics	2007–2011	Freeway	7:00 p.m.–12:00 p.m., younger driver (16–24 years), male driver, impaired driver
Iowa (*Savolainen et al., 2018*)	Descriptive statistics	2008–2017	All roadways	Interstate highway, urban area, dark condition, younger driver, older driver, male driver, impaired driver, driving alone
Illinois (*Zhou et al., 2012*)	Causal tables, Haddon matrix, significant test	2004–2009	Freeway	Alcohol impairment, driver age group, driver gender, driver physical condition, driver skills/experience/knowledge, time of day, interchange type, area type
North Carolina (*Braam, 2006*)	Descriptive statistics	2000–2005	Freeway	Younger driver, older driver, alcohol involvement, interstate route, rural area, midnight–5:59 a.m., month (February and June), two-quadrant parclo interchange, full diamond interchanges
California (*Copelan, 1989*)	Descriptive statistics	1983–1987	Freeway	Darkness, intoxicated driver, time of the day, urban area, interchanges with short sight distance, interchange types, ramp types, five-legged intersections near the exit ramp
Journal Article				
Author	**Method**	**Study Year**	**Roadway Type**	**Contributing Factors**

Fitzsimmons *et al.* (*2019*)	Ordinary logistic model	2005–2015	Divided highway	DUI driver, lighting condition, 55 years and older, uses old safety equipment
Jalayer *et al.* (*2018*)	Random parameters ordered probit model	2009–2013 for AL. 2004–2013 for IL	Controlled-access highway	Driver age, driver condition, roadway surface condition, lighting condition
Das *et al.* (*2018*)	Data mining ("Eclat") algorithm	2010–2014	All road types	Head-on collision, male drivers, off-peak hours
Pour-Rouholamin et al. (*2016a*)	Firth's penalized-likelihood logistic regression	2009–2013	Interstate highway	Driver age, time of day, driver condition, and driver residency
Pour-Rouholamin et al. (*2016b*)	Ordered logit, generalized ordered logit, partial proportional odds	2009–2013 for AL. 2004–2013 for IL	Controlled-access highway	Driver age, condition, seatbelt use, time of day, airbag deployment, type of setting, surface condition, lighting condition, type of crash
Ponnaluri (*2016*)	A binomial logistic regression model	2003–2010	Freeway and arterial	Driver age, driver condition, lighting condition, driver seatbelt use, license state, facility type, number of vehicles involved in the crash
Kemel (*2015*)	Logistic regression model	2008–2012	Divided road	Nighttime hours, non-freeway roads, older drivers, impaired drivers, older vehicles, passenger cars
Lathrop *et al.* (*2009*)	Chi-square, Fisher's extract test, Wilcoxon rank-sum tests, *t*-tests	1990–2004	Interstate highway	Darkness, intoxicated drivers, older drivers, male drivers, passenger cars, November, non-Hispanic and Native Americans

2.2 WW-related Countermeasures

The MUTCD provides states and agencies with standards and guidance on WW-related TCDs. As shown in **Figure 2.1**, at least one DO-NOT-ENTER (DNE) sign, at least one WW sign, and at least one ONE WAY sign for each direction must be placed at an off-ramp terminal (*MUTCD, 2009*). The additional ONE-WAY signs, WW signs, and WW arrow pavement markings may be used to supplement the signs and pavement markings (*MUTCD, 2009*).

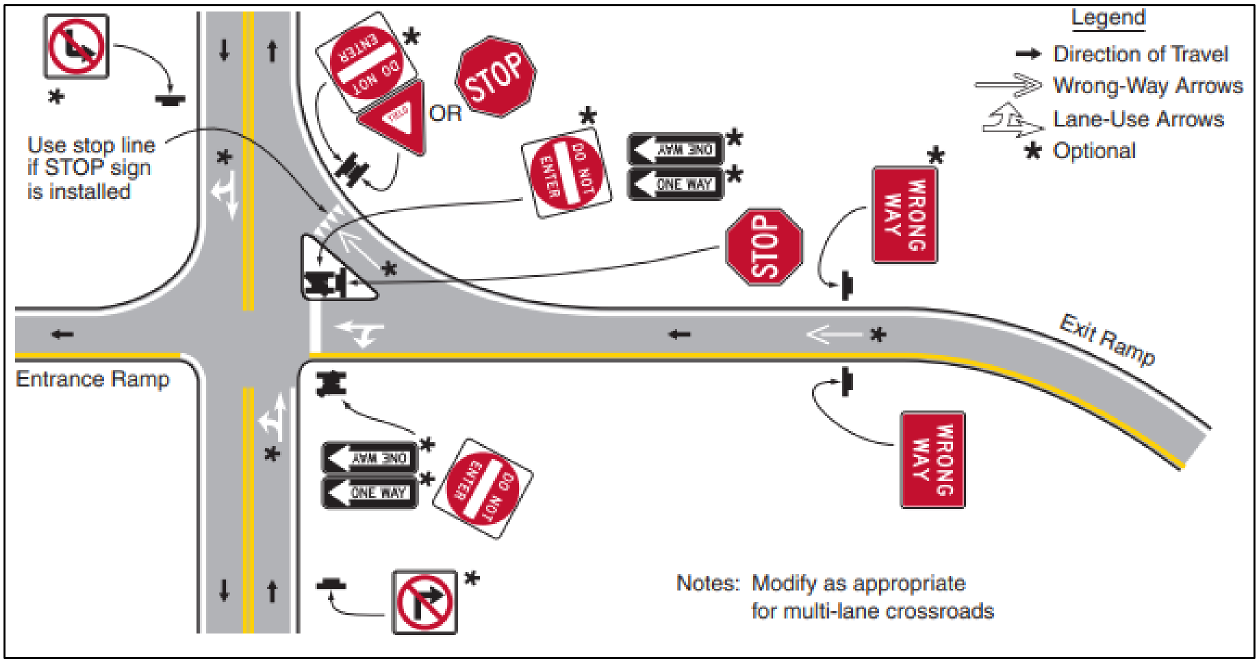


Figure 2.1. Application of Regulatory Signing and Pavement at an Exit Ramp Termination to Deter Wrong-Way Entry (MUTCD 2009)

Many state DOTs have developed additional guidelines on WW-related TCDs for ramp terminals at different interchanges. Table 2.2 lists existing guidelines developed by ten state DOTs.

Table 0.2 Guidelines on WW-related TCDs by 10 State DOTs

Year	State	Guidelines
2015	Florida	1. Include MUTCD "optional" signs: (second DNE sign, second WW sign, ONE WAY sign) 2. Include NO RIGHT TURN and NO LEFT TURN signs 3. Use 3.5 x 2.5 ft. WW signs with 4 ft. mounted height. Apply the retroreflective strip on sign supports 4. Include two to four dotted guideline striping for left turns 5. Include retroreflective yellow paint on-ramp median nose where applicable 6. Include a straight arrow and route Interstate shield pavement marking in left-turn lanes 7. Include a straight arrow and ONLY pavement message (*FDOT, 2015; and 2019*)
2015	Arizona	1. Use DNE sign and WW sign assembled on the same post 2. Use large-sized signs: DNE 48 x 48 in., and WW 48 x 36 in. 3. The minimum mounting height is 3 ft. 4. Strips of red retroreflective sheeting may optionally be placed on the signpost (*ADOT, 2015*)
2015	Connecticut	1. Mount larger-sized signs at exit ramps (48-in. DNE signs, 42 x 24 in. WW signs) 2. Low-mounted WW and DNE signs (5 ft., consideration of snow) 3. Applied red reflective delineator strips on the signpost 4. 24-in. wide stop bar applied 5. As for the locations with adjacent on/off ramps: (a) Applied the pavement marking extension lines at signalized locations (b) Double yellow centerline between the ramps (*Athey Creek Consultants, 2016*)
2015	Wisconsin	(a) Larger-sized DNE and WW signs (b) Stop bar and type-4 pavement arrows (c) Dotted pavement markings line extensions through the intersection 2. The following strategies are optional and shall only be used at side-by-side ramp locations that exhibit problems with WW drivers entering the freeway: (a) Additional WW sign mounted below the DNE sign at 3-ft. mounting height (b) Reflective strips on WW and DNE signposts (c) A freeway entrance sign (d) Dynamic (flashing) WW signs (*WisDOT, 2015*)
2016	Ohio	1. Two WW signs assembled on the same post with a low-mounted height (3 ft.) 2. Red reflective tape shall be added to the STOP sign, DNE sign, and WW sign 3. Include pavement marking extension line to guide drivers onto the right way 4. Include dual-directional route marker signs at the end of ramps 5. Include a yellow-painted island between the entrance and exit ramp 6. Additional signs followed MUTCD minimum requirements The DNE sign may be angled 45 degrees toward the left-turning vehicle (*Ohio DOT, 2016*)
2017	Michigan	1. The mounting height of DNE and WW signs shall be 4 ft. 2. Red reflective sheeting shall apply to the signposts. WW and DNE signs should be turned around 20 degrees from the crossroad to face the potential WW drivers (*Michigan DOT, 2011*)
2017	North Carolina	1. Low mounting height, reflective strips, dynamic signs, larger-sized signs, turn prohibition signs, etc. 2. WW pavement marking arrows, lane extensions, stop line, delineate median, etc. 3. Channelizing island, median, corner radius, median barrier, roundabout, lighting (UNC Highway Safety Research Center, 2017)
2018	Oregon	1. Additional guidance regarding low-mounted installations for WW entrance signing on the interstate freeways 2. The standard for low-mounted installations (*Oregon DOT, 2018*)

2019	California	1. The DNE (R5-1) sign and WW (R5-1a) sign shall be used at the exit end of a one-way road or ramp to inform motorists that an entrance thereto is prohibited. 2. At intersections where the left-turn lane treatment results in channelized offset left-turn lanes (e.g., a parallel or tapered left-turn lane between two medians), the size of the DNE (R5-1) sign or WW (R5-1a) sign, if used, should be of the next higher roadway classification, to reduce the potential for WW maneuvers by road users turning left from a stop-controlled, intersecting minor roadway. 3. Where there are no parked cars, pedestrian activity, or other obstructions such as snow or vegetation, and if an engineering study indicates that a lower mounting height would address WW movements on freeway or expressway exit ramps, a DNE sign(s) and/or a WW sign(s) that is located along the exit ramp facing a road user who is traveling in the wrong direction may be installed at a minimum mounting height of 3 ft., measured vertically from the bottom of the sign to the elevation of the near edge of the pavement. 4. A stop beacon shall be used only to supplement a STOP sign, DNE sign, or WW sign (*Caltrans, 2019*).
2019	Washington	1. Signing and Delineation DNE and WW signs, ONE WAY signs, turn restriction signs, red-backed raised pavement markers (RPMs), directional pavement arrows, yellow edge line on the left and white edge line on the right side of exit ramps, and pavement marking extension lines. 2. Intelligent Transportation Systems (ITS) 3. Geometric Design Separate on-and off-ramp terminals, reduced off-ramp terminal throat width, increased on-ramp throat width, intersection balance, visibility, and angular corners on the left of off-ramp terminals (*WSDOT, 2019*).

According to **Table 0.2**, common guidelines for additional WW-related countermeasures are summarized below:

Signage

- *Size:* Oversized signs (DNE sign, WW sign, or both) must be implemented on the roadside to ensure better visibility. The 48 x 48-in. DNE signs were commonly included in guidelines for those ten state DOTs. However, there is no uniform size for the WW sign.
- *Mounting height:* Low-mounted signs (DNE, WW, or both) were recommended. The recommended height of the sign varies from 3 to 5 ft. For example, due to winter snow accumulation, the 5 ft. DNE and WW signs were contained in Connecticut DOT's (CTDOT) guidelines (*Athey Creek Consultants*, *2016*).
- *Retroreflective tape:* Five (5) out of 10 state DOTs recommended applying retroreflective tape on the signpost. Four states set this guideline as standard, while one state regarded it as optional. However, there is no uniform requirement for retroreflective material.
- *Assembled sign:* Three state DOTs included the assembled sign in their guidelines; however, different states will assemble different signs on the same post. For example, ADOT put a DNE and WW sign on the same post (*ADOT, 2015*), whereas the Ohio DOT assembled two WW signs on the same post (*Ohio DOT*, *2016*).

Pavement Markings

- *Pavement marking extension line:* Six out of 10 state DOTs recommended applying pavement marking extension lines between ramps and crossroads to guide drivers in the right direction. However, there are no uniform requirements on the line type, the number of lines, or application conditions. For example, FDOT required two (2) or four (4) dotted guideline striping at the intersections between exit ramps and crossroads (*FDOT, 2015; FDOT, 2019*). However, in Connecticut, the extension line is only applied at signalized intersections with adjacent entrance and exit ramps (*Athey Creek Consultants, 2016*).
- *Lane use arrows:* Lane use arrows on the ramps are another common practice by several states. States often had different requirements for lane-use arrows.
- *Route shield signs:* Most states recommended route shield signs on arterials and stop bars on the off-ramp.

2.3 Evaluation of WWD Countermeasures

Although many agencies applied different kinds of WWD countermeasures, the evaluation of WWD countermeasures can be difficult due to the randomness of WWD crashes and the lack of before-and-after data. A survey study conducted by Pour-Rouholamin et al. *(2014*) gave an overview of the effectiveness and level of acceptance for over ten engineering countermeasures, including WW-related signage, pavement markings, geometric modification, and ITS technologies. An ENTERPRISE Transportation Pooled Fund Study by Athey Creek Consultants *(2016*) recommended grouping these countermeasures into two categories: preventative and reactive countermeasures. Preventative countermeasures refer to those that can prevent the vehicle from entering the WW. Reactive countermeasures are those that can warn WW drivers. **Table 2.3** summarizes the past evaluation study results of the traditional and emerging WW-related TCDs in these two categories.

Table 0.3 Evaluation Results of the Traditional and Advanced WW-related TCDs

Preventative Countermeasure					
State	Type of TCDs	Data	Evaluation Method	Effectiveness	Reference
CA	Lower-mounted Signs Specific requirements for sign installation	WWD incident	Before-and-after study	90% reduction in WWD incident frequency	*Leduc, 2008*
GA	Countermeasure combo (trailblazers, low-mounted WW signs, stop bar, yellow ceramic buttons	WWD incident	Before-and-after study	97% reduction in WWD incident frequency	*Campbell and Middlebrooks, 1988*
TX	Directional arrows	WWD incident	Before-and-after study	90% reduction in WWD incident frequency	*Chrysler and Schrock, 2005*
TX	Sign and Pavement marking improvement (repainting, striping additions, and WW sign on signal mast arms)	WWD incident	Before-and-after study	The number of WWD incidents decreased significantly after improvements	*Ouyang, 2013*
FL	Newly-develop signing and pavement marking (S&PM) standards	Survey data	Survey	Very positive effectiveness on arterials	*Lin et al., 2018*
AL	Pavement markings improvement (repainting, striping additions, and stop bar)	WWD incident	Before-and-after study	63% reduction in the number of WWD incidents	*Chang et al., 2019*
Reactive Countermeasure					
State	TCDs	Data	Evaluation Method	Effectiveness	Reference
AL	WW sign combined with WW arrow	WWD incident	Before-and-after study	More than 90% come back rate for WWD incidents	*Chang et al., 2019*

AL	Directional rumble strips	WWD incident	Before-and-after study	Improve self-correction rates and reduce WWD incidents while offering good visual attentiveness and applicability	*Zhou et al., 2020*
FL	Rectangular flashing beacon (RFB) WW Sign	911 calls and citation	Before-and-after study	48.5% reduction in 911 calls, 52.9% reduction in WWD citations, and 44.1% reduction in combined WWD 911 calls and citations	*Al-Deek et al., 2019*
		WWD incident	Before-and-after study	77% reduction in WWD incident frequency	*Lin et al., 2017*
FL	LED WW sign	WWD incident WWD crash Survey data	Field testing Crash/incident data Survey Driving simulator	14% reduction in WWD incident frequency	*Lin et al., 2018*
	Detection-triggered LED lights around WW signs			Effective for mitigating WWD	
	Detection-triggered blank-out signs that flash “WW”			Effective for mitigating WWD	
	Wigwag flashing beacons			Effective for mitigating WWD	
	Delineator along exit -ramps			The least effective countermeasures	
FL	Red Rectangular Rapid Flash Beacons (RRFBs)	WWD incident	Before-and-after study	60% – 85% self-correction rates	*Ozkul and Lin, 2017*

HI	Red Retroreflective Raised Pavement Markings (RRPMs)	WWD incident	Field observation Before-and-after study	RRPM helped drivers realize when they were going in the wrong direction. Replacing supplemental RRPMs with supplemental arrows constantly improved the self-correct rates	*Miles et al., 2014*

The evaluation methods by different agencies mainly focused on before-and-after studies of WWD crashes or incidents, driving simulations, surveys, field tests, and investigation of agency records. For preventative WWD countermeasures, five states have made the improvement or enhancement of traditional DNE or WW signs and pavement markings for deterring WWD incidents, which showed a significant reduction in WWD incidents by up to 97% (*Leduc, 2008; Lin et al., 2018; Ouyang, 2013; Chang et al., 2019; Campbell and Middlebrooks, 1988*). In addition, LED borders for DNE and WW signs and directional arrows on exit ramps were effective in deterring WWD incidents (Lin et al., 2018). Finaly, the raised/vertical longitudinal channelizing devices and geometric modifications for exit-ramp terminals can prevent WWD incidents (*Ouyang, 2013*).

As for reactive WWD countermeasures, transportation agencies tended to apply more advanced countermeasures to reduce WWD incidents, 911 calls, WWD citations, and the combined 911 calls and citations efficiently (*Kayes et al., 2019; Al-Deek et al., 2019 & Lin et al., 2018*). The reactive countermeasures like red RRFBs, wigwag flashing beacons, LED WW signs, detection-triggered blank-out signs that flash "WW" and detection-triggered LED lights around WW signs have been proven significantly effective for improving self-correction rates. The RRPMs are less effective than other advanced countermeasures (*Lin et al., 2018*), which can be considered a supplemental countermeasure. The traditional reactive countermeasures, such as a WW sign combined with a WW arrow and directional rumble strips (DRS), can also effectively reduce WWD incidents (*Chang et al., 2019*). Compared with the WWD countermeasures mentioned above, the delineators along exit ramps were considered the least-effective countermeasures (*Lin et al., 2018*).

2.4 Past Driving Simulator-Based Studies

Within the last decade, vehicle driving simulators have been widely accepted and adopted to conduct transportation research to evaluate drivers' reactions to roadway and roadside treatments. Yan et al. (2007) used a driving simulator to measure the effect of a "SIGNAL AHEAD" pavement marking countermeasure with a varied speed limit, treatment type, and yellow phase onset distance. The results suggested that the pavement markings reduced the uncertainty region from 17 meters to 10 meters at intersections with a 30 mph speed limit and from 31 meters to 16 meters at intersections with a 45 mph speed limit. The countermeasure also reduced the number of red-light running incidents by 65%. In another study, the effectiveness of steady burn warning lights was evaluated through driving simulator experiments and field tests. The simulator scenarios were created to mimic a work zone with and without steady burn warning lights. A comparison of the number of crashes within the experiment showed that the sites with warning lights had significantly more crashes than those without (*McAvoy, et al., 2006*).

A report by Robinson et al. discussed a driving simulator study as part of the evaluation of a complex at-grade rail crossing project in Ottawa, Canada. This scenario mimicked the at-grade rail crossing with a 32-degree skew angle, the widening of the roadway, an at-grade rail crossing, and a transitway extension at a 30-meter offset from the rail crossing. The simulator measured the velocity, stopping accuracy, the probability of drivers stopping when the light changes and they are in the dilemma zone, the maneuver type used when a truck was stalled beyond the crossing, and eye movements using a sophisticated eye-tracking camera. Forty-eight participants of varying ages completed the study. Overall, the results helped with the final development and optimization of the placement of the guidance and warning signs and signals (*Robinson et al., 2007*).

A study by Abbas et al. investigated driver perception of using a dynamic all-red interval extension in urban and suburban settings. Other factors considered include the presence of cross traffic, the extension being on a major or minor street, and the red-light runner being followed closely by another vehicle. The results showed that the urban/suburban setting was the only significant factor, and in urban areas, drivers were less likely to notice an extension and perceive red-light running as more dangerous (*Abbas et al., 2006*).

In a study by Noyce and Knodler, a driving simulator was used to evaluate drivers' comprehension of flashing yellow arrows that were retrofitted to three-section and five-section cluster signals. A total of fifty-six participants completed the study. Participants were presented with 12 intersections with different signal setups. The study found that there was not a significant difference in the driver's ability to comprehend the three-section signal, but the driver's comprehension was significantly lower for the inclusion of the flashing yellow arrow in the five-section cluster signal. Additionally, qualitative measures showed that 28% of drivers preferred the flashing yellow arrow in the middle section compared to 9% who preferred it in the bottom (*Noyce and Knodler*, *2014*).

Besides the abovementioned studies, a few driving simulator studies were found that were highly related to the WWD study. A study conducted by FDOT used the driving simulator to better understand the effectiveness of countermeasures to prevent WW entries and crashes (*Lin et al., 2017*). In this study, the participants were asked using the driving simulator to take an entrance ramp on the left to a destination city facing either the minimum WW countermeasure combination or the enhanced WW combination. A total of 40 older drivers (daytime scenarios) and 80 younger drivers (nighttime scenarios) completed the study, and half of the younger drivers wore goggles to simulate the impaired condition. The results indicate that a greater number and diversity of countermeasures may assist in reducing the number of WWD. Another study conducted by Lin et al. (*2018*) used adriving simulator to evaluate ITS WWD countermeasures in Florida. A total of 189 drivers were recruited and equally assigned to five different scenarios. The participants were asked to keep driving on the roadway, which simulated the environment after a highway off-ramp to include certain flashing and standard WW signs until the roadway condition seemed unsafe. The study found that Red Rectangular Rapid Flashing Beacons are the most effective countermeasure. A study by Seitzinger et al. (*2016)* used a driving simulator to investigate how low-mounted signs affected drivers under the influence of alcohol. Twenty-eight participants aged 19 to 61 (75% male and 15% female) completed the study and wore goggles to simulate an impaired condition of an estimated BrAC range of 0/17 to 0.20. Participants were asked to complete a scene that consisted of a series of alternating left and right turns at 13 intersections with signs mounted at 7ft and 3ft. The results showed that low-mounted signs improved the driver's reaction time and reduced the likelihood of the driver missing the sign.

2.5 Research Gaps

The literature review has revealed that driving under the influence (DUI) accounts for over 50% of WWD crashes, with young and male drivers being the most involved, and most of these crashes occurring at night. Although the Federal Highway Administration (FHWA) and state DOTs have developed and implemented various TCDs to deter WWD, their effectiveness on intoxicated drivers is not yet established. Some previous studies have evaluated engineering countermeasures for WWD using a driving simulator, but none of them tested the countermeasures with Caltrans' specifications and used the real alcohol.

CHAPTER 3 DRIVING SIMULATOR EXPERIMENT DESIGN

This chapter describes a driving simulator experiment designed to understand the communication methods for severely intoxicated drivers and the effectiveness of wrong-way related TCDs on driving behaviors. The laboratory devices overview section provides detailed information on the driving simulator and Tobii Pro Glasses 2 wearable eye tracker. The experiment design covers the target breath alcohol concentration (BrAC) level, participant recruitment, testing countermeasures, and scenario design. Finally, the lab testing procedure includes both familiarization and testing sessions.

3.1 Lab Devices Overview

Driving simulators provide researchers with the ability to examine driving behaviors in a controlled virtual environment. They provide a less expensive, repeatable, and safe alternative to field experiments. The driving simulator enables the investigation of various aspects of driving behaviors by highly intoxicated drivers. A National Advanced Driving Simulator (NADS) MiniSim^{TM} driving simulator and a Tobii Pro Glasses 2 wearable eye tracker were used in this research.

The NADS MiniSim^{TM} driving simulator is a PC-based driving simulator for which the NADS lab has developed software and hardware at the University of Iowa (*NADS*, *2022*). It has an anodized aluminum chassis with carpet, dashboard, steering wheel, pedals, and driver controls that accurately mimic a real car from the driver's perspective, facilitating a wide variety of research applications. As shown in **Figure 3.1**, the NADS MiniSim^{TM} driving simulator used in the lab consists of five displays for different purposes. Three 50-inch TV monitors are installed on the triple-floor standing monitor stand, giving the driver a 180-degree horizontal and 50-degree vertical field of view of the simulated environment. Each display has a resolution of 1360×768 pixels and a refresh rate of 60Hz. The 12-inch display in front of the car seat is a virtual instrument cluster that can provide drivers with information such as gear status and current speed. In addition, a 24-inch operator display is set aside, positioned for laboratory test operation by researchers.

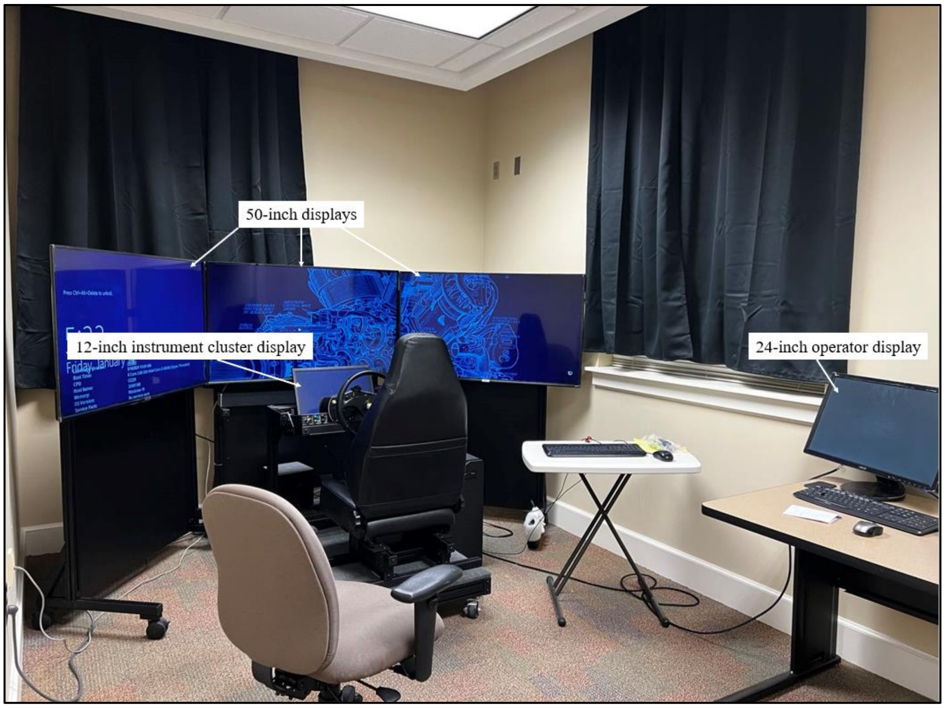


Figure 3.1 Driving Simulator Displays

The Tobii Pro Glasses 2 wearable eye tracker gives researchers deep and objective insights into human behavior by showing what a person looks at in real-time. It helps researchers understand how people interact with their environment, what catches their attention, drives their behavior, and influences decision-making (*TobiiPro, 2022*). The system tracks corneal reflection and dark pupil using a 50 Hz sampling rate. The Tobii Pro Glasses 2 wearable eye tracker incorporates a head unit and recording unit, illustrated in **Figure 3.2**. The head unit is a highly sophisticated measuring device. The head unit contains a high-definition scene camera that captures a full HD video of what is in front of the participant and a microphone that picks up sound from the participant and his surroundings. It also contains eye-tracking sensors to record eye orientation and infrared illuminators (so-called IR illuminators) to illuminate the eyes to support the eye-tracking sensors. The recording unit is a small computer that controls the head unit and connects with the head unit using a cable. It records and stores eye-tracking data, sounds, and scene camera video on a removable SD memory card. The recording unit carries a replaceable and rechargeable Li-ion battery that supplies power to both the recording and head units.

Figure 3.2 Tobii Pro Glasses 2 Wearable Eye Tracker

3.2 Experimental Design

3.2.1 Target BrAC Level

When evaluating relevant alcohol and driving simulation studies, the highest reported target Breath Alcohol Content (BrAC) researchers had dosed participants is 0.10 BrAC (*Mets et al., 2011, Helland et al., 2016; Huizinga et al., 2019; Finley et al., 2014, 2017; Subramaniyam et al., 2018; Irwin et al., 2017*) with a maximum observed BrAC of 0.12. As for laboratory-based alcohol administration studies in general, the highest reported target BrAC is 0.12, with a maximum observed BrAC of 0.15 (*Stock et al., 2014, 2016; Wolff et al., 2016; Chmielewski et al., 2018; Zink et al., 2019*). Based on previous literature and considering that around 40% of fatal WWD crashes due to alcohol intoxication in the U.S. occurred at or above a BrAC of 0.12, the target BrAC level used for this study is 0.12.

3.2.2 Recruiting and Screening Participants

Sample size estimates were based on an a priori power analysis conducted using G*Power (*Faul et al., 2007*). Estimates were based on the planned within-subject (e.g., participants complete all test conditions and serve as their own control group). A medium effect size was selected for this study, which is commonly used in studies on the effects of alcohol intoxication on simulated driving (*Irwin et al., 2017*). Additionally, the medium effect size used for estimation is conservative since the alcohol doses used in the study would likely produce more significant effects. Calculations were based on a desired power of .80 (e.g., 80% likelihood of accepting the proposed research hypothesis if true), which is considered a strong statistical test and the standard value used in experimental research. These parameters yielded a recommended sample size of 27 participants. Thus, the final sample size of 30 participants should be more than sufficient to answer the research question.

Before any study activities involving human subjects, an approved protocol was obtained through the Auburn University Institutional Review Board (IRB; #21-061 MR 2102) Two recruitment methods were used to contact local participants. The university students were recruited through an online research participation system operated by the Department of Psychological Sciences at Auburn University. Individuals from the community were recruited via local print advertising and posted on various social media platforms. Regardless of the population or recruitment mechanism, all participants were directed to an online screening survey that we used to assess the inclusion and exclusion criteria described below.

As per the protocol, we recruited male adult drivers, at least 21, since males are more likely to engage in intoxicated WWD based on previous literature. Female participants were excluded from the study due to the potential hazards of alcohol administration during pregnancy or breastfeeding and to avoid possible confounds relating to hormonal changes/the menstrual cycle. Additionally, there is no upper limit on age-related inclusion criteria, as data have indicated that older adults are also overrepresented in WWD crashes.

Considering the relatively high BrAC level used for the study, potential participants are required to fill out the online screening materials to identify participants who would not be adversely impacted, with a target sample of heavy social drinkers. The screening materials required participants to self-report frequency, duration, and amount of alcohol use within the last month.

Then the highest approximate BrAC was calculated based on their weight and height. This method has been utilized in past alcohol-related laboratory studies (*Chmielewski et al., 2018*). This ensured that participants had been familiarized with the dose of alcohol administered in the laboratory session to reduce the risk of adverse events in laboratory testing as well as increase the ecological validity of our study. This study also excluded individuals who meet the criteria for alcohol use disorder or have previously sought treatment and/or are currently in treatment relating to substance use. The individuals who reported current or previous history of treatment for alcohol abuse were also excluded from the study. The study also excluded individuals who reported visual impairments, as well as any psychiatric and/or medical condition that the investigators deemed could potentially interfere with the study procedures. Lastly, participants who self-report currently taking a medication that interacts adversely with alcohol were also excluded from the study. All of these exclusion criteria are common practice in laboratory-based alcohol administration studies (*Van Dyke and Fillmore, 2014, 2017; Chmielewski et al., 2018*).

Individuals who met the criteria for the three-session study and expressed an interest in participating were scheduled for a laboratory session at Auburn University. Participants were compensated $200 for completing all study procedures.

3.2.3 Testing countermeasures

Six proposed countermeasures were selected for the study, including a standard WW sign (a), DNE/WW signs on the same post (b), a WW sign with an LED border (c), a WW pavement arrow with retroreflective raised pavement markers (RRPMs) (d), LaneAlert 2X (e), and directional rumble strips (f), as shown in **Figure 3.3**.

Figure 3.3 Testing Countermeasures

The standard WW sign (WW) (**Figure 3.3(a)**) followed the specifications listed in the MUTCD. As illustrated in **Figure 3.3(b)**, the DNE and WW sign on the same post (DNEWW) followed CAMUTCD requirements, which are enlarged and low-mounted at 3ft. The WW sign with an LED border (WWFlashing), as shown in **Figure 3.3 (c),** had the same dimensions as the traditional WW sign. Red LED lights are embedded on the sign border and will be triggered when the WW vehicle is detected by inductive loops and a thermal camera. The RRPM pavement system adopted by Caltrans uses enhanced pavement markings with the installation of RPMs along lane lines, stop bars, and WW arrows to warn WW drivers. The LaneAlert 2X (LaneAlert) pavement marking system followed Caltrans' experimental design. Only WW drivers can see the red arrows and warning messages on the pavement markings. The directional rumble strips (DRS) followed the specification developed by the Alabama DOT study.

3.2.4 Driving simulator scenario development

Two software programs, the Tile Mosaic Tool (TMT) and the Interactive Scenario Authoring Tool (ISAT) provided by NADS miniSim^{TM}, were used for the driving simulator scenario development. The TMT is used to assemble a road network from a library of 95 road/landscape segments called “tiles” and export a complete database to the ISAT. The ISAT is designed for building scenarios based on the assembled database. Since the library did not contain the desired tiles for the study, three basic tiles were modified based on the existing tiles, as illustrated in **Figure 3.4**. The roadway tile (**Figure 3.4 (a)**) contains a rural roadway 24ft wide. All the land markings were removed to avoid additional visual aids on the roadway. The T-intersection tile (**Figure 3.4 (b)**) is a three-leg intersection at the center of the tile. The turn-around tile (**Figure 3.4 (c)**) contains a large round space that simulates a dead-end and allows the driver to turn around. The roadway network can be assembled using the three tiles described above. The roadway network developed for this study contains several T-intersections connected by a different number of straight roadway tiles. At the end of a roadway segment, a turn-around around area was provided to guide WW drivers back to the right way.

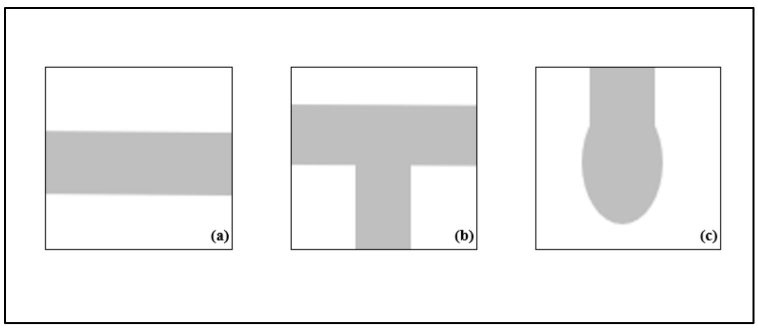


Figure 3.4 Three Basic Tiles Used for Scenario Development: (a) Roadway Tile; (b) T-Intersection Tile; (c) Turn-Around Tile

Besides the roadway network development, testing countermeasure models also needed to be either modified or created. DNE and WW signs in the driving simulator object library have smaller sizes and higher mounting heights than Caltrans’ standards. They were modified to meet Caltrans’ standards. 3D models were created for three testing countermeasures (LaneAlert 2X, WW pavement arrows, and DRS) not available in the ISAT library. The developed models were converted into the open flight file (.flt), the top view file (.dxf), and the ¾ view model file (.bmp) and then saved in the object’s library with the texture image in the driving simulator. After coding the countermeasures (dimensions, color, texture, etc.) on the backend of the driving simulator, the three countermeasure models worked as planned in the driving simulator. The procedures for developing 3D models are illustrated in **Figure 3.5**.

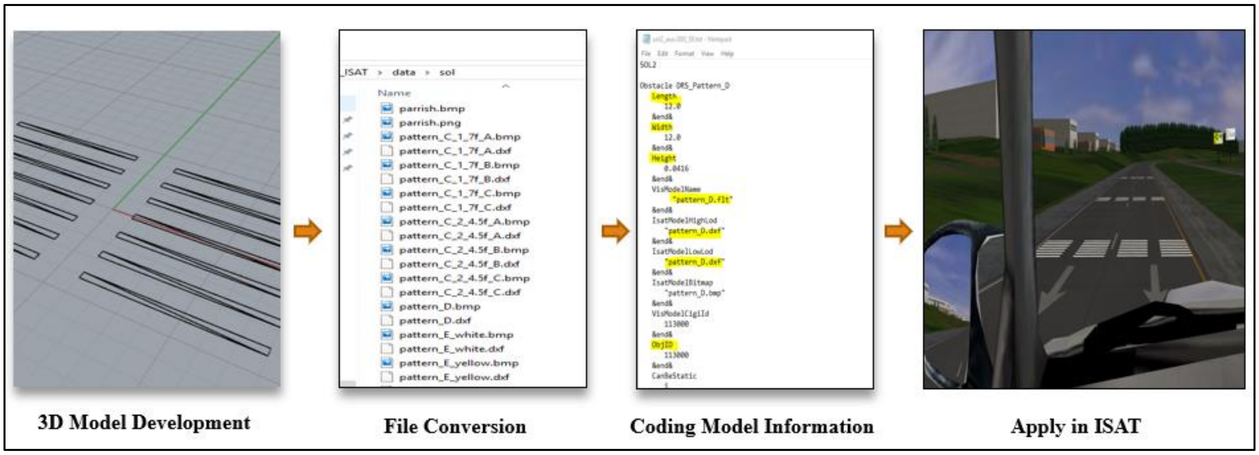


Figure 3.5 Procedures for Creating Countermeasure Models

Since WWD usually happens at night, the nighttime condition was applied for the driving simulator scenario development. Four scenarios were developed for this study for different purposes. The training scenario aims to familiarize participants with the driving simulator. Participants were not informed of the experiment's purpose. In the training scenario, no proposed testing countermeasures were implemented on the road/roadside, and no other vehicles were presented on the roadway. Participants were given instructions on the TV monitors on how to make left/right turns, speed up, slow down, and turn around, which helped the drivers familiarize themselves with the maneuvers used in the testing session. Three testing scenarios were developed for this study, each of them containing several T-intersections. One side of the T intersection is used to simulate the off-ramp with the countermeasures. The participants can make a left/right turn in the correct direction when facing the WW-related countermeasures. The first testing scenario is aimed at evaluating the effectiveness of individual countermeasures. In this scenario, each proposed countermeasure was randomly placed at a T-intersection and directly faced the drivers, as illustrated in **Figure 3.6**. Several blank T-intersections with no countermeasures were included to prevent drivers' self-learning. Participants can make a U-turn back to the roadway network if they enter the wrong way. As shown in **Figure 3.7**, the second testing scenario aims to test whether the current countermeasures in the CAMUTCD are more effective than those in the national MUTCD. This scenario had a similar roadway layout to the first testing scenario, but with two different sets of countermeasures. The countermeasures were placed according to specifications in the MUTCD and the CAMUTCD. The third testing scenario analyzes the effectiveness of WW sign and pavement marking combinations. In this scenario (**Figure 3.8**), the driver encountered two types of WW signs (standard WW sign and WW sign with flashing LED border) and three types of pavement markings (wrong-way arrow with RRPM, LaneAlert 2X, and DRS). This scenario examines the effectiveness of six different sign/marking combinations in deterring WWD movements.

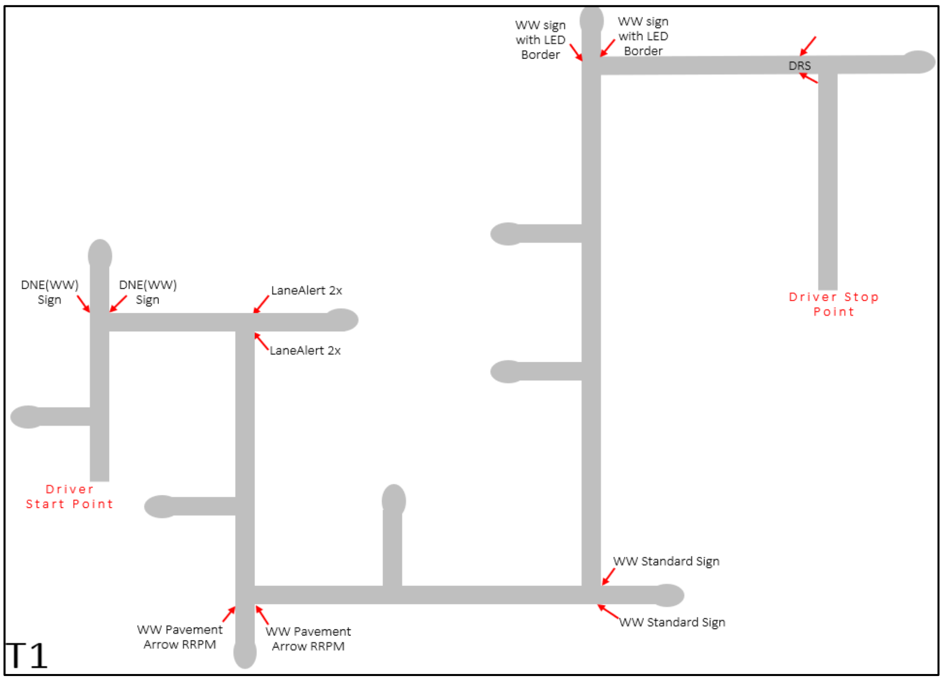


Figure 3.6 Testing Scenario One

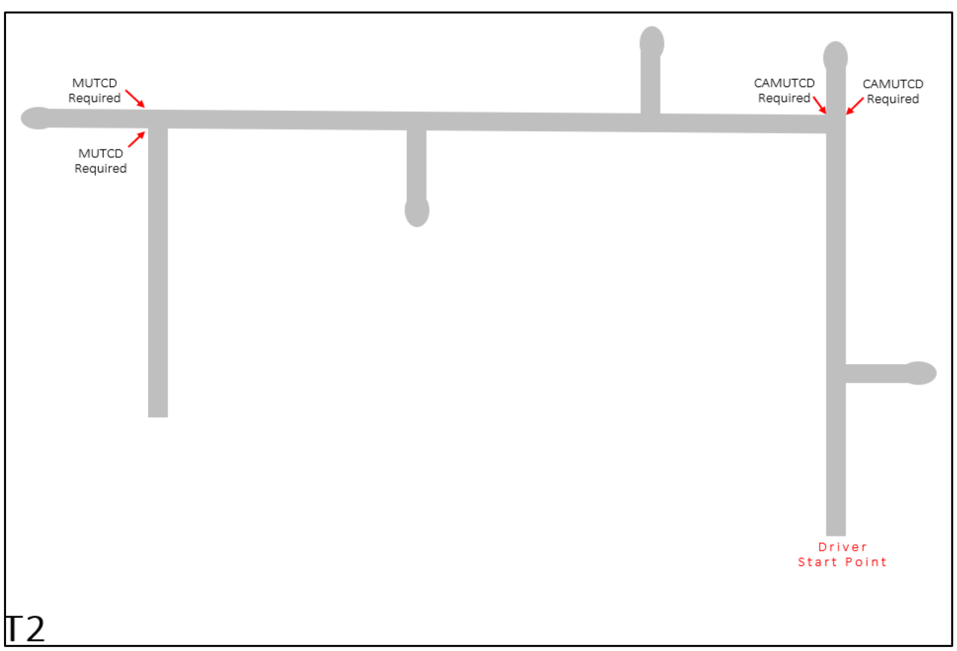


Figure 3.7 Testing Scenario Two

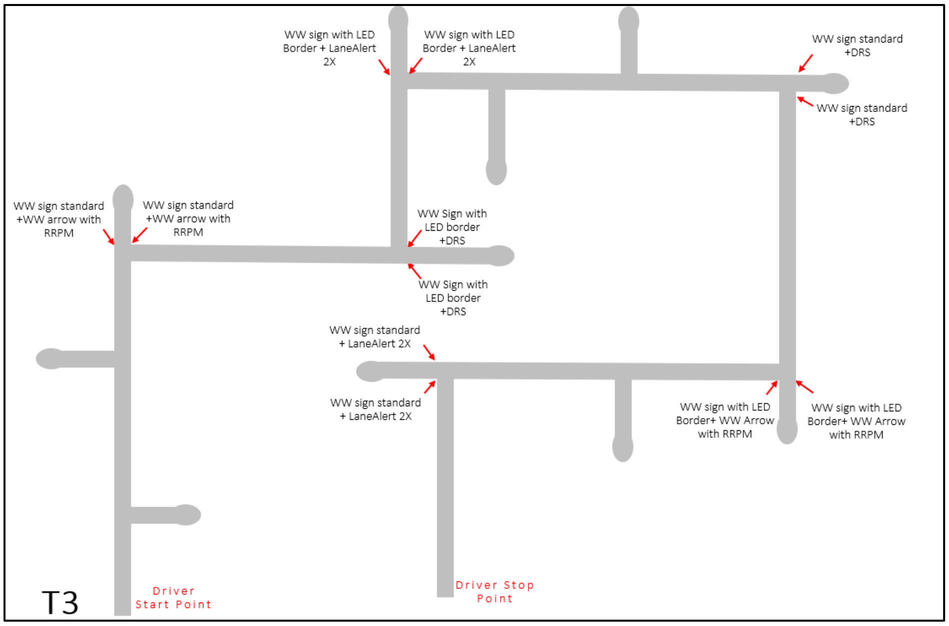


Figure 3.8 Testing Scenario Three

3.3 Lab Session Procedures

Based on the screening results, eligible individuals were invited to participate in the study and asked to attend three in-person lab sessions. The familiarization session is always the first session that requires attending, and participants were randomized to experience the alcohol and non-alcohol sessions in a counterbalanced order. The study did not employ a true placebo condition or make any attempt to deceive participants into believing they consumed alcohol in the no-alcohol dosing session. Therefore, participants in the current study were aware of when they did and did not receive alcohol at the time of dosing. In some studies, a placebo group is helpful in eliminating potential expectancy effects of receiving alcohol on driving and performance-related tasks (e.g., Kenntnre-Mabila et al., (*2015a, c, e; Mets et al., 2011; Weafer et al., 2008; Laude & Fillmore, 2015; Marczinski & Fillmore 2009*); however, placebo conditions tend to only be effective when the active alcohol condition targets a lower BrAC (and produces less salient intoxication effects; *Martin & Sayette, 1993*). Given the relatively high BrAC used in the current study and the stark differences in perceived intoxication between 0.00 and the target doses, a true placebo would not be effective in deceiving participants into believing that they have consumed alcohol and were deemed unnecessary. This also allowed research staff and participants to anticipate and plan for the length of each session.

3.3.1 Familiarization session

The first session is a familiarization session, which is common among alcohol and driving simulation studies to avoid potential confounds in driving performance related to first exposure to the driving simulator and other kinds of devices. During this session, participants were provided with and signed the informed consent. After that, the researchers verified inclusion criteria (relevant drinking history, driver's license status, age, etc.), which were self-reported by participants during the screening process and collected relevant demographic information. Two eye tests - standard visual acuity test and color blindness - were prepared for participants to ensure they had at least a minimal level of acceptable vision (20/40 and not color blind).

Participants were next given an opportunity to get familiar with all the devices used in the testing session. First, participants learned how to blow the breathalyzer. After that, participants were required to wear the eye-tracking system and complete the training scenario on the driving simulator. Finally, participants became familiarized with the Go/No-Go and Grooved Pegboard task, which were commonly applied in previous alcohol and driving simulator studies (*Van Dyke & Fillmore, 2014, 2017*). The Go/No-Go test is used to assess inhibitory control, which has been shown to be related to impulsive decision-making and behaviors. The Grooved Pegboard Task is a behavioral task used to assess motor coordination. Both tasks served as a validity check for the study. The results can be used to compare the driving simulator performance, motor control, and inhibitory control between alcohol and non-alcohol sessions.

3.3.2 Testing sessions

The testing sessions contained the non-alcohol dosing session and alcohol dosing session. As a requirement for both sessions, participants were required to abstain from alcohol and all other drugs for 24 hours and food for 4 hours prior to each testing session. Sessions began with collecting a breath alcohol measurement to ensure that no alcohol had been consumed prior to the session. For the alcohol session, the participant's weight was measured at the beginning of the session to calculate the amount of alcohol consumption. The alcohol dose was calculated based on body weight and administered as one part absolute alcohol (95% alc/vol) mixed with three parts carbonated lemon/lime flavored soda. Participants consumed each dose in 10 minutes. The target 0.12 BrAC was typically reached 60–70 min after consumption. BrACs were sampled every 10 minutes until participants were within 0.01 of the target BrAC, at which time testing began. In the no-alcohol condition, participants consumed the same volume of liquid as the alcohol dose session to standardize the procedure across both sessions, but with no alcohol in the beverage.

For both alcohol and non-alcohol sessions, the participants were required to complete three testing scenarios in counterbalance order with the eye-tracking glasses. The real-time BrAC level was measured at the beginning of each scenario. After completing driving simulator tasks, they completed the Go/No-Go Task and the Grooved Pegboard Task to assess inhibitory control and measure motor coordination, respectively.

For safety reasons, after completing all required procedures, participants were required to stay in the lab for approximately 5 hours after consumption of their alcohol dose and until their BrAC was below .03. Participants would then have the option of leaving the lab with a friend or by having the research personnel obtain a ride for them (e.g., Uber or other services) to take the participant home. In either case, research personnel escorted the participant to the parking lot to ensure that the participant had entered the correct vehicle. Before leaving the laboratory, participants were able to lounge in a room with access to video games, television and streaming services, and a comfortable chair to sit in. Food and beverages were also provided.

CHAPTER 4 DATA COLLECTION AND ANALYSIS

This chapter provides detailed information regarding data collection and analysis methods used to evaluate the effectiveness of TCD(s) on driving behaviors. Two types of data were collected for this study, including eye-tracking data and driving-simulator data.

4.1 Data Collection

4.1.1 Eye-Tracking Data

The eye-tracking device used in this study recorded the participant's gaze with a sampling rate of 50 Hz, meaning it captured 50 individual gaze points per second. The gaze points show where the eyes are looking. If a series of gaze points are very close to each other in time and/or space, the cluster of gaze points forms a fixation, indicating that the eyes are locked on an object (*Farnsworth, 2022*). The eye-tracking device can deliver the video output data containing the driver's fixation point denoted as a red circle for each scenario during each session. As a result, a total of 210 videos were collected in the study.

After that, 180 videos, excluding training session videos, were transferred into the data analysis software named *Tobii Pro Lab* (*Tobii AB, 2014*) for further data reduction, which then contained more than 1,500 minutes of videos. The TCD(s) included in the video data can be regarded as dynamic stimuli since they constantly change (from small to large and from far to close). As a result, mapping procedures were conducted to aggregate participants' fixation points on the static snapshots that contain the target TCD(s). During the mapping procedures, two criteria need to be determined for the study:

- Time of Interest (TOI) allows researchers to organize the recorded data according to intervals of time during which meaningful behaviors and events take place (*Tobii Academy, 2022*). For this study, the TOI was defined as a period that starts when the TCD can be first seen on TV monitors and ends when the participant makes either a correct (a left/right turn going the right way) or wrong (a straight movement going the wrong way) decision. The researchers ensured that each TOI has a similar period within each scenario. **Table 4.1** lists the average TOI for proposed TCD(s) under different conditions.

Table 4.1 Average TOI for Proposed TCD(s) under Different Conditions

Scenario	TCD	TOI (s)	
		NONALC	ALC
1	DNEWW	27.94	28.48
	WW	21.28	20.94
	WWFlashing	22.34	21.51
	DRS	13.36	12.41
	RRPM	19.29	17.24
	LaneAlert	17.95	17.24
2	MUTCD	26.90	25.86
	CAMUTCD	24.10	24.01
3	WW+DRS	13.01	13.43
	WW+LaneAlert2X	13.06	13.42
	WW+RRPM	13.73	14.50
	WWFlashing+DRS	15.37	14.71
	WWFlashing+LaneAlert2X	14.35	15.46
	WWFlashing+RRPM	14.55	15.25

- Area of Interest (AOI) allows researchers to define areas of the stimulus based on research needs (*Tobii Academy, 2022*), and by doing this, the eye movement on a defined area can be calculated precisely. For this study, the AOI was defined as a single TCD or a combination of TCDs.

Figure 4.1 provides an example of automatically mapping fixation points on the DNE/WW sign from the original video on the left to the right image using software. The researchers reviewed all automatically mapped fixation points and manually corrected any points that were not accurately mapped by the software.

Figure 4.1 Illustration of Mapping Fixation Points on Snapshot Images.

Once all fixation points within the defined Time of Interest (TOI) were mapped, the data matrices could be exported for selected participant conditions and Areas of Interest (AOIs). The software exported data in Excel format, containing several variables such as total interval, total fixation count, total fixation duration, and more. For each variable, a table was generated on the results for each AOI and participant. **Figure 4.2** illustrates an example of the output of fixation data in the defined seven AOI regions.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Normal															
2	**Total Fixation Duration**	**Participant**	**Conditions**	**Region1**	**Region2**	**Region3**	**Region4**	**Region5**	**Region7**	**Region 6**	**Average**	**Median**	**Sum**	**Total Time of Interest Duration**	**Total Recording Duration**	
3	Recording002	9	ALC	13.87	30.78		2.94	1.90	1.48	6.62	9.60	4.78	57.59	85.57	507.64	
4	Recording002	25	ALC	18.99	50.65	0.44	0.74		2.40	7.90	13.52	5.15	81.11	97.94	644.01	
5	Recording002	11	ALC	6.18	53.35	0.34	1.38	1.02	0.74	9.31	10.33	1.38	72.32	88.73	615.20	
6	Recording002	19	ALC	0.58	0.10	0.74		0.12		0.18	0.34	0.18	1.72	58.21	755.50	
7	Recording002	20	ALC	9.01	36.26		0.78	0.64	0.14	27.54	12.40	4.90	74.38	83.09	730.03	
8	Recording002	8	ALC	7.92	43.18	0.34	5.40	4.02	3.00	7.00	10.12	5.40	70.84	83.53	688.70	
9	Recording002	5	ALC	5.60	61.78					5.18	24.19	5.60	72.56	74.02	437.26	
10	Recording003	23	ALC	17.71	55.77		0.10	0.54		8.12	16.45	8.12	82.23	100.68	500.95	
11	Recording003	18	ALC	6.02	52.91		1.66	1.96	0.22	15.91	13.11	3.99	78.67	89.33	560.04	
12	Recording003	21	ALC	2.80	88.19					9.93	33.64	9.93	100.92	104.68	848.06	
13	Recording004	29	ALC	21.13	38.60	0.84	1.20	1.06	1.04	9.13	10.43	1.20	73.00	97.40	500.33	
14	Recording004	17	ALC	5.26	70.66		0.26	0.26	0.48	20.15	16.18	2.87	97.06	106.90	882.79	
15	Recording004	13	ALC		65.22		0.36	0.26		16.77	20.65	8.57	82.61	95.19	600.93	
16	Recording004	24	ALC	9.61	45.05	0.34			0.84	24.33	16.03	9.61	80.17	93.31	648.73	
17	Recording004	14	ALC	2.62	47.51	0.30	0.88	1.96	1.10	17.85	10.32	1.96	72.22	82.07	866.27	
18	Recording005	1	ALC	3.48	24.85				0.80	32.26	15.35	14.16	61.39	67.96	745.01	
19	Recording005	16	ALC	5.98	54.95	2.42	2.12	0.36	1.28	10.33	11.06	2.42	77.44	100.90	501.12	
20	Recording005	2	ALC	2.20	43.72		1.04		0.60	10.61	11.63	2.20	58.17	87.45	742.82	
21	Recording006	6	ALC	11.49	46.33	0.12			1.36	3.82	12.62	3.82	63.12	82.63	558.32	
22	Recording006	10	ALC	19.97	31.60		4.60		1.20	6.12	12.70	6.12	63.48	84.75	447.60	
23	Recording007	7	ALC	5.92	29.26		1.34		0.78	14.63	10.39	5.92	51.93	84.33	527.69	
24	Recording007	27	ALC	57.53			0.26	1.52	0.40	6.08	13.16	1.52	65.78	94.29	434.97	
25	Recording008	22	ALC	20.67	41.06	2.16	1.72	0.40		9.13	12.52	5.65	75.14	101.72	563.27	
26	Recording009	15	ALC	36.50	8.26		0.44	1.36	0.22	4.54	8.55	2.95	51.31	61.12	725.78	
27	Recording009	4	ALC	2.14	9.11	4.00	0.62	2.08	2.28	0.22	2.92	2.14	20.45	55.63	381.16	
28	Recording009	3	ALC	5.02	46.65	0.16	0.32			15.89	13.61	5.02	68.04	81.25	537.19	
29	**Average**			11.93	43.03	1.02	1.41	1.22	1.07	11.52	13.15	4.83	67.45	86.26	613.51	
30	**Share of Total Time (%)**			17.00	61.35	0.70	1.60	1.11	1.16	17.08						
31	**Percentage Fixated (%)**			96.15	96.15	46.15	76.92	61.54	73.08	100.00						
32	**Variance**			160.77	388.96	1.46	2.03	1.04	0.61	63.79	39.29	10.41	421.24	192.78	19805.68	
33	**Standard Deviation (n-1)**			12.68	19.72	1.21	1.43	1.02	0.78	7.99	6.27	3.23	20.52	13.88	140.73	
34																

Figure 4.2 Sample of the Eye-Tracking Data Output

4.1.2 Driving Simulator Data

The MiniSimTM V2.3 software was programmed to collect data on the vehicle's position, velocity, acceleration rate, brake force, and more. Data were collected at a rate of 60 Hz for each scenario, resulting in 60 data points in one second. All data files were saved as .daq files by the driving simulator. To extract the data, the ISAT software was used to open the .daq files and export data to a .csv file. Users could then select variables to export to an Excel file from the data export menu. **Figure 4.3** shows an example of driving simulator data output in .csv format.

	A	B	C	D	E	F	G	H	I	J	K
1	Frame Number	CFS_Accelerator_ Pedal_Position	CFS_Brake_ Pedal_Force	SCC_Lane_ Deviation param 1	SCC_Lane_ Deviation param 2	SCC_Lane_ Deviation param 3	SCC_Lane_ Deviation param 4	VDS_Eyep oint_Pos param 1	VDS_Eyep oint_Pos param 2	VDS_Eyep oint_Pos param 3	VDS_Veh _Speed
2	109005	0	121.3019028	0	0	0	0	-2927.797	-324.8471	8.2265808	6.35E-05
3	109006	0	121.3019028	0	0	0	0	-2927.797	-324.8471	8.2265808	6.35E-05
4	109007	0	121.3019028	0	0	0	0	-2927.797	-324.8471	8.2265808	6.35E-05
5	109008	0	121.3019028	0	0	0	0	-2927.797	-324.8471	8.2265808	6.35E-05
6	109009	0	121.3019028	0	0	0	0	-2927.797	-324.8471	8.2265808	6.35E-05
7	109010	0	121.3019028	0	0	0	0	-2927.797	-324.8471	8.2265808	6.35E-05
8	109011	0	121.3019028	0	0	0	0	-8905.902	-2012.897	3.6923637	0.002893
9	109012	0	120.8432159	1	-0.7714214	12	0	-8905.902	-2012.897	3.6922499	0.002462
10	109013	0	121.3019028	1	-0.7714161	12	0	-8905.902	-2012.897	3.692155	0.002003
11	109014	0	120.8432159	1	-0.7714124	12	0	-8905.902	-2012.897	3.6920813	0.001538
12	109015	0	121.3019028	1	-0.7714111	12	0	-8905.902	-2012.897	3.6920292	0.001084
13	109016	0	121.3019028	1	-0.7714112	12	0	-8905.902	-2012.897	3.6919972	0.000656
14	109017	0	121.3019028	1	-0.7714117	12	0	-8905.902	-2012.897	3.6919835	0.000275
15	109018	0	121.3019028	1	-0.7714115	12	0	-8905.902	-2012.897	3.6919861	0.000186
16	109019	0	121.3019028	1	-0.7714103	12	0	-8905.902	-2012.897	3.692003	0.000475
17	109020	0	121.3019028	1	-0.771408	12	0	-8905.902	-2012.897	3.6920326	0.000753
18	109021	0	121.3019028	1	-0.7714049	12	0	-8905.902	-2012.897	3.6920729	0.000993
19	109022	0	121.3019028	1	-0.7714013	12	0	-8905.901	-2012.897	3.6921221	0.001189
20	109023	0	121.3019028	1	-0.7713978	12	0	-8905.901	-2012.897	3.6921786	0.001343
21	109024	0	121.3019028	1	-0.7713944	12	0	-8905.901	-2012.897	3.6922405	0.001455
22	109025	0	121.3019028	1	-0.7713914	12	0	-8905.901	-2012.897	3.6923061	0.001527
23	109026	0	121.3019028	1	-0.7713889	12	0	-8905.901	-2012.897	3.6923736	0.001562
24	109027	0	120.8432159	1	-0.7713869	12	0	-8905.901	-2012.898	3.6924414	0.001562
25	109028	0	121.3019028	1	-0.7713856	12	0	-8905.901	-2012.898	3.6925081	0.00153
26	109029	0	121.3019028	1	-0.7713847	12	0	-8905.901	-2012.898	3.6925723	0.001471
27	109030	0	121.3019028	1	-0.7713842	12	0	-8905.901	-2012.898	3.6926329	0.001389
28	109031	0	121.3019028	1	-0.7713843	12	0	-8905.901	-2012.898	3.692689	0.001286
29	109032	0	121.3019028	1	-0.7713848	12	0	-8905.901	-2012.898	3.6927399	0.001168
30	109033	0	121.3019028	1	-0.7713856	12	0	-8905.901	-2012.898	3.6927849	0.001038
31	109034	0	121.3019028	1	-0.7713867	12	0	-8905.901	-2012.898	3.6928239	0.000899
32	109035	0	120.8432159	1	-0.7713897	12	0	-8905.901	-2012.898	3.6928572	0.000771
33	109036	0	120.8432159	1	-0.7713947	12	0	-8905.901	-2012.898	3.6928849	0.000635
34	109037	0	121.3019028	1	-0.7713993	12	0	-8905.901	-2012.898	3.6929061	0.000495
35	109038	0	121.3019028	1	-0.771403	12	0	-8905.901	-2012.898	3.6929206	0.000359

Figure 4.3 An Example of the Driving Simulator Data Output

Each .csv file represented one trip by one participant under a specific scenario and condition. As a result, 180 excel files (excluding the training session) containing driving data by 30 participants for three scenarios under both intoxicated and sober conditions were manually exported. As illustrated in **Figure 4.3**, each file contains 11 variables, such as real-time coordinates, brake force, and speed. Each row in the dataset represents one data point collected every 0.017 seconds (60 Hz). The total number of data points collected for each participant depends on their trip duration. For this study, a total of 5,506,580 data points were collected in the raw dataset.

4.2 Data Analysis Method

Descriptive statistics are a type of statistical analysis used to summarize and describe the main features of a dataset. They are used to provide an overview of the data and to identify any patterns, trends, or anomalies. In this study, descriptive statistics were used to summarize general information about the participants, such as age and BrAC levels. A heatmap is a visual representation of data that uses color-coding to show the intensity of values. In this study, a heatmap was used to visualize the drivers' fixation points, allowing researchers to see where drivers were looking on the screen during the simulation. A chi-square test is a statistical test used to compare the observed distribution of data with the expected distribution. In this study, a chi-square test was used to compare the distribution of fixation points in the seven regions between sober and alcohol-impaired conditions. MOEs, or measures of effectiveness, are used to evaluate the effectiveness of TCD(s). In this study, three MOEs were used: the number of WWD events, fixation durations, and brake response. These measures were used to assess the impact of different TCDs on driving behavior. T-tests and ANOVA tests are statistical tests used to compare the means of two or more groups. In this study, these tests were used to compare the fixation durations and brake response between sober and alcohol-impaired conditions. The detailed methods are described below.

4.2.1 Descriptive Statistics

Descriptive statistics can be regarded as the initial step for data analysis, which aims to provide an understanding of the basic features of the dataset (*Sheshkin, 2007*). Descriptive statistics were used to summarize the general demographic information on participants, such as age, race, visual acuity, and actual BrAC level, with the calculation of mean value, standard deviation (SD), and maximum and minimum values. Results from the Grooved Pegboard and Go/No-Go tasks, used to assess the behavioral effects of the administered alcohol, were also presented.

4.2.2 Distribution of Drivers' Fixation Points

The drivers' fixation points collected by eye-tracking device were used to compare the forward driving scene under sober and alcohol-impaired conditions. The researchers defined a TOI with no visual cue and TCDs on the roadway and then mapped fixation points for all participants under the same condition into one snapshot. A heatmap was then generated for sober and alcohol-impaired conditions, respectively. The heatmap aggregates the fixation points of all 30 participants in a static image over a certain period (*Tobii Connect, 2022*). It uses a scheme of different colors to depict the number of fixations on different AOIs (*Tobii Connect, 2022*). Colors were used on the heatmap to illustrate the number of fixations.

To compare the distribution of drivers' fixation points under sober and intoxicated conditions, seven regions were defined on the snapshot, and the percentage of total fixation points for each region was calculated. Finally, a chi-square test was performed to examine if there is a statistical difference in the distribution of fixation points between the two groups of drivers (sober vs. intoxicated) by the following equation:

$$\chi^2 = \sum_{i=1}^{I} \sum_{j=1}^{J} \frac{(Y_{ij}-E_{ij})^2}{E_{ij}}$$ **Equation 4-1**

Where,

$\chi^2 = Chi - square\ test\ statistic$

$Y_{ij} = Observed\ fixation\ count$

$E_{ij} = Estimated\ expected\ fixation\ count$

The result of the chi-square test is used to measure the discrepancy between the observed and expected fixation count statistics (*Spiegelman et al., 2011*). The greater the chi-squared value, the more considerable the discrepancy between groups (*Spiegelman et al., 2011*). For this study, the chi-square test was used to determine if the fixation points in the seven regions were dependent on driver conditions at a 95% confidence interval.

4.2.3 Effectiveness of TCD(s)

To evaluate the effectiveness of TCD(s), three measures of effectiveness (MOEs) were identified: i) the number of WWD incidents, ii) fixation durations and iii) brake response. These three criteria were used in some past driving simulator studies. The detailed analysis method was summarized as follows:

4.2.3.1 Number of WWD incidents

A WWD incident was defined as the driver not making a correct left/right turn at the T-intersection and entering the wrong way after passing through the WW-related TCDs (DNE/WW signs, etc.).

The number of WWD incidents was collected by reviewing the video data recorded by the eye-tracking device. Several past studies used it as a single criterion to evaluate the effectiveness of countermeasures (*Lin et al., 2017; Seitzinger et al., 2015)*. This study used the number of WWD incidents at each intersection as a critical MOE to evaluate the effectiveness of the TCDs installed at that location.

4.2.3.2 Fixation durations

Fixation duration, fixation point order, pupil size, sight angle, and other eye movement parameters have been applied to study the visual effect of the objects in many previous studies (*Jacob and Karn, 2003; Mele and Federici, 2012; Khan and Lee, 2019*). Past studies found that fixation duration, fixation frequency, and spatial distribution were significantly correlated with drivers' performance in driving tasks (*Reimer, 2009; Bian and Andersen, 2017*). Specifically, more complex cognitive activities are often accompanied by reduced eye movements, prolonged gaze duration, and reduced spatial distribution of gaze.

For this study, both the total and average fixation duration were used for the evaluation of installed TCD(s). The total fixation duration was defined as how long a participant spends on the object during the defined TOI (*Geisen and Bergstrom, 2017*). The total fixation duration may consist of single or multiple fixations on the same object. The longer total fixation duration indicates an area that generates more interest (Burridge, 2014). In other words, the TCD(s) with longer total fixation duration indicated that they generate more attraction to the drivers. The average fixation duration refers to the average time for each fixation. Average fixation duration is associated with processing. A longer average fixation duration suggests increased complexity (*Tullis et al., 2013*; *Geisen et al., 2017*).

The data exported from the Tobii Pro Lab software contains the total and average fixation durations. For this study, a small percentage of participants were excluded from the analysis because the eye-tracking device did not correctly capture their eyeball movements, resulting in fewer or no fixation point data. **Table 4.2** lists the sample size (# of participants) collected for each TCD under sober (NONALC) and intoxicated (ALC) driving conditions.

In this study, independent samples t-tests and the Analysis of Variance (ANOVA) tests were used to compare the total fixation duration and average fixation duration on the TCDs by a group of drivers under two conditions. The independent samples t-test compares the means of two unrelated datasets (*Field et al., 2012*). Before applying the t-test, a Shapiro-Wilk test should be conducted to check the normality of the data. If the data did not satisfy the assumptions of normality, the non-parametric test- the Mann-Whitney U test- should be used to replace the t-test. ANOVA is used to compare the means among three or more groups. Tukey's multiple comparison tests were conducted to compare all possible pairs of means and identify any difference between the two means.

Table 4.2 Eye-Tracking Data Sample Size for Each TCD(s)

Scenario	TCD(s)	Sample Size	
		NONALC	ALC
Single TCD	DNEWW	27	26
	WW	27	25
	WWFlashing	27	25
	DRS	24	20
	RRPM	22	23
	LaneAlert	21	19
MUTCD VS. CAMUTCD	MUTCD	28	26
	CAMUTCD	26	25
Sign & Pavement Marking Combination	WW+DRS	26	26
	WW+LaneAlert	26	27
	WW+RRPM	26	27
	WWFlashing+DRS	26	27
	WWFlashing+LaneAlert	26	27
	WWFlashing+RRPM	26	27

4.1.3.3 Hard brake response distance

The hard brake response distance was used in several past studies to analyze the driver's reaction to specific TCDs (*Lin et al., 2017; Seitzinger et al., 2015*). The results suggest that the TCDs that increase the brake response distance are more effective in improving safety. This study selected the hard brake response distance as the third MOE to evaluate the effectiveness of TCD(s). The brake application status data with "1" (brake applied) and "0" (brake not applied) was first downloaded from the driving simulator. The variable "brake force" was recorded as the force applied on the brake pedal. This study analyzed the brake status and brake force between 1,000 ft before the TCD(s) and 300 ft after the TCD(s). The percentage of drivers who applied the brake can be calculated at different distances.

Based on the brake force data, the hard brake response can be estimated as 5% of the maximum force (180 lbs), which is approximately 10 lbs, according to past literature (*Lin et al., 2017*). As a result, the hard brake distance is the corresponding distance that the driver applied a hard brake before the TCD(s). The participants who did not use the hard brake were removed for further analysis. **Table 4.3** lists the sample size based on the hard brake status for each TCD(s) under both conditions.

Table 4.3 Driving Simulator Data Sample Size for Each TCD(s)

Scenario	**TCD(s)**	**Sample Size**	
		NONALC	**ALC**
Single TCD	DNE/WW	22	22
	WW	21	21
	WWFlashing	20	20
	DRS	14	14
	RRPM	19	19
	LaneAlert	17	17
MUTCD VS. CAMUTCD	MUTCD	23	23
	CAMUTCD	23	23
Sign & Pavement Marking Combination	WW+DRS	26	26
	WW+LaneAlert	24	24
	WW+RRPM	23	23
	WWFlashing+DRS	22	22
	WWFlashing+LaneAlert	23	23
	WWFlashing+RRPM	23	23

The paired-sample t-test and ANOVA test were applied to analyze the hard brake response distance data to determine if there is a significant difference between sober and intoxicated drivers and among TCD(s) under the same condition. Additionally, Tukey's multiple comparison tests were conducted to examine whether the groups' differences were significant.

CHAPTER 5 RESULTS AND DISCUSSIONS

This chapter summarizes the results of the driving simulator study in three sections: i) general information about participants, such as age and the BrAC level; ii) results on drivers' fixation point distribution for sober and intoxicated conditions; iii) results on the effectiveness of TCDs based on the driving simulator and eye-tracking data.

5.1 General Information

Six hundred eighty individuals completed the online screening survey, and 83 were qualified and contacted to participate in the lab session. Finally, 30 of them completed all three lab testing sessions. Their average age was 25, with a standard deviation (SD) of 7. The ages ranged from 21 to 59. The average visual acuity was 20/18.

The target BrAC level for this study was set to 0.12 g/dL. Based on the online screening survey results, the average self-reported BrAC for study eligibility was estimated as 0.19 g/dL, calculated according to participants' self-reported drinking activities. The researchers reviewed BrAC level data measured immediately before each testing scenario started and computed the average BrAC level for each scenario. **Table 5.1** contains the descriptive statistics on the overall BrAC level.

Table 5.1 Overall BrAC Level Descriptive Statistics

Scenario	Target Level (g/dL)	Average (g/dL)	SD (g/dL)	Minimum (g/dL)	Maximum (g/dL)
1	0.12	0.109	0.04	0.012	0.177
2	0.12	0.107	0.04	0.017	0.173
3	0.12	0.113	0.04	0.007	0.179

As shown in the table, the average BrAC level for scenarios 1, 2, and 3 were 0.109 g/dL, 0.107 g/dL, and 0.113 g/dL, respectively. The SD for each scenario was 0.04. The average BrAC level for this study was very close to the target level. **Table 5.1** also shows the maximum and minimum BrAC levels obtained during the lab testing. It should be noted that the minimum BrAC level of 0.007 was for one participant who became sick after the first dose of alcohol.

The Grooved Pegboard and Go/No-Go tasks were collected to validate the obtained BrAC results by confirming behavioral differences between the alcohol and non-alcohol sessions. Both tasks were administered after the completion of all driving scenarios. Participants performed significantly slower on the Grooved Pegboard in the alcohol condition (m = 88.08 s) compared to training (72.25 s) and non-alcohol sessions (67.01 s), with $p < .001$, effect size = .492, observed power = 1.00. Participants also had significantly slower reaction time on the Go/No-Go task in the alcohol condition (m = 1158.05 ms) compared to training (1148.85 ms) and non-alcohol sessions (976.24 ms), $p < .001$, effect size = .236, power = .947. The results on both tasks confirm that participants' fine motor coordination and reaction time were negatively impacted during the alcohol sessions.

5.2 Fixation Point Distribution for Sober and Intoxicated Drivers

One past study found that alcohol-impaired drivers were more likely to focus on pavement surfaces (*Finley et al., 2014*). In this study, the heatmap was developed to visualize drivers' fixation point distribution for both sober and alcohol-impaired conditions, as shown in **Figure 5.1.**

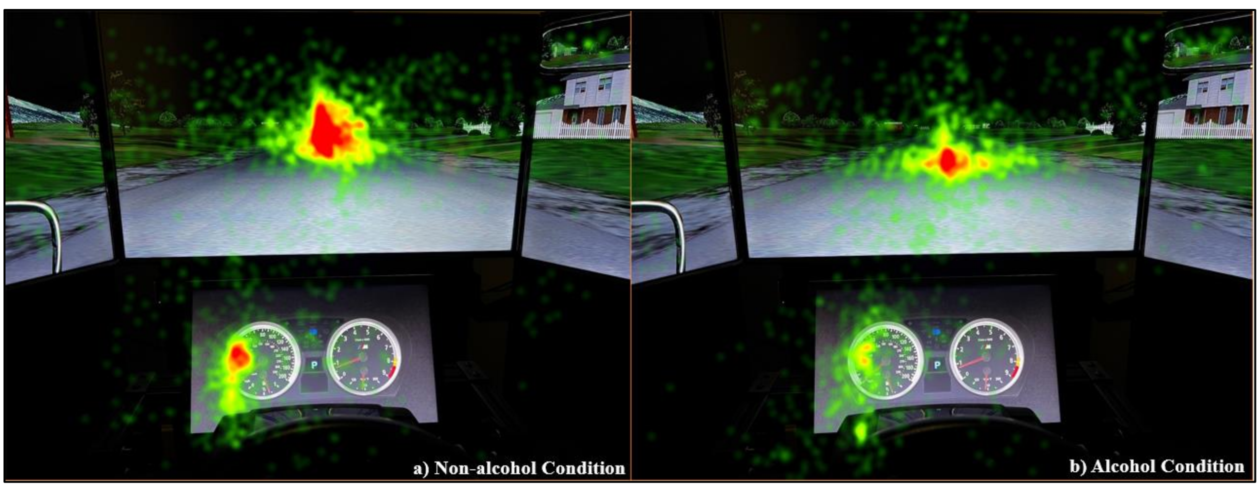


Figure 5.1 Drivers' Fixation Distribution Heatmap under a) Non-alcohol and b) Alcohol

The heatmaps aggregated the drivers' fixation points to help visualize the fixation distribution when there is no TCD installation. The colors such as red and yellow indicate the areas that attracted more fixations. The figure reveals that alcohol-impaired drivers' concentration areas are closer to the pavement surface than those of sober ones.

A three-step approach was applied to examine if there is a significant difference between alcohol-impaired and sober drivers' fixation distribution, including i) defining seven regions in front of the driver, ii) estimating the percentage of the fixation points in each region, and iii) conducting a chi-square test to determine if the distribution of fixation points in the seven regions are statistically different between the two groups.

Figure 5.2 illustrates the seven regions in the driver's front view. Region 1 indicated the area in front of the vehicle inside the headlight illumination area. Region 2 showed the area of the far roadway horizon. Region 3 was above all other regions and included the sky area. Regions 4 and 5 included the area that contained left and right fixation points. Region 6 covered the vehicle's dashboard, and region 7 included the rear view mirror of the vehicle.

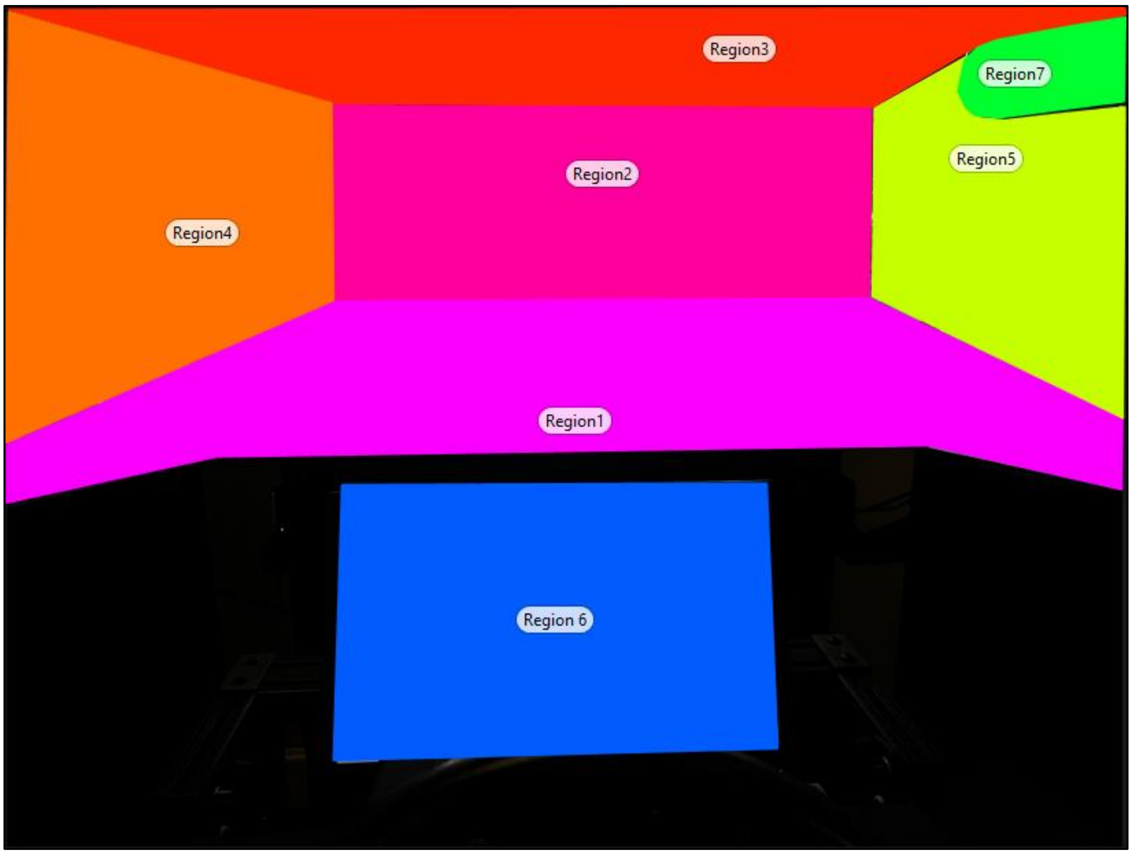


Figure 5.2 Defined Seven Regions for Fixation Distribution Analysis

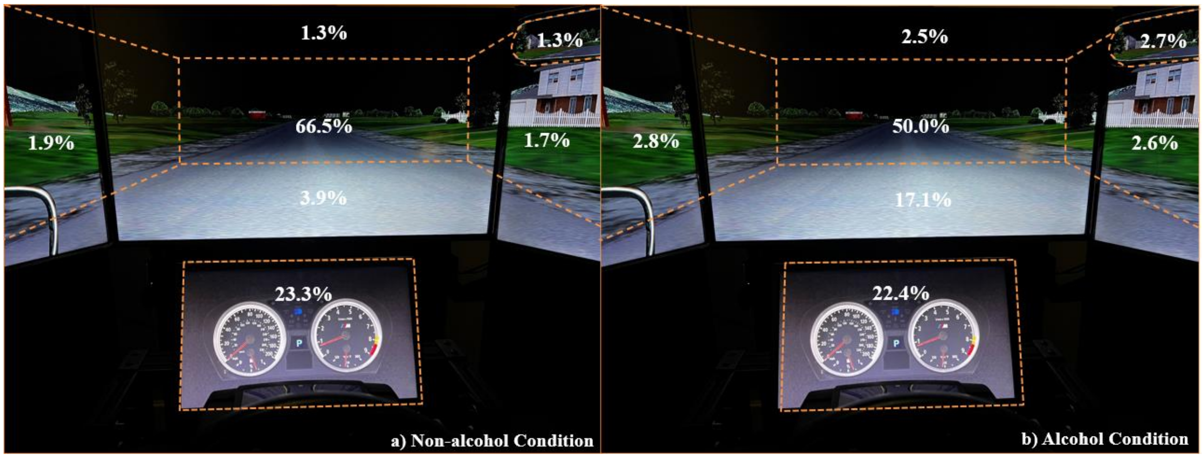


Figure 5.3 Percentage of the Fixation Point at Each Region Under a) Non-alcohol Condition; and b) Alcohol Condition

In **Figure 5.3**, it can be observed that alcohol-impaired drivers had a reduced percentage of fixation points at the far roadway horizon (Region 2) from 66.5% to 50%, while the percentage of fixation points above the front pavement area (Region 1) increased significantly from 3.9% to 17.1%. This suggests that intoxicated drivers tend to focus more on the pavement area in front of the vehicle, which is consistent with a previous field testing study *(Finley et al., 2014)*. Moreover, the percentage of fixation points in regions 3, 4, and 5 was higher under alcohol-impaired conditions (2.5%, 2.8%, and 2.6%, respectively) compared to sober conditions. This may be due to intoxicated drivers' slow eye movement and recognition capability, leading to them needing more time to check the surrounding condition, even without visual cues. This behavior was also observed in a previous Texas-based study (*Finley et al., 2014*), which suggested that participants were searching for signs.

The distribution of fixation points in the seven regions was analyzed using a bivariate chi-square test to determine if it was dependent on the drivers' condition (alcohol-impaired or sober). The test results showed that the chi-square value was 378.72 with six degrees of freedom and a p-value < 0.05, indicating a significant difference in the proportion of fixation points between alcohol-impaired and sober driving conditions.

5.3 Effectiveness for TCD(s)

In this study, three MOEs were analyzed to evaluate the effectiveness of TCD(s): the number of WWD incidents, fixation durations collected by the eye-tracking device, and bard brake distances collected by the driving simulator.

5.3.1 Number of WWD Incidents

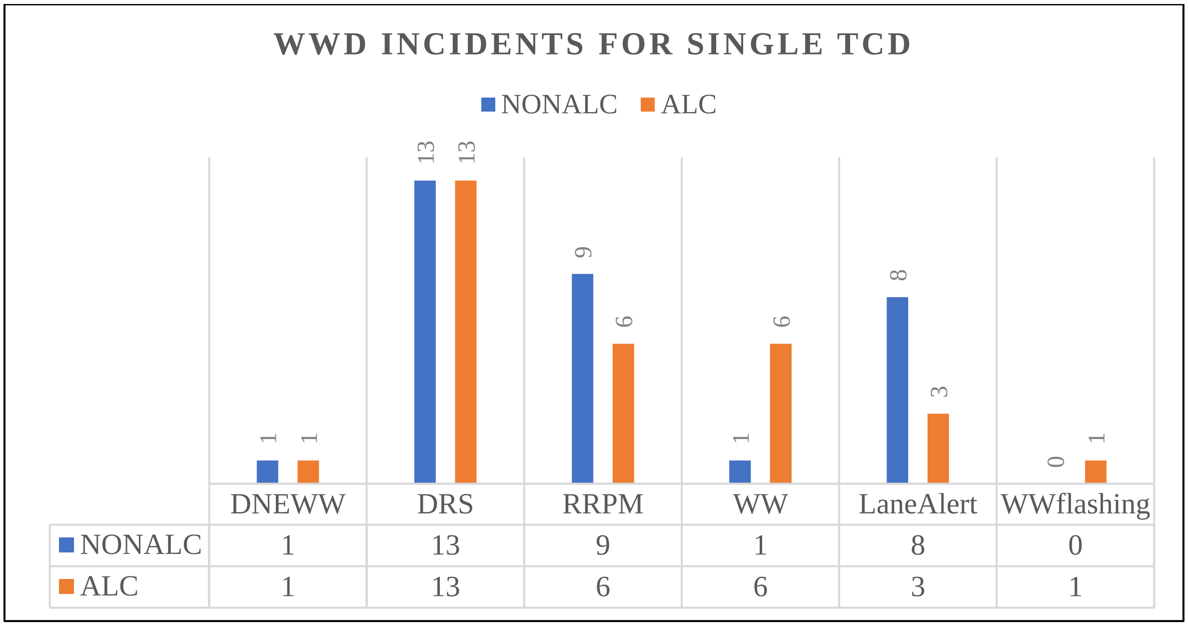


Figure 5.4 WWD Events for Single TCD Scenario

Figure 5.4 presents the results of the number of wrong-way driving (WWD) events detected during scenario one with single TCDs. A total of 62 WWD events were recorded, with 32 made by alcohol-impaired drivers and 30 by sober drivers. Among the three types of signs tested, DRS had the most WWD events due to its ability to generate sounds and vibrations to alert drivers of other regulatory/warning signs. The other two pavement markings, RRPM (15) and LaneAlert 2X (11), also had many WWD incidents. Notably, 67% of the WWD events related to these pavement markings were made by sober drivers, possibly because alcohol-impaired drivers tended to focus more on the pavement surface. In contrast, fewer WWD events were observed when drivers encountered single signs, especially under sober conditions. Of the three proposed signs, the WW sign had the highest number of incidents, with six out of ten being made by alcohol-impaired drivers. The DNE/WW sign and the WW sign with a flashing border had fewer incidents.

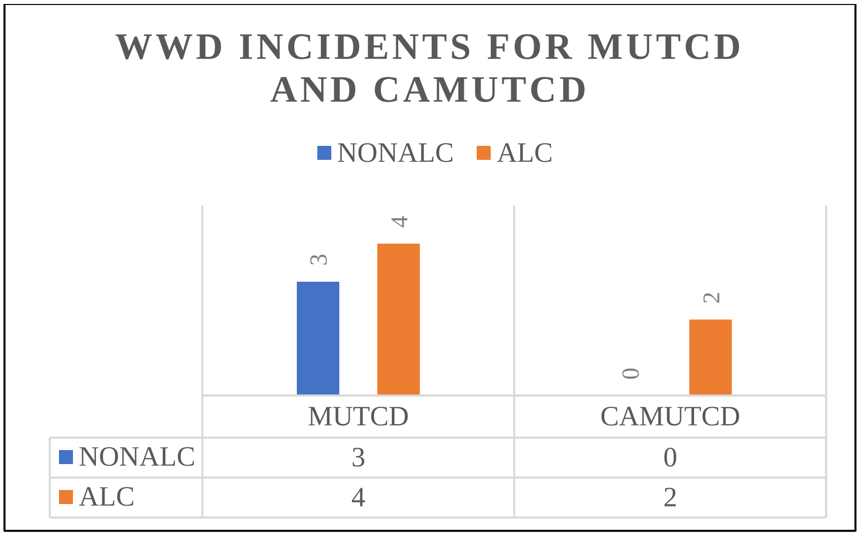


Figure 5.5 WWD Events for MUTCD and CAMUTCD

In **Figure 5.5**, the captured WWD incidents for scenario 2 (TCD combinations based on the MUTCD and the CA MUTCD) are presented. The TCD combination recommended by the MUTCD had a total of seven WWD events, with three incidents caused by sober drivers and four by alcohol-impaired drivers. However, for the TCD combination recommended by the CA MUTCD, no WWD incidents were recorded for sober drivers, and only two events were found for alcohol-impaired drivers. This suggests that the CA MUTCD-recommended TCD combination is more effective in preventing WWD events for both sober and alcohol-impaired drivers than the MUTCD-recommended TCD combination.

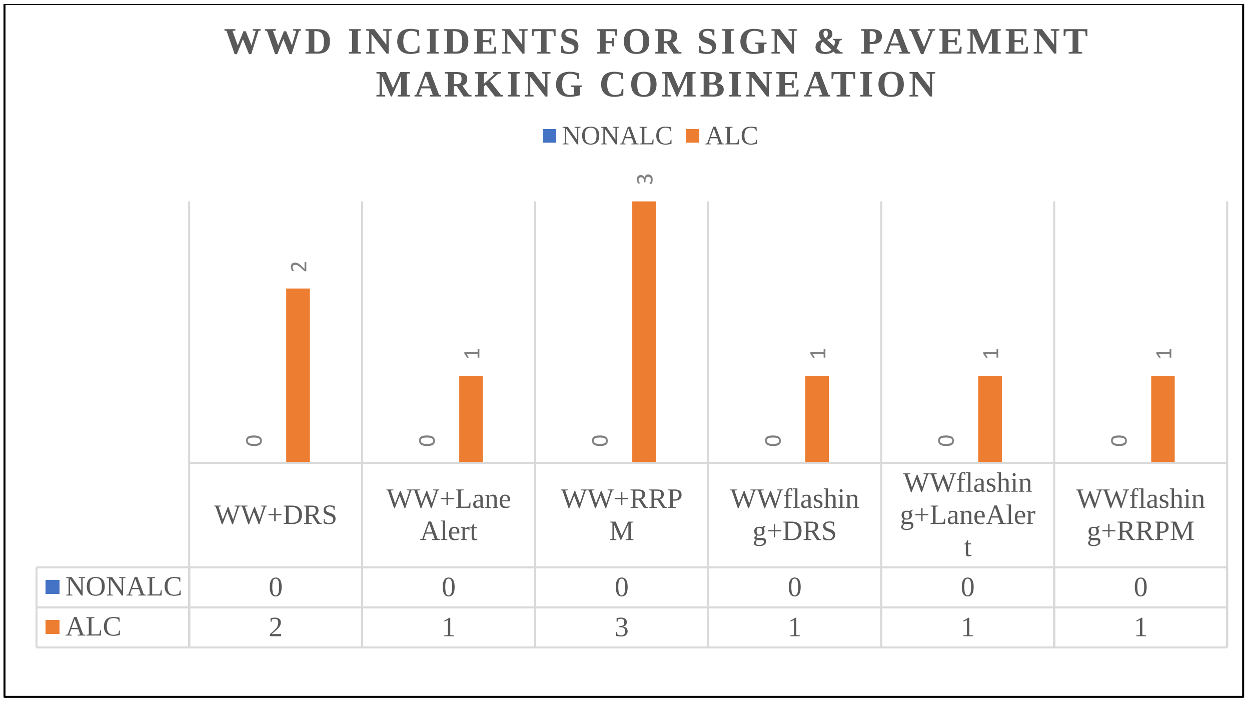


Figure 5.6 WWD Events for Sign and Pavement Marking Combinations

For scenario 3, six sign and pavement marking combinations were used, and the number of WWD events for each combination is shown in **Figure 5.6**. A total of nine WWD incidents were recorded by alcohol-impaired drivers, while sober drivers did not produce any WWD events. Among the nine WWD incidents by alcohol-impaired drivers, six of them occurred before the regular WW sign, while only three occurred before the WW flashing sign. This indicates that the WW sign with a flashing LED border had a greater potential to deter alcohol-impaired drivers from entering the WW.

5.3.2 Fixation Duration

The effectiveness of TCD(s) was evaluated using the average and total fixation durations as MOEs. The Shapiro-Wilk test was used to determine if the sample data followed a normal distribution. **Table 5.2** presents the p-values for the Shapiro-Wilk test conducted for three scenarios. The sample data is considered to have a normal distribution if the p-values are greater than 0.05. The p-values for total fixation durations are greater than 0.05, indicating that the sample data has a normal distribution. The independent t-test and ANOVA test were used to compare the total fixation durations between sober and intoxicated drivers. For average fixation duration, some p-values were less than 0.05, including RRPM and LaneAlert for sober drivers and DNEWW, WW, DRS, and RRPM for intoxicated drivers. The Mann-Whitney U-test was used to compare the average fixation duration on single TCDs between sober and alcohol-impaired driver groups, except for the WW flashing sign. Moreover, the Kruskal-Wallis test was used for group comparison, except for the sign group during non-alcohol conditions.

Table 5.2 Shapiro-Wilk Test Results for Each TCD(s)

Scenario	Variable	TCD	P-value	
			NONALC	ALC
Single TCD	Total Fixation Duration	DNEWW	0.117	0.267
		WW	0.330	0.612
		WW Flashing	0.732	0.112
		DRS	0.373	0.865
		RRPM	0.244	0.055
		LaneAlert	0.104	0.460
Single TCD	Average Fixation Duration	DNEWW	0.979	0.007
		WW	0.339	0.028
		WW Flashing	0.145	0.515
		DRS	0.128	0.005
		RRPM	0.048	0.000
		LaneAlert	0.004	0.087
MUTCD VS. CAMUTCD	Total Fixation Duration	MUTCD	0.379	0.189
		CAMUTCD	0.227	0.763
Sign & Pavement Marking Combination	Total Fixation Duration	WW+DRS	0.207	0.350
		WW+LaneAlert2X	0.338	0.3214
		WW+RRPM	0.116	0.524
		WW Flashing+DRS	0.659	0.641
		WW Flashing+LaneAlert2X	0.195	0.743
		WW Flashing+RRPM	0.229	0.092

5.3.2.1 Scenario 1 Single TCD

Based on Table **Table 5.3**, it can be seen that the mean total fixation duration for each TCD varies among non-alcohol and alcohol-impaired drivers. For non-alcohol drivers, the longest total fixation duration was observed for DNEWW (8.24 seconds), followed by WWFlashing (6.09 seconds), WW (5.35 seconds), RRPM (4.20 seconds), LaneAlert (2.88 seconds), and DRS (2.52 seconds). On the other hand, for alcohol-impaired drivers, the longest total fixation duration was observed for DNEWW (6.07 seconds), followed by WW (4.23 seconds), WWFlashing (4.20 seconds), DRS (2.47 seconds), LaneAlert (2.68 seconds), and RRPM (1.81 seconds).

The unpaired t-test results indicate that there are significant differences in total fixation duration between non-alcohol and alcohol-impaired drivers for DNEWW, WWFlashing, RRPM, and LaneAlert (p-value < 0.05). However, there is no significant difference in total fixation duration between non-alcohol and alcohol-impaired drivers for WW and DRS (p-value > 0.05).

Based on the bar chart in **Figure 5.7**, it can be seen that DNEWW has the highest total fixation duration for both non-alcohol and alcohol-impaired drivers, followed by WWFlashing, WW, RRPM, LaneAlert, and DRS. Additionally, the difference in total fixation duration between non-alcohol and alcohol-impaired drivers is larger for RRPM and DNEWW compared to other TCDs.

Table 5.3 Total Fixation Duration for Single TCD and T-Test Results

	NONALC		**ALC**		**T Stat**	**P-value**
	N	**Mean**	**N**	**Mean**		
DNEWW	27	8.24	26	6.07	2.80	0.0071*
WW	27	5.35	25	4.23	1.77	0.0828
WWFlashing	27	6.09	25	4.20	2.92	0.0052*
DRS	24	2.52	20	2.47	0.11	0.9138
RRPM	22	4.20	23	1.81	2.75	0.0088*
LaneAlert	21	2.88	19	2.68	0.42	0.67941
Note: * means that the p-value is less than 0.05.						

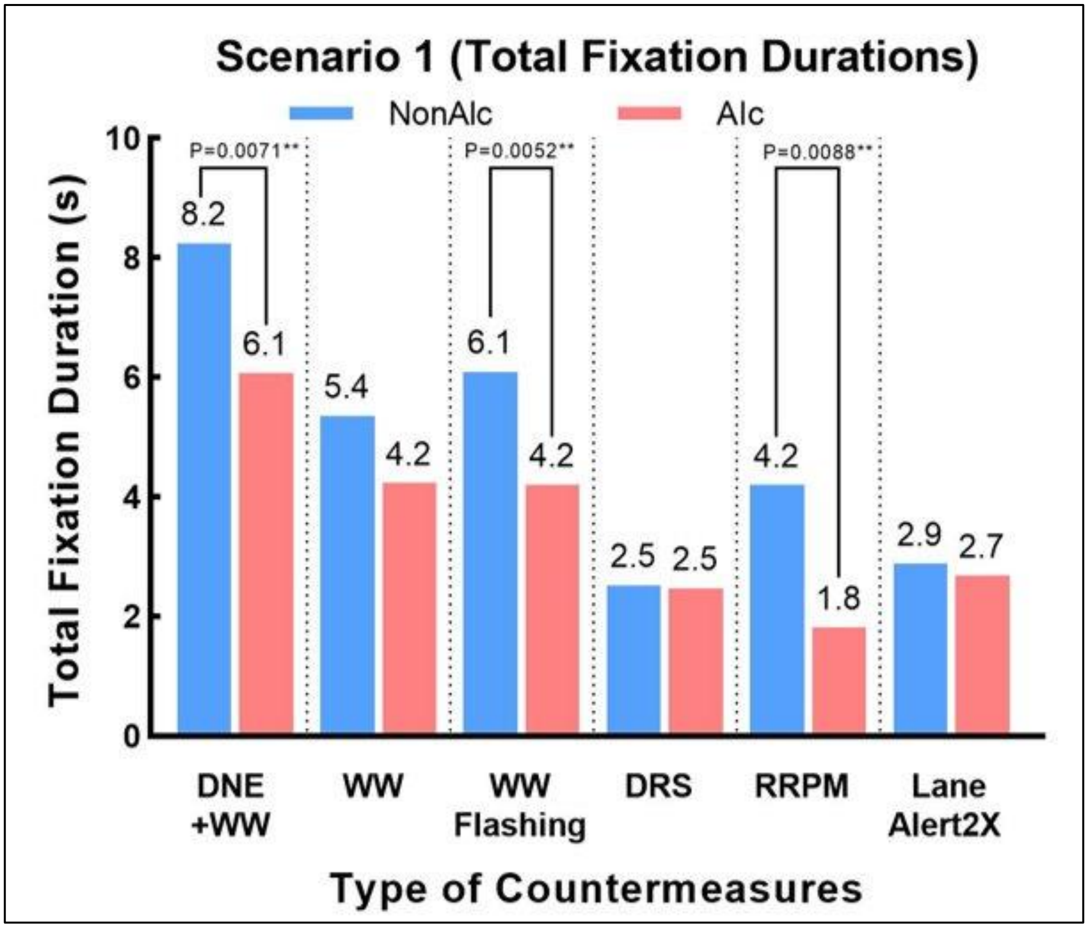


Figure 5.7 Total Fixation Duration for Single TCD

The total fixation duration represents the amount of time that a driver spends looking at a TCD, while the average fixation duration represents the average length of time that a driver fixates on a TCD before shifting their gaze to another object. By examining both metrics, researchers can gain insights into how much attention drivers are devoting to TCDs and how easily they are able to comprehend them. **Table 5.4** lists the number of observations, the mean value, and the Mann-Whitney U test results to compare the average fixation duration between sober and intoxicated drivers. The results suggest that intoxicated drivers have significantly longer average fixation durations on all the signs and markings (except RRPM) than sober drivers. **Figure 5.8** illustrates the Mann-Whitney U-test results in **Table 5.4** and an additional t-test for the WW flashing sign, indicating a statistically significant difference in average fixation duration on flashing signs between sober and impaired drivers.

Table 5.4 Average Fixation Duration for Single TCD and Mann-Whitney U Test Results

	NONALC		ALC		W	P-value
	N	Mean	N	Mean		
DNEWW	27	0.98	26	1.40	154.00	0.0003*
WW	27	0.84	25	1.63	126.5	0.0001*
DRS	24	0.75	20	1.28	121.00	0.0043*
RRPM	22	0.82	23	1.11	202.50	0.2566
LaneAlert	21	1.07	19	1.87	98.50	0.0054*
Note: * means that the p-value is less than 0.05.						

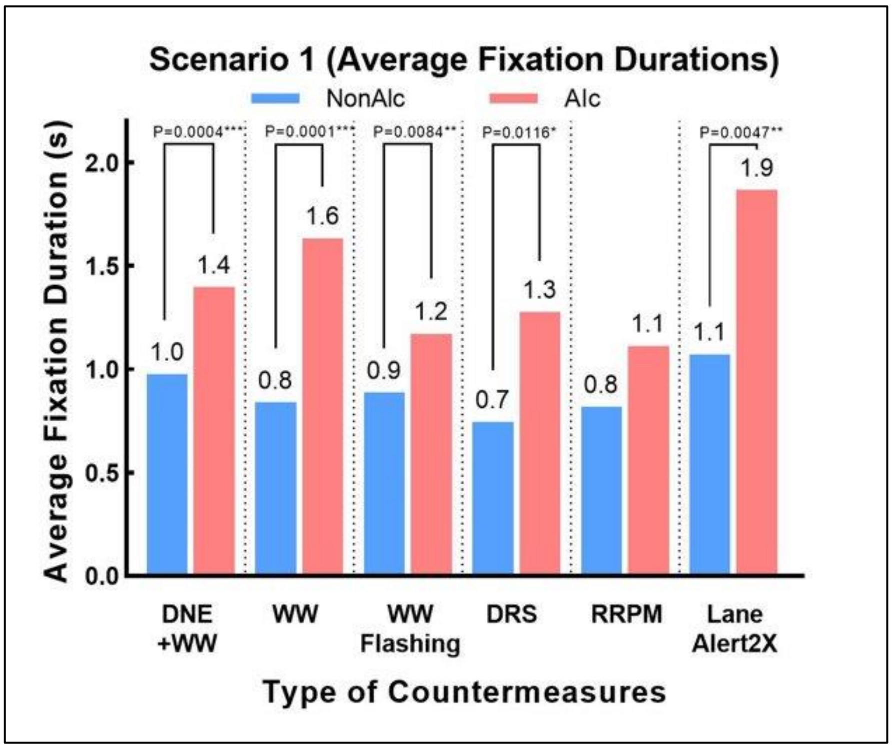


Figure 5.8 Average Fixation Duration for Single TCD

The Kruskal-Wallis test is a non-parametric test used to determine if there are differences among three or more groups. In this case, the test was used to compare the average fixation duration among signs for intoxicated drivers and among signs and pavement markings for sober drivers. Dunn's multiple comparisons test is a post-hoc test used to compare pairs of TCDs in each group after a significant Kruskal-Wallis result. The ANOVA (Analysis of Variance) test, on the other hand, is a parametric test used to determine if there is a statistically significant difference among three or more groups. In this case, the ANOVA test was conducted for the comparison among signs for sober drivers. The results of the ANOVA test can provide information about which group means are significantly different from each other. All of these tests are used to compare groups and determine if there are significant differences among them. The choice of test depends on the nature of the data and the research question being asked.

Table 5.5 lists the results of Kruskal-Wallis and Dunn's multiple comparisons tests. The Kruskal-Wallis test results indicated that there were no significant differences in average fixation duration among signs under alcohol-impaired conditions (p-value = 0.167) and among pavement markings under sober driving conditions (p-value = 0.1245). There was a statistically significant difference among pavement markings under alcohol-impaired conditions (p-value=0.0064). It appears that there is no significant difference among signs under sober conditions, according to the ANOVA result (F=1.14 and p-value = 0.325). Additionally, Dunn's multiple comparison tests suggested that the average fixation duration on RRPM is significantly different from LaneAlert for intoxicated drivers (P-value = 0.0055).

Table 5.5 Results of Kruskal-Wallis Test and Dunn's Comparison Test for Single TCD

Condition	Group	Kruskal-Wallis Stat	P-value	Dunn's Multiple Comparison Test			
				Comparison		Mean Rank Diff	P-Value
ALC	Signs	3.645	0.167	DNE	WW	-2.053	0.99
				DNE	WW Flashing	9.127	0.4199
				WW	WW Flashing	11.18	0.2202
NONALC	Pavement Markings	4.167	0.1245	DRS	RRPM	-3.144	0.99
				DRS	LaneAlert	-11.6	0.1392
				RRPM	LaneAlert	-8.451	0.4652
ALC	Pavement Markings	10.09	0.0064	DRS	RRPM	4.816	0.99
				DRS	LaneAlert	-12.6	0.0877
				RRPM	LaneAlert	-17.42	0.0055*

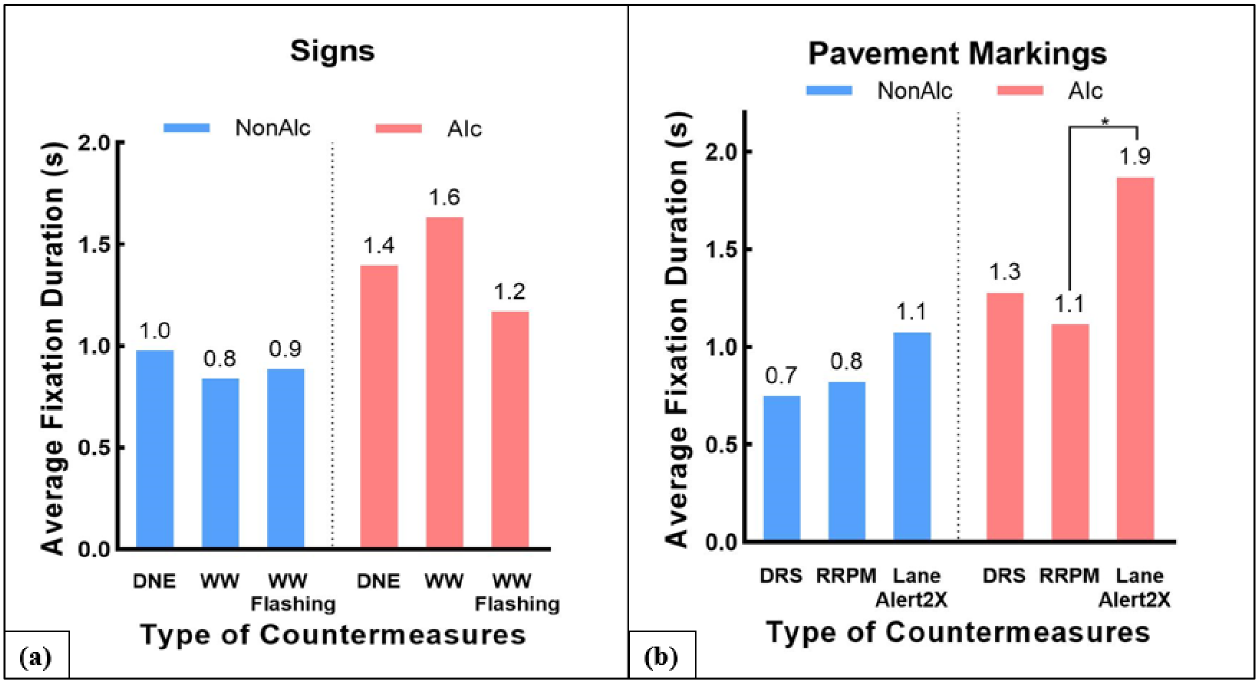


Figure 5.9 Results of Kruskal-Wallis and ANOVA Tests for a) Signs; and b) Pavement Markings

Figure 5.9 illustrates the Kruskal-Wallis and ANOVA test results. It was found that sober drivers spend a similar average fixation time on signs (1.0 seconds on the DNE sign, 0.8 seconds on the WW sign, and 0.9 seconds on the WW flashing sign). Intoxicated drivers had longer average fixation durations on signs (1.4 seconds on the DNE sign, 1.6 seconds on the WW sign, and 1.2 seconds on the WW flashing sign). It should be noticed that WW flashing signs reduced the average fixation duration for intoxicated drivers by 0.4 seconds compared to WW signs. Similar trends were found for pavement markings. It should be noted that the average fixation duration for the LaneAlert increased dramatically from 1.1 seconds for sober drivers to 1.9 seconds for intoxicated drivers.

5.3.2.2 Scenario 2: MUTCD and CAMUTCD Signs

Table 5.6 lists the number of observations, the mean value, and the unpaired t-test results for TCD combinations in scenario 2. **Figure 5.10** compares the mean value of total fixation duration between sober and intoxicated drivers. The results suggest that the CA MUTCD-required sign combination increased both sober and drunk drivers' entire fixation duration from 8.03 and 3.05 seconds on the MUTCD-required combination to 9.13 and 5.27 seconds. The unpaired t-test was conducted, and the results indicate significant differences in the total fixation duration between alcohol-impaired and sober driving conditions for both the MUTCD and CA MUTCD-required sign combinations (p-value = 0.0001).

Table 5.6 Total Fixation Duration between MUTCD and CA MUTCD Signs

	NONALC		ALC		T Stat	P-value
	N	**Mean**	**N**	**Mean**		
MUTCD	28	8.04	26	3.05	6.16	<0.0001*
CA MUTCD	26	9.13	25	5.27	4.49	<0.0001*
Note: * means that the p-value is less than 0.05.						

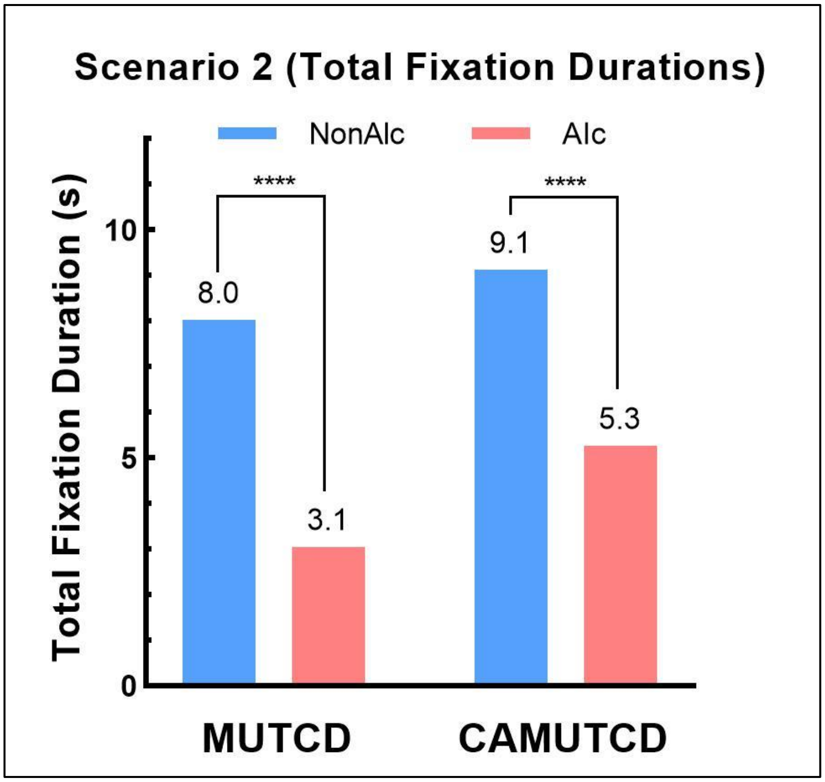


Figure 5.10 Total Fixation Duration Between MUTCD and CA MUTCD Signs

Table 5.7 T-Test Results for the MUTCD and CA MUTCD Sign Comparison

	Comparison		T Stat	P-Value
NONALC	MUTCD	CA MUTCD	1.053	0.2972
ALC	MUTCD	CA MUTCD	4.318	<0.0001*
Note: * means that the p-value is less than 0.05.				

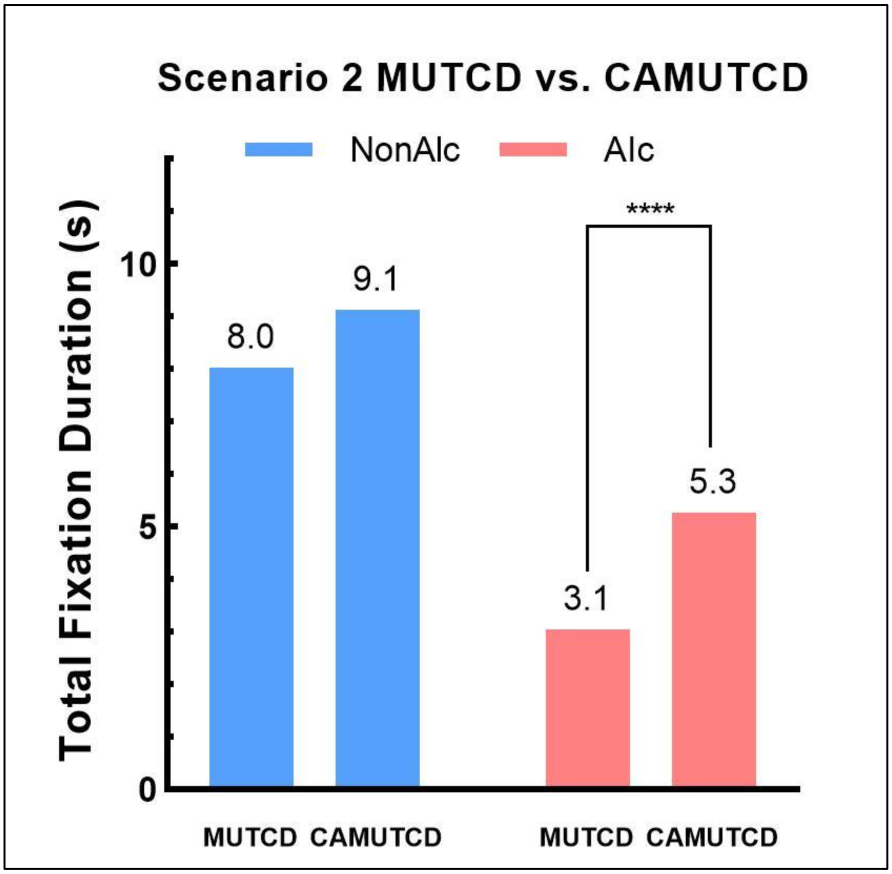


Figure 5.11 T-Test Results for MUTCD and CA MUTCD Sign Comparison

Another unpaired t-test was conducted to examine if there is a significant difference in the total fixation duration between the MUTCD and CA MUTCD-required sign combinations. The results are listed in **Table 5.7** and **Figure 5.11**. The results indicate a statistically significant difference in total fixation duration between MUTCD and CA MUTCD combinations for intoxicated drivers; however, no statistically significant difference in total fixation duration for sober drivers.

5.3.2.3 Scenario 3: Combination of TCDs

Table 5.8 lists the number of observations, the mean value of total fixation duration, and the unpaired t-test results on the difference between the two driving conditions for all combinations of TCDs. The overall results indicate that sober drivers had longer total fixation duration on all combinations of TCDs than alcohol-impaired drivers, which is consistent with the previous results for scenarios 1 and 2. The data analysis indicates that the WW flashing sign and DRS had the longest total fixation duration for intoxicated drivers. The WW flashing sign and RRPM combination had the greatest total fixation duration for sober drivers. **Figure 5.12** compares the total fixation durations by sober and intoxicated drivers for each combination of TCDs.

Table 5.8 Total Fixation Duration for Sign and Pavement Marking Combinations

	NONALC		ALC		T Stat	P-value
	N	Mean	N	Mean		
WW+DRS	22	2.77	18	2.14	1.87	0.0694
WW+LaneAlert	23	2.70	19	1.80	2.53	0.0157*
WW+RRPM	26	2.31	24	1.58	2.00	0.0511
WWFlashing+DRS	25	3.28	23	**2.92**	0.74	0.4656
WWFlsfhing+LaneAlert	25	3.09	24	1.94	2.53	0.0148*
WWFlashing+RRPM	25	**3.44**	26	2.75	1.54	0.1291
Note: * means that the p-value is less than 0.05.						

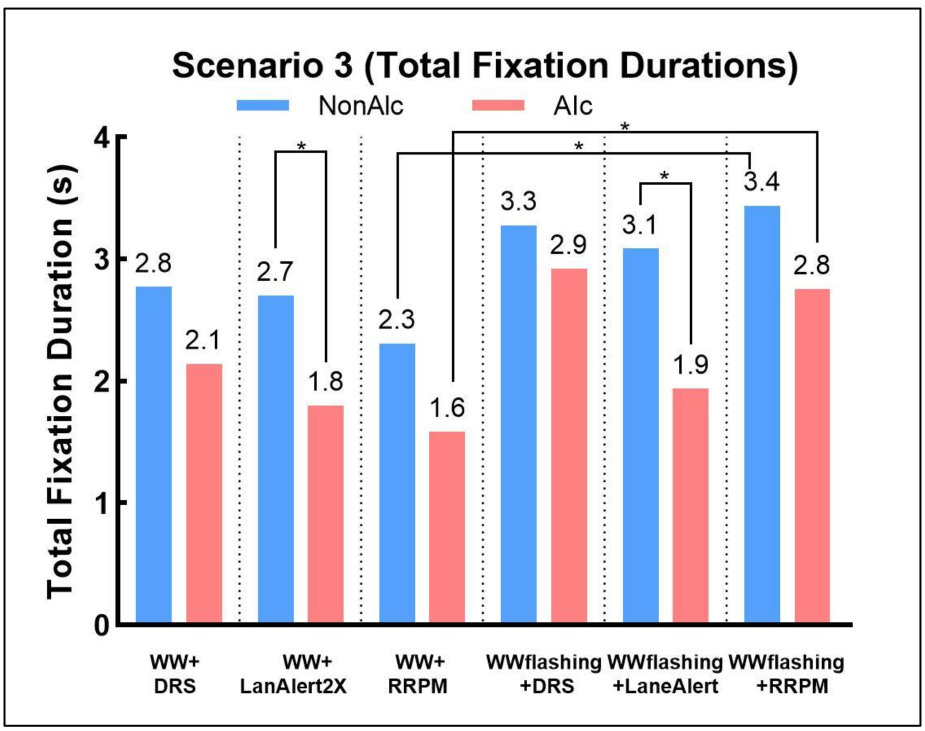


Figure 5.12 Total Fixation Duration for Sign and Pavement Marking Combinations

The unpaired t-test was applied to examine if there is a statistically significant difference in the total fixation duration between sober and alcohol-impaired driving conditions. The results suggest that the difference is significant at a 95% confidence level for two combinations of TCDs (WW sign and LaneAlert 2X combination and WW flashing sign and LaneAlert 2X combination), and the p-value for a combination of WW sign and RRPM is very close to the 0.05. The rest of the two WW flashing combinations had the longest total fixation durations but had no statistically significant difference between the two driving conditions.

The one-way ANOVA test was conducted to determine if there is a statistical difference among all three combinations in each group (WW sign and WW flashing sign). Tukey's multiple comparisons tests were then applied to compare two combinations within each group. The results of the ANOVA test and Tukey's multiple comparisons test are listed in **Table 5.9** and **Figure 5.13**.

The ANOVA test results indicate statistically significant differences among combinations with WW flashing signs under alcohol-impaired conditions ($p = 0.0461$). No significant difference in total fixation duration was found among other combinations. Tukey's multiple comparisons tests found a significant difference between the DRS and the LaneAlert with WW flashing sign combinations for alcohol-impaired drivers (p-value=0.05).

Table 5.9 Results of ANOVA Test and Tukey's Comparison Test for Sign and Pavement Combinations

Condition	Group	F	P-value	Tukey's Multiple Comparisons Test			
				Comparison		Mean Diff	P-Value
NONALC	WW	0.84	0.4352	DRS	LaneAlert	0.07	0.9836
				DRS	RRPM	0.46	0.4663
				LaneAlert	RRPM	0.39	0.5677
ALC	WW	1.84	0.1677	DRS	LaneAlert	0.34	0.5141
				DRS	RRPM	0.56	0.1428
				LaneAlert	RRPM	0.22	0.7276
NONALC	WWflashing	0.25	0.7806	DRS	LaneAlert	0.19	0.9215
				DRS	RRPM	-0.16	0.9456
				LaneAlert	RRPM	-0.35	0.7619
ALC	WWflashing	3.22	0.0461*	DRS	LaneAlert	0.98	0.05*
				DRS	RRPM	0.17	0.9134
				LaneAlert	RRPM	-0.82	0.117

Note: * means that the p-value is less than 0.05.

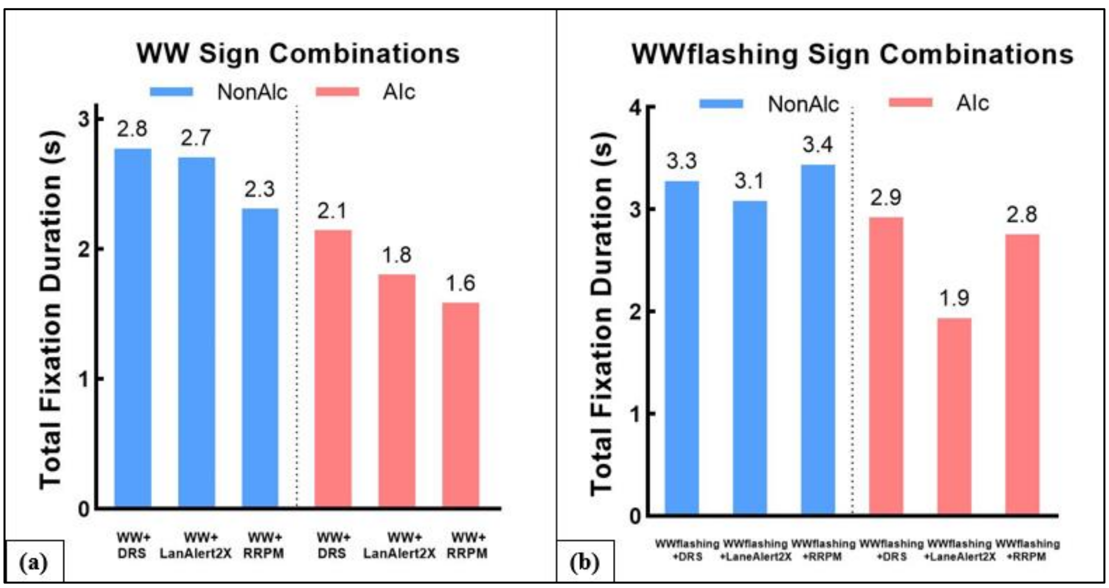


Figure 5.13 Results of ANOVA Test and Tukey's Comparison Test for a) WW Sign; and b) WW Flashing Sign

5.3.3 Analysis of Brake Usage

The brake usage data recorded by the driving simulator were downloaded for each scenario for further analysis. **Figure 5.14** shows an example of brake usage when drivers approach the

DNEWW and DRS TCDs for sober and alcohol-impaired conditions. The data shows that the DNEWW sign and DRSs could increase brake usage distance by intoxicated drivers to 400 feet from the intersection. **Appendix I** contains the braking usage data figures to visualize how participants applied the brake when approaching the TCD(s). **Table 5.10** summarizes the data on where most drivers applied the brake for each TCD (s).

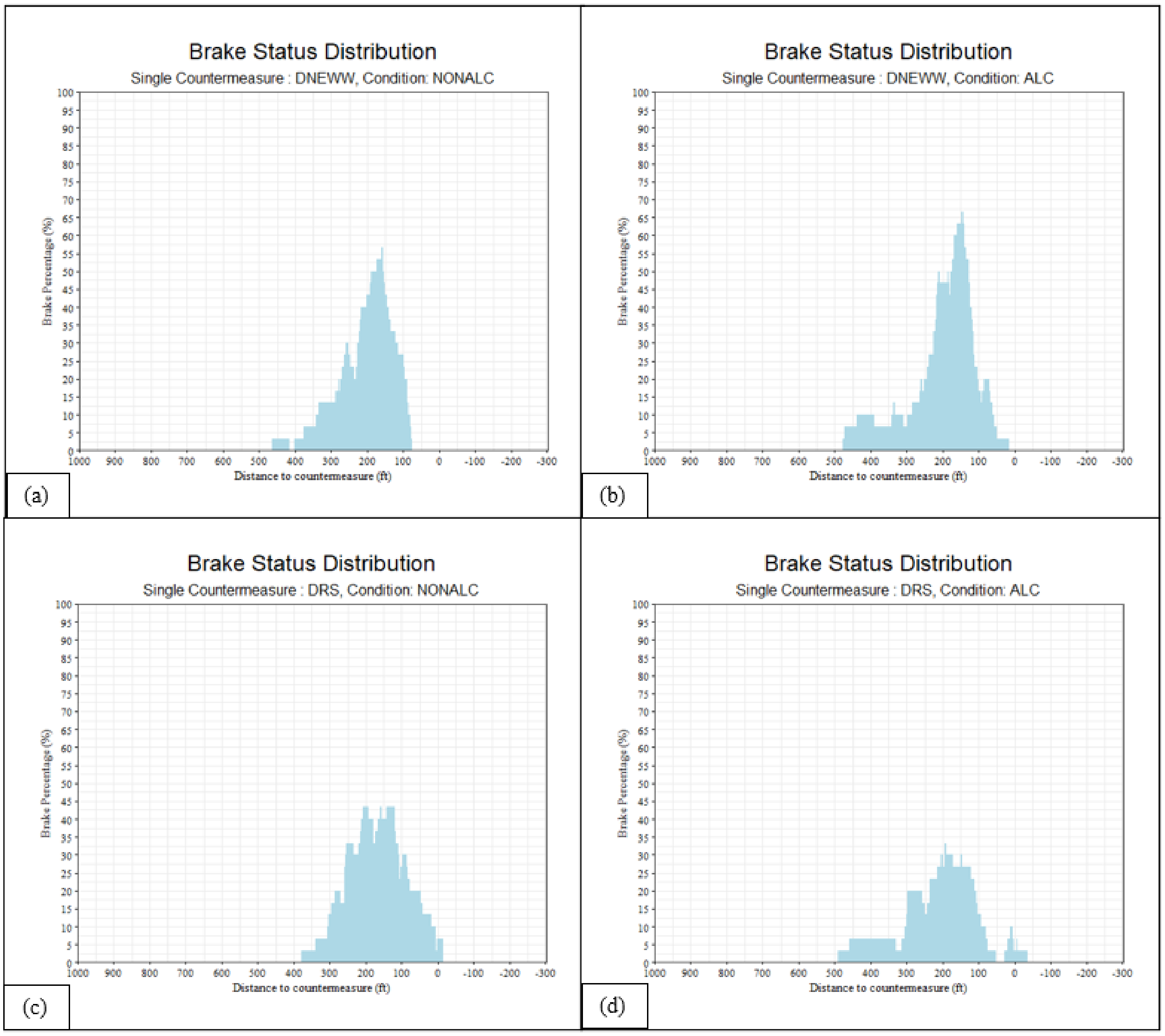


Figure 5.14 Examples of Brake Usage for DNEWW Sign and DRS

Table 5.10 Where Most of the Drivers Applied Brake

Scenarios	TCD (s)	NONALC		ALC	
		Distance to Countermeasure (ft)	Percentage of Drivers who Applied Brake	Distance to Countermeasure (ft)	Percentage of Drivers who Applied Brake
1	DNEWW	219	53%	201	46%
	WW	199	57%	167	60%
	WWFlashing	215	60%	231	60%
	DRS	176	63%	228	53%
	RRPM	215	70%	200	57%
	LaneAlert 2X	215	50%	186	43%
2	MUTCD	137	70%	208	63%
	CAMUTCD	179	60%	200	63%
3	WW+DRS	219	53%	201	46%
	WW+LaneAlert2X	215	60%	231	60%
	WW+RRPM	215	70%	200	57%
	WWFlashing+DRS	199	57%	167	60%
	WWFlashing+LaneAlert2X	215	60%	231	60%
	WWFlashing+RRPM	215	50%	186	43%

As shown in **Table 5.10**, for scenario 1, the WW flashing sign and DRS increased the braking distance from 215 ft. and 176 ft. by most sober drivers to 231ft. and 228 ft. by most intoxicated drivers, respectively. For scenario 2, the CAMUTCD signs increased the braking distance by 30% for most sober drivers compared to MUTCD signs. However, no significant change in the braking distance was found for intoxicated drivers. For scenario 3, the results reveal that the WW+LaneAlert2X and WWFlashing+LaneAlert2X combinations had the longest braking distance for intoxicated drivers (231 ft.) and sober drivers (215 ft.).

Additionally, hard-brake data were analyzed to identify if any TCDs can significantly increase intoxicated drivers' hard-brake response distance. The Shapiro-Wilk test was conducted to check if the data sample has a normal distribution, which is the precondition for applying the t-test and ANOVA test. **Table 5.11** lists the p-values for each TCD or TCD combination based on the Shapiro-Wilk test. It can be seen that all the p-values are larger than 0.05, which means the sample of hard-brake distances follows a normal distribution.

Table 5.11 Shapiro-Wilk Test Results for Hard Brake Distances

Scenario	Variable	TCD	P-value	
			NONALC	ALC
Single TCD	Hard Brake Distance	DNEWW	0.189	0.139
		WW	0.073	0.154
		WWFlashing	0.088	0.016
		DRS	0.398	0.349
		RRPM	0.157	0.374
		LaneAlert	0.368	0.338
MUTCD VS. CAMUTCD	Hard Brake Distance	MUTCD	0.895	0.681
		CAMUTCD	0.086	0.999
Sign & Pavement Marking Combination	Hard Brake Distance	WW+DRS	0.240	0.197
		WW+LaneAlert2X	0.083	0.9729
		WW+RRPM	0.290	0.709
		WWFlashing+DRS	0.267	0.647
		WWFlashing+LaneAlert2X	0.587	0.730
		WWFlashing+RRPM	0.583	0.113

Table 5.12 lists the sample size, mean value of hard brake distance, and paired t-test results for scenario 1. The results show that the WW flashing sign, DRS, and RRPM TCDs increased hard brake distances for intoxicated drivers compared to sober drivers by 10%, 16%, and 12%,

respectively. No change in hard brake distance was found for the WW sign and LaneAlert 2X TCDs. The Paired-Samples t-test results indicate no statistically significant differences in hard brake response distance between sober and intoxicated drivers for all six single TCDs in scenario 1.

Table 5.12 Paired T-Test Results on Hard Brake Distance for Scenario 1

	NONALC		ALC		T Stat	p-value	% Of Change
	N	Mean	N	Mean			
DNEWW	22	244	22	244	-0.02	0.98	0%
WW	21	266	21	262	0.17	0.87	0%
WWFlashing	20	253	20	279	-0.88	0.39	10%
DRS	14	228	14	265	-0.79	0.45	16%
RRPM	19	259	19	290	-1.43	0.17	12%
LaneAlert	17	258	17	256	0.07	0.95	0%
Note: * means that the p-value is less than 0.05.							

Table 5.13 Results of ANOVA Test and Tukey's Comparisons Test for Scenario 1

Condition	Group	F	P-value	Tukey's Multiple Comparisons Test			
				Comparison		Mean Diff	P-Value
NONALC	Signs	0.4281	0.6537	DNE	WW	-22	0.6285
				DNE	WW Flashing	-9	0.9242
				WW	WW Flashing	13	0.8588
ALC	Signs	0.68	0.5105	DNE	WW	-18	0.8233
				DNE	WW Flashing	-35	0.4782
				WW	WW Flashing	-17	0.8357
NONALC	Pavement Markings	0.5909	0.5578	DRS	RRPM	-31	0.5895
				DRS	LaneAlert	-30	0.619
				RRPM	LaneAlert	1	0.9992
ALC	Pavement Markings	0.7543	0.5758	DRS	RRPM	-25	0.6912
				DRS	LaneAlert	9	0.957
				RRPM	LaneAlert	34	0.4669

According to **Table 5.12**, under non-alcohol conditions, drivers have the longest hard brake response distance when facing the WW sign (266 ft) and have the shortest hard brake response distance when facing the DNEWW sign (244 ft). As for alcohol conditions, it was found that intoxicated drivers had the longest hard brake distance when facing the WW flashing sign (279 ft) and had the shortest hard brake distance when facing the DNEWW sign (244 ft). As for the pavement markings, intoxicated drivers had the longest hard brake distance when facing RRPMs, followed by DRSs and the LaneAlert TCD. However, there is no significant difference in the hard brake distance among sign and pavement marking groups for both sober and intoxicated conditions, as shown in **Table 5.13.**

Table 5.14 Paired T-Test Results on Hard Brake Distance for Scenario 2

	NONALC		**ALC**		**T Stat**	**p-value**
	N	**Mean**	**N**	**Mean**		
MUTCD	23	239	23	269	-1.45	0.16
CAMUTCD	23	250	23	246	0.26	0.80
Note: * means that the p-value is less than 0.05.						

Table 5.14 lists the sample size, mean value, and the paired t-test results on hard brake distance for scenario 2. The paired t-test results indicate no significant difference in the hard brake response distance between alcohol-impaired and sober drivers when facing these two types of combinations.

Table 5.15 Paired T-Test Results for MUTCD and CAMUTCD Combination

	MUTCD		**CAMUTCD**		**T Stat**	**p-value**
	N	**Mean**	**N**	**Mean**		
NONALC	23	239	23	250	-0.46181	0.65
ALC	23	269	23	246	1.096964	0.28
Note: * means that p-value is less than 0.05.						

Table 5.15 lists the paired t-test results to compare the difference between the MUTCD and CAMUTCD-required TCDs. The results reveal no significant difference regarding the hard brake response distance between the two combinations for sober and intoxicated drivers.

Table 5.16 Paired T-Test Results on Hard Brake Distance for Scenario 3

	NONALC		ALC		T Stat	p-value
	N	Mean	N	Mean		
WW+DRS	26	231	26	232	-0.04	0.97
WW+RRPM	23	242	23	246	-0.14	0.89
WW+ LaneAlert2X	24	233	24	242	-0.76	0.45
WWFlashing+DRS	22	238	22	278	-1.54	0.14
WWFlashing+RRPM	23	235	23	290	-2.71	0.01*
WWFlashing+ LaneAlert2X	23	281.17	23	305.30	-1.19	0.25
Note: * means that the p-value is less than 0.05.						

Table 5.17 Results of ANOVA Test and Tukey's Comparison Test for Scenario 3

Condition	Group	F	P-value	Tukey's Multiple Comparison Test			
				Comparison		Mean Diff	P-Value
NONALC	WW	0.1251	0.8826	DRS	RRPM	-11	0.8836
				DRS	LaneAlert	-2	0.996
				RRPM	LaneAlert	9	0.9225
ALC	WW	0.2306	0.7947	DRS	RRPM	-14	0.7922
				DRS	LaneAlert	-10	0.8819
				RRPM	LaneAlert	44	0.9832
NONALC	WW Flashing	3.043	0.0545	DRS	RRPM	4	0.9831
				DRS	LaneAlert	-43	0.1143
				RRPM	LaneAlert	-46	0.0743
ALC	WW Flashing	0.627	0.5374	DRS	RRPM	-12	0.8765
				DRS	LaneAlert	-27	0.5078
				RRPM	LaneAlert	-15	0.8024

Table 5.16 lists the sample size, the mean value of hard brake distance, and the paired t-test results to compare the two groups of drives for scenario 3. T-test results reveal that only the WW flashing sign with RRPMs significantly increased the hard brake distance for intoxicated drivers at a 95% significant level. **Table 5.17** lists the ANOVA test results of hard brake distance among sign and pavement marking groups. The results show no significant difference in the hard brake distance between the WW and WW flashing sign groups under both driving conditions.

Table 5.18 Paired T-Test Results on WW and WW Flashing Sign

	WW Sign		WW Flashing Sign		T Stat	p-value
	N	**Mean**	**N**	**Mean**		
NONALC	75	242	75	256	-1.2574	0.11
ALC	71	257	71	275	-1.5945	0.05*
Note: * means that the p-value is less than 0.05.						

Table 5.18 summarizes the results of an additional paired t-test conducted to determine whether there was a significant difference between the WW sign group and the WW flashing sign group. The analysis revealed that alcohol-impaired drivers exhibited a significant increase in their hard brake distance when presented with the flashing WW sign.

CHAPTER 6 CONCLUSION

The aim of this research project was to assess the effectiveness of WW-related TCDs on intoxicated drivers (BrAC level 0.12) using a driving simulator experiment. The study collected data on the number of WWD incidents, total/average fixation durations, and brake usage/hard brake distance. The key findings are presented as follows:

- Alcohol-impaired drivers tend to focus more on the pavement area in front of the vehicle, with a significant increase in the percentage of total fixation points on this area (from 4% by sober drivers to 17% by alcohol-impaired drivers).

- Drivers had fewer WWD incidents when facing a single WW-related sign than a single pavement marking. WW signs compliant with the CA MUTCD had fewer WWD events than those required by the MUTCD for both alcohol-impaired and sober drivers. WW signs with LED flashing borders resulted in approximately 50% fewer WWD entries by intoxicated drivers compared to traditional WW signs.

- Sober drivers spent more time on WW-related TCDs than alcohol-impaired drivers, a finding consistent throughout all scenarios. Scenario 1 (single TCDs) showed that drivers typically had a longer total fixation duration on signs than on pavement markings. Scenario 2 results indicated that intoxicated drivers' total fixation durations on CA MUTCD sign combinations were statistically significantly longer than on MUTCD signs. Scenario 3 results suggested that WW flashing signs typically caused a longer total fixation duration than traditional WW signs. WW flashing signs combined with DRSs and RRPMs caused the longest total fixation durations by alcohol-impaired drivers.

- Results of the average fixation duration analysis showed that (1) for single TCDs, drivers typically had longer average fixation durations under alcohol-impaired conditions than sober driving conditions, suggesting that intoxicated drivers may need more time to understand a single TCD; (2) the average fixation duration on WW flashing signs was significantly shorter than WW signs for intoxicated drivers, implying that the flashing border made the WW sign easier to understand by impaired drivers; and (3) intoxicated drivers had a significantly longer average fixation time on the LaneAlert2X than the RRPM, suggesting that drivers need more time to understand the LaneAlert2X than the RRPM.

- Brake usage analysis found that (1) WW flashing signs and DRSs increased the braking distance for most intoxicated drivers, and (2) CA MUTCD signs increased the braking distance by 30% for most sober drivers compared to MUTCD signs. WW+LaneAlert2X combinations and WWFlashing+LaneAlert2X TCD combinations caused the longest braking distance for intoxicated drivers (231 ft.) and sober drivers (215 ft.).

- Results of the hard brake response distance showed that (1) only the WW flashing sign with RRPMs significantly increased the hard brake distance for intoxicated drivers at a 95% significant level, and (2) the WW flashing sign can significantly increase intoxicated drivers' hard brake response distance compared to the WW signs.

The study is the first attempt to use actual alcohol in a driving simulator study of the effectiveness of WW-related TCDs. However, some limitations and future studies are identified, such as the limited BrAC level, the small sample size, and the driving scenarios' potential improvements. Future studies could apply more measures of effectiveness to driver behavior, such as speed change point, acceleration/deceleration rates, among others.

REFERENCES

Abbas, M., S. Chrysler, and A. Williams. Investigating Dynamic All-Red Extension: A Driver Simulator Study. in Transportation Research Board 85th Annual Meeting, 2006.

Al-Deek, H. et al., 2019. Wrong-Way Driving Phase-3 Study: Allocating and Evaluating Countermeasures on CFX Roadway. Submitted to Central Florida Expressway Authority. Final Research Report. Department of Civil, Environmental, and Construction Engineering, University of Central Florida.

Allen, R. W., Jex, H. R., McRuer, D. T., & DiMarco, R. J. Alcohol Effects on Driving Behavior and Performance in a Car Simulator. IEEE Transaction on Systems, Man, and Cybernetics: Systems, 1975. SMC-5(5), 498-505.

Anarkooli, A. J., and M. H. Hosseinlou. Analysis of the Injury Severity of Crashes by Considering Different Lighting Conditions on Two-Lane Rural Roads. Journal of Safety Research, 2016. 56:57-65.

Arizona DOT (ADOT), 2015. Traffic Engineering Guideline and Processes, Section 314, Wrong Way Driving.

Athey Creek Consultants, 2016. Countermeasures for Wrong-Way Driving on Freeways. Project Summary Report. ENTERPRISE Transportation Pooled Fund Study TPF-5 (231).

Baireddy, R., H. Zhou, and M. Jalayer. Multiple Correspondence Analysis of Pedestrian Crashes In Rural Illinois. Transportation Research Record: Journal of the Transportation Research Board, 2018. 2672 (38): 116-127.

Baratian-Ghorghi, F., H. Zhou, and J. Shaw. Overview of Wrong-Way Driving Fatal Crashes in the United States. ITE Journal, 2014. 41-47.

Berkeley Safe Transportation Research and Education Center (SafeTREC). Traffic Safety Facts: Alcohol-Impaired Driving. Summer 2020. https://safetrec.berkeley.edu/sites/default/files/safetrecfactsalcoholimpaireddriving1.pdf. Accessed November 29, 2020.

Bian, Z., R. Pierce, and G. Andersen. Eye Movement Patterns and Driving Performance. Driving Assessment Conference, 2017.

Boot, W. R., Charness, N., Mitchum, A., Roque, N., Stothart, C., & Barajas, K. 2015. Driving Simulator Studies of the Effectiveness of Countermeasures to Prevent Wrong-Way Crashes. Report No. BDV30-977-10. Florida. Department of Transportation.

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

Braxton, J. You're Going the Wrong Way! – Why Wrong Way Driving Happens. Hg.org Legal Resources, 2021 [updated 2021; cited 2021 July 27]. Available from: https://www.hg.org/legal-articles/you-re-going-the-wrong-way-why-wrong-way-driving-happens-32188.

California DOT (Caltrans), 2019. California Manual on Uniform Traffic Control Devices, 2014 Edition, Revision 4. Sacramento, CA.

Campbell, B.E., and P. B. Middlebrooks, 1988. Wrong-Way Movements on Partial Cloverleaf Ramps. Report No. FHWA-GA-88-8203. FHWA, U.S. Department of Transportation.

Chang, Q., M. Atiquzzaman and H. Zhou, 2019. "Evaluation of Low-cost Countermeasure for Preventing wrong-way Driving Incidents Based on Two Before- and- After Case Studies." In Conference Proceedings: 98th Annual Transportation Research Board Meeting, Washington, D.C.

Chmielewski, W. X., N. Zink, K. Y. Chmielewski, C. Beste, and A. K. Stock. How High-Dose Alcohol Intoxication Affects the Interplay of Automatic and Controlled Processes. Addiction Biology, 2018. Volume 25: e12700.

Chrysler, S. T. and S. D. Schrock, 2005. Field Evaluations and Driver Comprehension Studies of Horizontal Signing. Report No. FHWA/TX-05/0-4471-2. Texas Transportation Institute, College Station, TX.

Cooner, S. A, A. S. Cothron, S.E. Ranft. Countermeasures for Wrong-Way Movement on Freeway: Overview of Project Activities and Findings. Publication FHWA/TX-04/4128-1. Texas Transportation Institute, College Station, TX, 2004a.

Cooner, S. A, A. S. Cothron, S. E. Ranft. Countermeasures for Wrong-Way Movement on Freeway: Guidelines and Recommendation Practices. Publication FHWA/TX-04/4128-2. Texas Transportation Institute, College Station, TX, 2004b.

Copelan, J. E. Prevention of Wrong-Way Accidents on Freeways. Publication FHWA/CA-TE-89-2, Sacramento. California Department of Transportation, Sacramento, CA, 1989.

Das, S., A. Dutta, M. Jalayer, A. Bibeka, and L. 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, 2018. 7: 114-123.

Das, S., R. Avelar, K. Dixon, and X. Sun. Investigation on the Wrong Way Driving Crash Patterns Using Multiple Correspondence Analysis. Accident Analysis and Prevention, 2018. 111:43-55.

Farnsworth, B. Eye Tracking: The Complete Pocket Guide. IMOTIONS. https://imotions.com/blog/learning/best-practice/eye-tracking/. Accessed December 6, 2022.

Fatality Analysis Reporting System (FARS). National Highway Traffic Safety Administration (NHTSA), Washington, D.C. https://www-fars.nhtsa.dot.gov/QueryTool/QuerySection/SelectYear.aspx. Accessed July 30, 2019.

Fatality Analysis Reporting System. National Highway Traffic Safety Administration (NHTSA), Washington, D.C.; 2021 [cited 2021 July 27]. Available from: https://www.nhtsa.gov/crash-data-systems/fatality-analysis-reporting-system

Faul, F., E. Erdfelder, A. G. Lang, and A. Buchner. G*Power: A Flexible Statistical Power Analysis Program for the Social, Behavioral, and Biomedical Sciences. Behavior Research Methods, 2007. Volume 39: pp. 175-191.

Federal Highway Administration (FHWA). About Intersection Safety: Wrong-Way Driving Crashes. https://safety.fhwa.dot.gov/intersection/about/. Accessed April 20th,2022.

Florida DOT (FDOT), 2015. Roadway Design Bulletin 15-08/ Traffic Operation Bulletin 03-15. Tallahassee, FL.

Florida DOT (FDOT), 2019. FDOT Design Manual: 230. Signing and Pavement Marking.

Field, A., J. Miles, and Z. Field. Discovering Statistics Using R. SAGE Publications Ltd. 2012

Finely, M. D., S. P. Venglar, V. Iragavarapu, J. D. Miles, E. S. Park, S. A. Cooner and S. E. Ranft. Assessment of The Effectiveness of Wrong Way Driving Countermeasures and Mitigation Methods. Publication FHWA/TX-15/0-6769-1. Texas A&M Transportation Institute, College Station, TX, 2014.

Finley, M. D, J. D. Miles, and E. S. Park. Closed-Course Study to Examine the Effect of Alcohol Impairment on a Driver's Ability to Identify and Read Signs. Transportation Research Record: Journal of the Transportation Research Board, 2017. Volume 2660: pp. 86-93.

Fitzsimmons, E. J., J.R. Cunningham IV, S. Dissanayake, and J. Liang. An Evaluation of Wrong-Way Crashes From Highway Ramps in Kansas, USA. International Journal of Injury Control and Safety Promotion, 2019. 26 (3): 233-241.

François Husson, Sébastien Lê, and Jérôme Pagès. Exploratory Multivariate Analysis by Examply Using R. A Chapman & Hall Book, CRC press, 2017.

Geisen, E., and J. R. Bergstrom. Chapter 5 – Developing the Usability Testing Protocol. Usability Testing for Survey Research, pp. 111-129, 2017.

Greenacre, M. Correspondence Analysis in Practice, Second Edition. Chapman &Hall/CRC, Taylor & Francis Group, LLC., New York, 2007.

Greenacre, M., O. Nenadic, and M. Friendly. ca: Simple, Multiple and Joint Correspondence Analysis. R package, version 0. 71.1. Accessed July 3, 2020.

Helland, A., S. Lydersen, L. Lervåg, G. D. Jenssen, J. Mørland, L. Slørdal. Driving Simulator Sickness: Impact on Driving Performance, Influence of Blood Alcohol Concentration, and Effect of Repeated Simulator Exposures. Accident Analysis and Prevention, 2016. Volume 94: pp. 180-187.

Huizinga, C. R., R. G. Zuiker, M. L.

Huizinga, C. R., R. G. Zuiker, M. L. de Kam, D. Ziagkos, J. Kuipers, Y. Mejia, J. M. van Gerven, A. F. Cohen. 2019. Evaluation of simulated driving in comparison to laboratory-based tests to assess the pharmacodynamics of alprazolam and alcohol. Journal of Psychopharmacol.33(7):791-800.

Hulbert, S. and J. Beers. Wrong-Way Driving: Off-Ramp Studies. Highway Research Record, 1966. Volume 122: pp.35-49.

Intoximeters. Handheld Breath Testers, Alco-Sensor IV. https://www.intox.com/product/alco-sensor-iv/, accessed by April 19th, 2022.

Irwin, C., E. Iudakhina, B. Desbrow, D. McCartney. Effects of Acute Alcohol Consumption on Measures of Simulated Driving: A Systematic Review and Meta-Analysis. Accident Analysis and Prevention, 2017. Volume 102: pp. 249-266.

Jacob, R. and K. S. Karn. Commrntary on Section 4. Eye Tracking in Hunman-Computer Interaction and Usability Research: Ready to Deliver the Promises. Minds Eye, 2003. 2(3):573-605.

Jalayer, M., M. Pour-Rouholamin, and H. Zhou. Wrong-Way Driving Crashes: A Multiple Correspondence Approach to Identify Contributing Factors. Traffic Injury Prevention, 2018. 19 (1): 35-41.

Jalayer, M., R. Shabanpour, M. Pour-Rouholamin, N. Golshani, H. Zhou. Wrong-Way Driving Crashes: A Random-Parameters Ordered Probit Analysis of Injury Severity. Accident Analysis & Prevention, 2018. 117: 128-135.

Kassambara, Alboukadel. Practical Guide to principal Component Methods in R. Published by Statistical Tools for High-throughput Data Analysis (STHDA), 2017.

Kayes, M. I., Sandt, A., Al-Deek, H., Uddin, N., Rogers Jr, J. H., & Carrick, G. 2019. Modeling wrong-way driving entries at limited access facility exit ramps in Florida. Transportation Research Record, 2673(8), 567-576.

Kemel, E. Wrong-Way Driving Crashes on French Divided Roads. Accident Analysis & Prevention, 2015.75:69-76.

Khan, and Lee. Gaze and Eye Tracking: Techniques and Applications in ADAS. Sensors, 2019. 19(24): 5540.

Kittelson & Associates, Inc. Statewide Wrong Way Crash Study Final Report. Project No. 12274.03. Florida Department of Transportation, Tallahassee, FL, 2015.

Kruskal W. H. and W. A. Wallis. Use of Ranks in One–Criterion Variance Analysis. Journal of the American Statistical Association, 47 (260), pp. 583-621, 2012.

Lathrop, A. L., T. B. Dick, and K. B. Nolte. Fatal Wrong-Way Collisions om New Mexico's Interstate Highways, 1990-2004. Journal of Forensic Sciences, 2009. 55 (2): 432-437.

Laude, J. R., and M. T. Fillmore. 2015. Simulated driving performance under alcohol: Effects on driver-risk versus driver-skill. Drug and alcohol dependence, 154, 271–277. https://doi.org/10.1016/j.drugalcdep.2015.07.012

Leduc, J. L. K, 2008. "Wrong Way Driving Countermeasures." https://www.cga.ct.gov/2008/rpt/2008-r-0491.htm (Last Accessed: October 16, 2019).

Lee, C. and M. Abdel-Aty. Presence of passengers: Does it increase or reduce driver's crash potential? Accid. Anal. Prev. 2008. 40 (5), 1703–1712.

Lin, P.-S., Ozkul, S., Boot, W. R., Alluri, P., Hagen, L. T., & Guo, R. (2017). Comparing countermeasures for mitigating wrong-way entries onto limited access facilities (FDOT-BDV25-977-29). Florida Department of Transportation, Florida, USA.

Lin, P. S., Ozkul, S., Guo, R., & Chen, C. 2018. Assessment of countermeasure effectiveness and informativeness in mitigating wrong-way entries onto limited-access facilities. Accident Analysis & Prevention, 116, 79-93.

Martin, C. S., and M. A. Sayette. 1993. Experimental design in alcohol administration research: limitations and alternatives in the manipulation of dosage-set. Journal of studies on alcohol, 54 6, 750-61.

Marczinski, C. A., and M. T. Fillmore. 2009. Acute alcohol tolerance on subjective intoxication and simulated driving performance in binge drinkers. Psychology of addictive behaviors: Journal of the Society of Psychologists in Addictive Behaviors, 23(2), 238–247. https://doi.org/10.1037/a0014633.

McAvoy, D. S., K. L. Schattler, and T. K. Datta. A Study of the Effectiveness of Steady Burn Warning Lights on Drums in Construction Work Zones. in Transportation Research Board 85th Annual Meeting, 2006.

Mele, M. L., and S. Federici. Gaze and Eye-Tracking Solutions for Psychological Research. Cognitive Processing, 2012. 13(1): pp. 261-265.

Mets, M. A., E. Kuipers, L.M. Domis, M. Leenders, B. Olivier, and J. C Verster. Effects of Alcohol on Highway Driving in the STIDIM Driving Simulator. Hum. Psychopharmacol Clin Exp, 2011, Volume 26: pp. 434-439.

Michael Greenacre and Jörg Blasius. Multiple Correspondence Analysis and Related Methods. Chapman & Hall, CRC Press, 2006.

Michigan DOT (MDOT), 2011. Manual on Uniform Traffic Control Devices.

Miles, J., P. Carlson, B. Ullman, and N. Trout, 2014. "Red Retroreflective Raised Pavement Markings: Driver Understanding of Their Purpose." Transportation Research Record: Journal of the Transportation Research Board, Vol. 2056, Issue 1, pp. 34-42.

Moler, S. Stop! You're Going the Wrong Way! Public Roads, 2002. Volume 66, Issue 2.

Morena, D. A., and T. J. Leix. Where These Drivers Went Wrong. Public Roads, 2012. Volume 75, Issue 6. https://highways.dot.gov/public-roads/mayjune-2012/where-these-drivers-went-wrong.

National Advanced Driving Simulator. MiniSim™. https://www.nads-sc.uiowa.edu/minisim/ , accessed by April 19th, 2022.

National Highway Traffic Safety Administration (NHTSA). Identifying Situations Associated with Older Drivers' Crashes. Report No. 380. U.S Department of Transportation, NHTSA, Washington, D.C., 2009.

National Transportation Safety Board (NTSB). Highway Special Investigation Report, Wrong-Way Driving. Publication NTSB/SIR-12/01. NTSB, Washington, D.C., 2012.

Nenadić, O., and M. Greenacre. Correspondence Analysis in R, With Two-and Three-Dimensional Graphics: The ca Package. Journal of Statistical Software, 2007. 20 (3):1-13.

Noyce, D. A., and M. Knodler. Evaluation of the Flashing Yellow Arrow (FYA) Permissive Left-Turn in Shared Yellow Signal Sections. 2014.

Ohio DOT, 2016. Enhanced Wrong-Way Traffic Control for Ramps. Office of Roadway Engineering.

Oregon DOT, 2018. ODOT Traffic Sign Design Manual, 3rd Edition. Technical Services, Traffic- Roadway Section, Traffic Standards &Asset Management Unit.

Ouyang, Y., 2013. "North Texas Tollway Authority's (NTTA) Wrong Way Driving Program: from a Traffic Engineer's Perspective." In Conference Proceedings: the 2013 National Wrong-Way Driving Summit, Edwardsville, IL.

Ozkul, S. and P. Lin, 2017. "Evaluation of Red RRFB Implementation at Freeway Off-Ramps and Its Effectiveness on Alleviating Wrong-Way Driving." Transportation Research Procedia, Vol. 22, pp. 570-579.

Ponnaluri, R.V. The Odds of Wrong-Way Crashes and Resulting Fatalities: A Comprehensive Analysis. Accident Analysis & Prevention, 2016. 88:105-116.

Pour-Rouholamin, M., H. Zhou. Analysis of Driver Injury Severity in Wrong-Way Driving Crashes on Controlled-access Highways. Accident Analysis & Prevention, 2016. 94: 80-88.

Pour-Rouholamin, M., H. Zhou, J.Shaw and P. Tobias, 2014. "Overview of safety countermeasures for wrong-way driving crashes." ITE Journal-Institute of Transportation Engineers, Vol. 84, Issue 12, pp.31-38.

Pour-Rouholamin, M., H. Zhou, B. Zhang, and R. Turochy. Comprehensive Analysis of Wrong-Way Driving Crashes on Alabama Interstates. Transportation Research Record, 2016b. 2601.

Reimer, B. Impact of Cognitive Task Complexity on Drivers' Visual Tunneling. Transportation Research Record: Journal of the Transportation Research Board, 2009. 2138 (1): 13-19.

Robinson, J., A. Smiley, J. Caird, G. Millen, and J. Copeland. Evaluation of Complex At-Grade Crossing Designs Using a Driver Simulator. Insitute of Transportation Engineers 2007 Annual Meeting & Exhibit, Pittsburgh, Pennsylvania, 2007.

Roux, B., and H. Rouanet. Multiple Correspondence Analysis. Sage Publications, Inc., Thousand Oaks, 2010.

Savolainen, P. T., N. Hawkins, A. Abatan, H. Chawla, T. J. Kirsch and M. U. M. Johari. Investigation of Wrong-Way Driving. InTrans Project 17-623. Center for Transportation Research and Education, Iowa State University, Ames, IA, 2018.

Scifres, P., and R. Loutzenheise. Wrong-Way Movements on Divided Highways. Purdue University Joint Highway Research Project. Report No. JHRP-13-75, pp.46.

Seitzinger, R., R. Fries, Y. Qi, and H. Zhou. A Driving Simulator Study Evaluation Traffic Sign Mounting Height for Preventing Wrong-Way Driving. In proceedings of Transportation Research Board 95th Annual Meeting, Washington, DC, 2016.

Sheskin, D. J. Handbook of Parametric and Nonparametric Statistical Procedures: Fourth Efition. Taylor and Francis Group, LLC. January 2007.

Simpson, S.A. Wrong-way Vehicle Detection: Proof of Concept. Publication FHWA-AZ-13-697. United Civil Group Corporation, Phoenix, AZ, 2013.

Spiegelman, C., E. S. Park, and L. R. Rilett. Transportation statistics and Microsimulation. Taylor and Francis Group, LLC. 2011.

Stevens, S. E., C. J. Schreck III, S. Saha, J. E. Bell, and K. E. Kunkel. Precipitation and Fatal Motor Vehicle Crashes, Continental Analysis with High-Resolution Radar Data. American Meteorological Society, 2019. 8: 1453-1461.

Statistical Tooles for High-Throughput Data Analysis (STHDA). Normality Test in R. http://www.sthda.com/english/wiki/normality-test-in-r. Last Accessed: October 14, 2022.

Stock, A. K., T. Schulz, M. Lenhardt, M. Blaszkewicz, and C. Beste. High-Dose Alcohol Intoxication Differentially Modulates Cognitive Subprocesses involved in Response Inhibition. Addiction Biology, 2014. Volume 21: pp. 136-145.

Stock, A. K., S. Hoffman, and C. Beste. Effects of Binge Drinking and Hangover on Response Selection Sub-Processes— A Study Using EEG and Drift Diffusion Modeling. Addiction Biology, 2016. Volume 22: pp. 1355-1365.

Subramaniyam, M., S. E. Kim, S. N. Min, H. Lee, S. H. Hong, and S. J. Park. Study of Effects of Blood Alcohol Consumption (BAC) Level on Drivers Physiological Behavior and Driving Performance under Simulated Environment. International Journal of engineering & Technology, 2018. Volume 7, Issue 2.8: pp. 86-91.

Tobii AB. Tobii Pro Lab Software. https://www.tobiipro.cn/siteassets/tobii-pro/user-manuals/Tobii-Pro-Lab-User-Manual/?v=1.194. 2014.

Tobii Academy. Foundations of Eye Tracking – Wearable. https://connect.tobii.com/s/tobii-academy?language=en_US&t=1673191857822. Accessed by September 13, 2022.

Tobii Connect. How to Analyze Recordings Made with the Mobile Device Stand. Tobii Connect Tutorials. https://connect.tobii.com/s/article/how-to-analyze-recordings-made-with-the-mobile-device-stand?language=en_US. September 13, 2022.

TobiiPro. Tobii Pro Glasses 2 Product Description. https://www.tobiipro.com/siteassets/tobii-pro/product-descriptions/tobii-pro-glasses-2-product-description.pdf/?v=1.95, accessed by April 19th, 2022.

U.S Department of Transportation. Manual on Uniform Traffic Control Devices. 2009 Edition.

Van Dyke, N. A., and M. T. Fillmore. Laboratory Analysis of Risky Driving at 0.06% and 0.08% Bloof Alcohol Concentration. Drug and Alcohol Dependence, 2017. Volume 175: pp. 127-132.

Van Dyke, N. A., and M. T. Fillmore. Acute Effects of Alcohol on Inhibitory Control and Simulated Driving in DUI Offenders. Journal of Safety Research, 2014. Volume 49: pp. 5-11.

Vaswani, N. K. Measures for Preventing Wrong-Way Entries on Highways. Report Number VHRC 72-R41. Virginia Highway Research Council, Charlottesville, VA, 1973.

Villavicencio, L.I., V. Añorve and L.S. Arnold. Fatal Wrong-Way Crashes on Divided Highways. (Research Brief.). AAA Foundation for Traffic Safety, Washington, D.C., 2021.

Vollrath, M., T.Meilinger and H.P Kruger. How the presence of passenger influences the risk of a collision with another vehicle. Accid. Anal. Prev. 2002. 34 (5), 649–654.

Weafer, J., D. Camarillo, M. T. Fillmore, R. Milich, and C. A. Marczinski. 2008. Simulated driving performance of adults with ADHD: comparisons with alcohol intoxication. Experimental and clinical psychopharmacology, 16(3), 251–263. https://doi.org/10.1037/1064-1297.16.3.251

Wickham, H. ggplot2: Elegant Graphics for Data Analysis. Springer, New York, 2009.

Wisconsin DOT (WisDOT), 2017. Traffic Guidelines Manual, Chapter 2-Signs.

Wolff, N., P. Gussek, A. K. Stock, and C. Beste. Effects of High-Dose Ethanol Intoxication and Hangover on Cognitive Flexibility. Addiction Biology, 2016. Volume 23: pp. 503-514.

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

Yan, X., E. Radwan, and D. Guo. Effect of a Pavement Marking Countermeasure on Improving Signalized Intersection Safety. ITE Journal, 2007, August, pp. 30-39.

Yang, L., H. Zhou and L. Zhu, 2018. "New Concept Design of Directional Rumble Strips for Deterring Wrong-Way Freeway Entries." Journal of Transportation Engineering, Part A: Systems, Vol. 144, Issue 5.

Zablotski, Y. Kruskal-Wallis Test: Compare More Than Two Groups. September 17, 2019. https://yury-zablotski.netlify.app/post/kruskal-wallis-test/.

Zhou, H., J. Zhao, R. Fries, M.R. Gahrooei, L. Wang, B. Vaughn, K. Bahaaldin, and B. Ayyalasomayajula. Investigation of Contributing Factors Regarding Wrong-Way Driving on Freeways. Research Report FHWA-ICT-12-010. Illinois Department of Transportation, Springfield, 2012.

Zhou, H., and M. P. Rouholamin, 2014a. Guidelines for Reducing Wrong-Way Crashes on Freeways. Report FHWA-ICT-14-010, Illinois Center for Transportation, Department of Civil and Environmental Engineering, Urbana, Illinois.

Zhou, H., and Pour-Rouholamin M. 2014b. Proceedings of the 2013 National Wrong-way Driving Summit. Report No. FHWA-ICT-14-009, Illinois Department of Transportation, Springfield, IL. https://www.ideals.illinois.edu/items/49035.

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

Zhou, H., M. Pour-Rouholamin, B. Zhang, J. Wang, and R. Turochy. A Study of Wrong-Way Driving Crashes in Alabama, Volume 1: Freeways. Publication ALDOT-Belt-SP07(906)-Wrong Way. Alabama Department of Transportation, Montgomery, AL, 2017a.

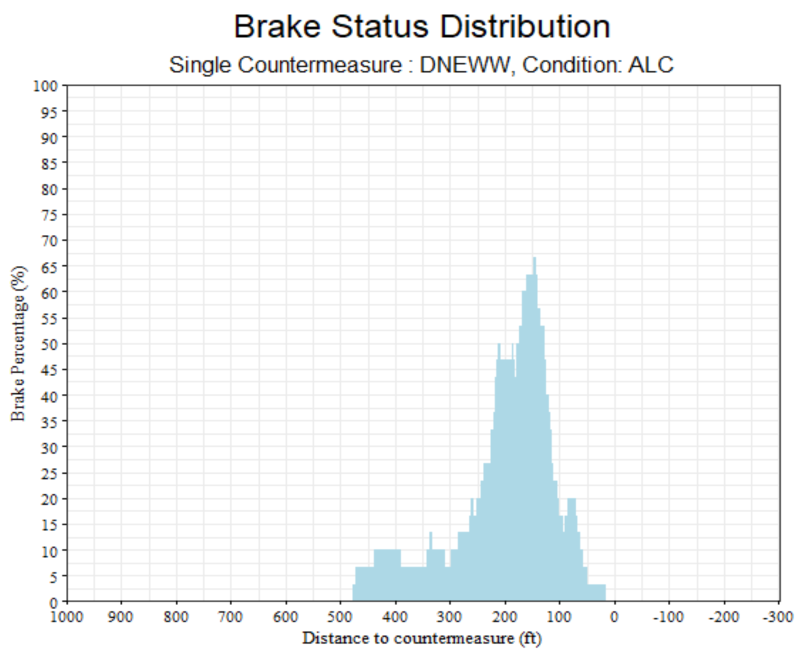
Zhou, H., M. Pour-Rouholamin, B. Zhang, J. Wang, and R. Turochy. A Study of Wrong-Way Driving Crashes in Alabama, Volume 2: Divided Highways. Publication ALDOT-Belt-SP07(906)-Wrong Way. Alabama Department of Transportation, Montgomery, AL, 2017b.

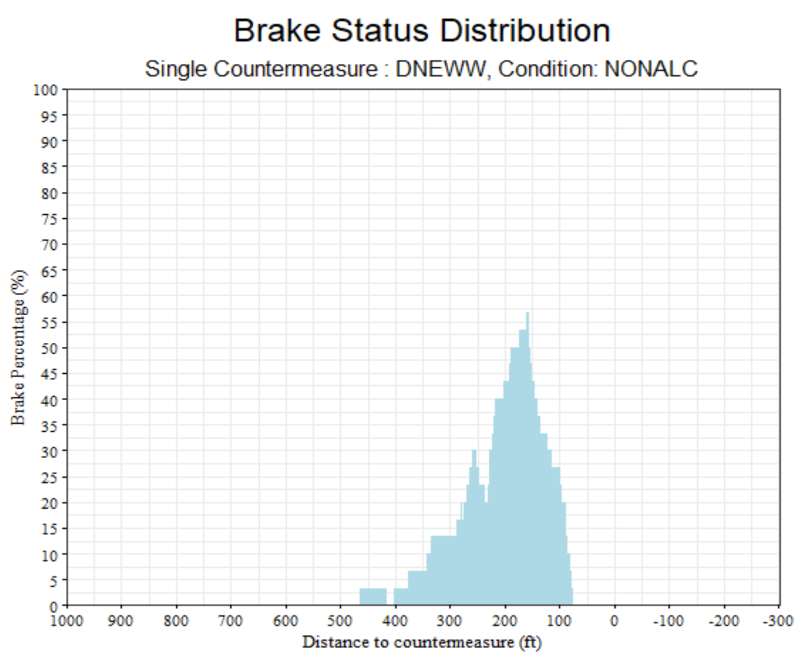
Zhou, H., C. Xue, Q. Chang, Y. Song, and B. Zhang. Field Implementation and Evaluation of Low-Cost Countermeasures for Wrong-Way Driving Crashes in Alabama. Publication ALDOT 930-965. Alabama Department of Transportation, Montgomery, AL, 2020.

Zink, N., R. Zhang, W. X. Chmielewski, C. Beste, A. K. Stock. Detrimental Effects of a High-Dose Alcohol Intoxication on Sequential Cognitive Flexibility are Attenuated by Practice. Progress in Neuropsychopharmacology & Biological Psychiatry, 2019. Volume 89: pp. 97-108.

Appendix I: Braking usage distributions

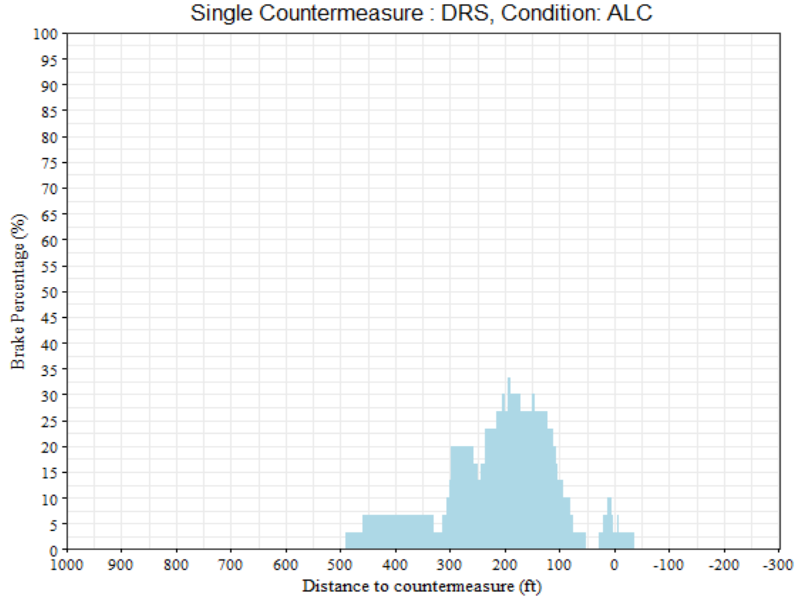
Scenario 1





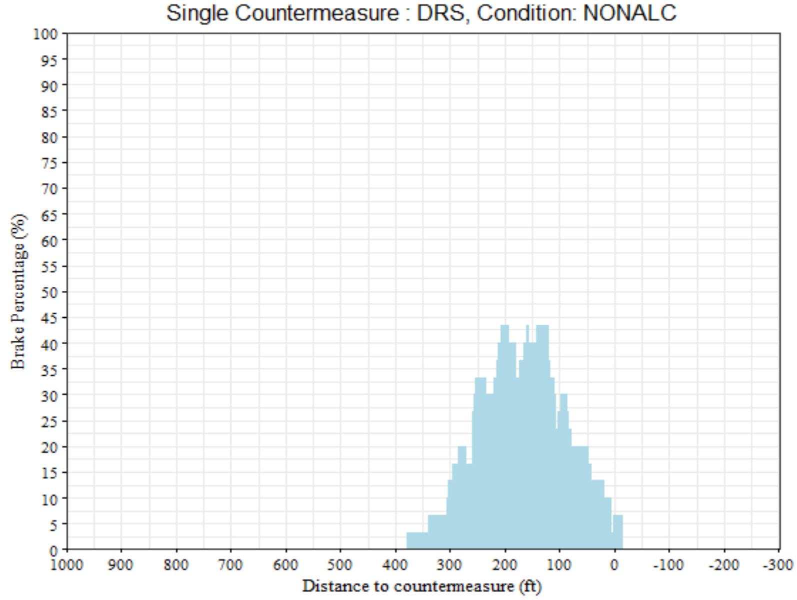
Brake Status Distribution

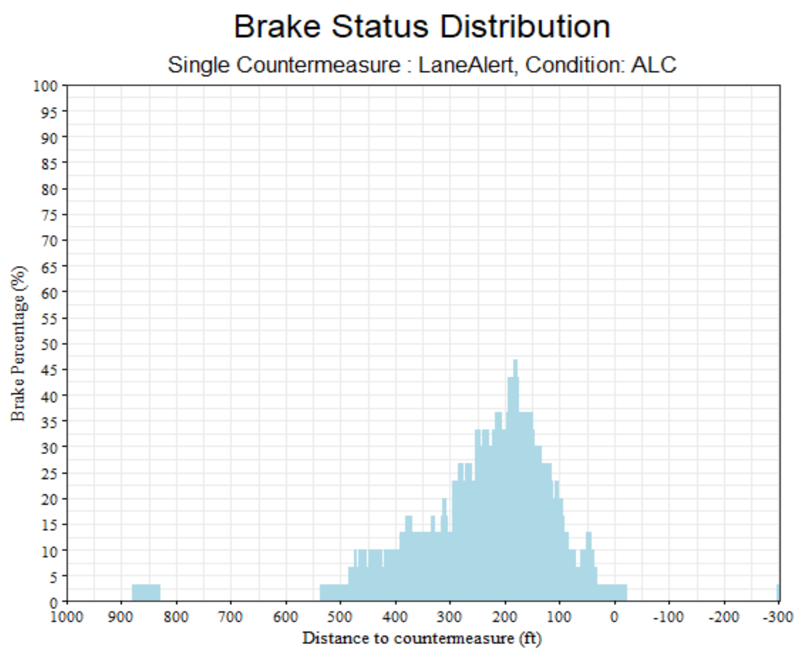
Single Countermeasure : DRS, Condition: ALC

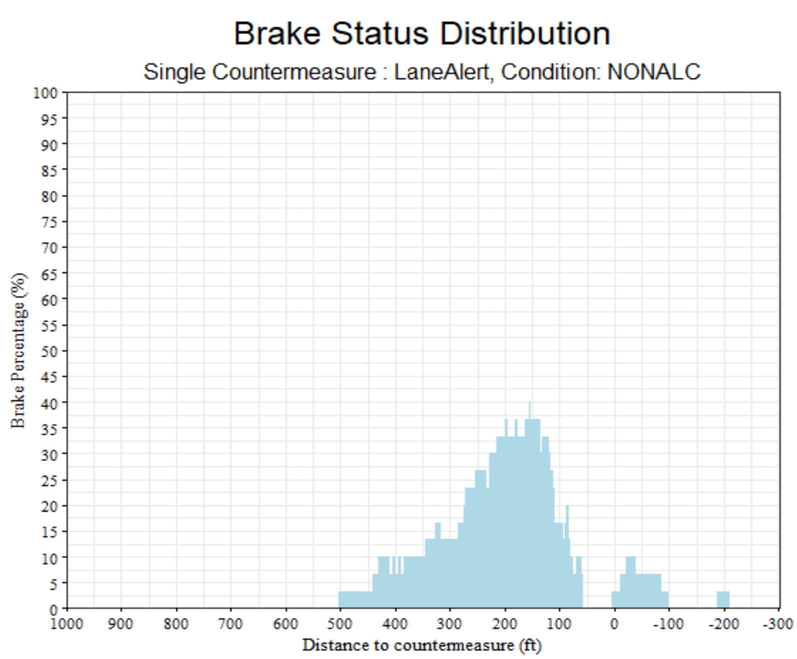


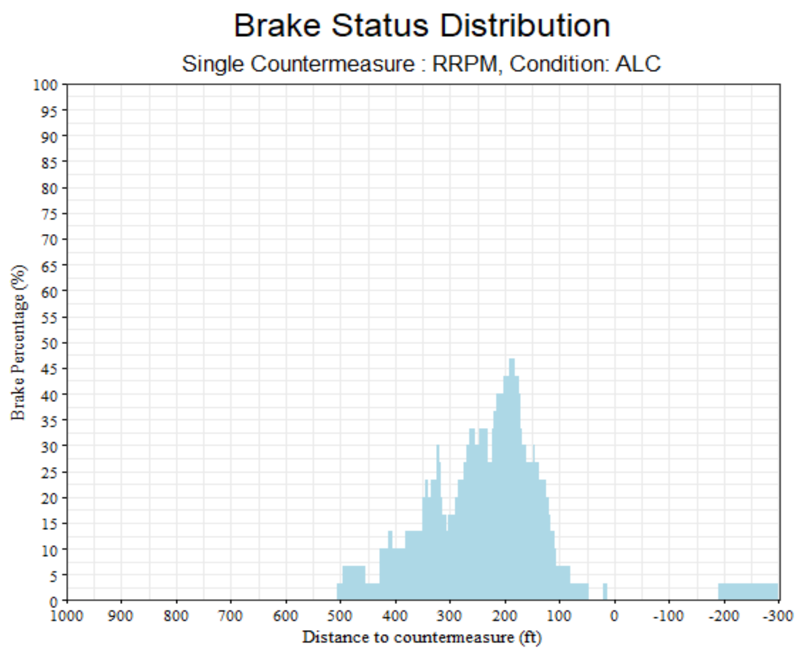
Brake Status Distribution

Single Countermeasure : DRS, Condition: NONALC

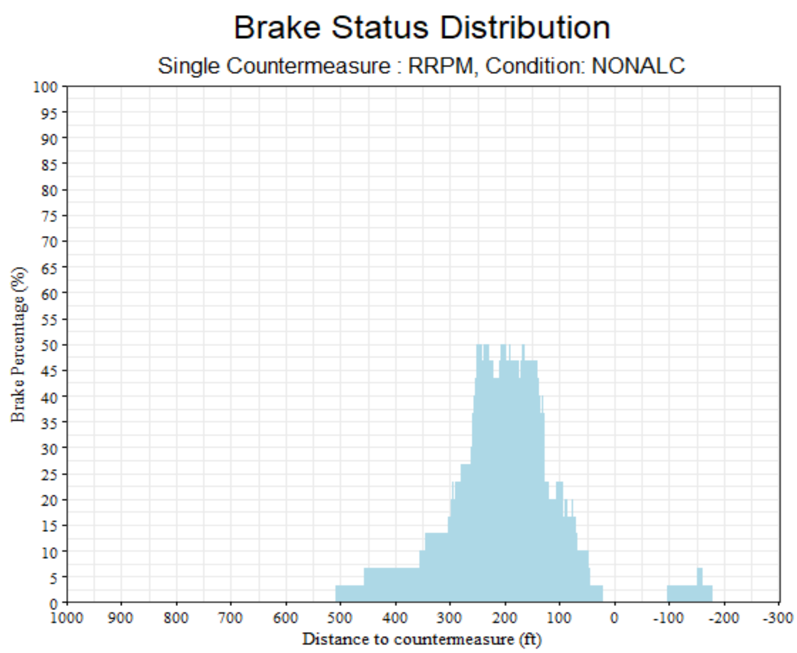



Brake Status Distribution
Single Countermeasure : LaneAlert, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)

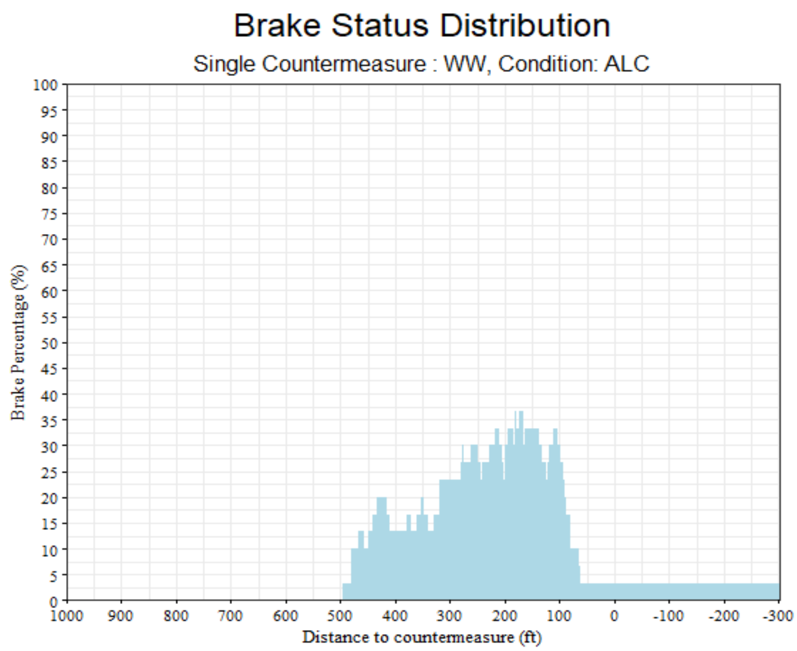

Brake Status Distribution
Single Countermeasure : LaneAlert, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)



Brake Status Distribution
Single Countermeasure : RRPM, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)



Brake Status Distribution
Single Countermeasure : RRPM, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)


Brake Status Distribution
Single Countermeasure : WW, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)
100
95
90
85
80
75
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60
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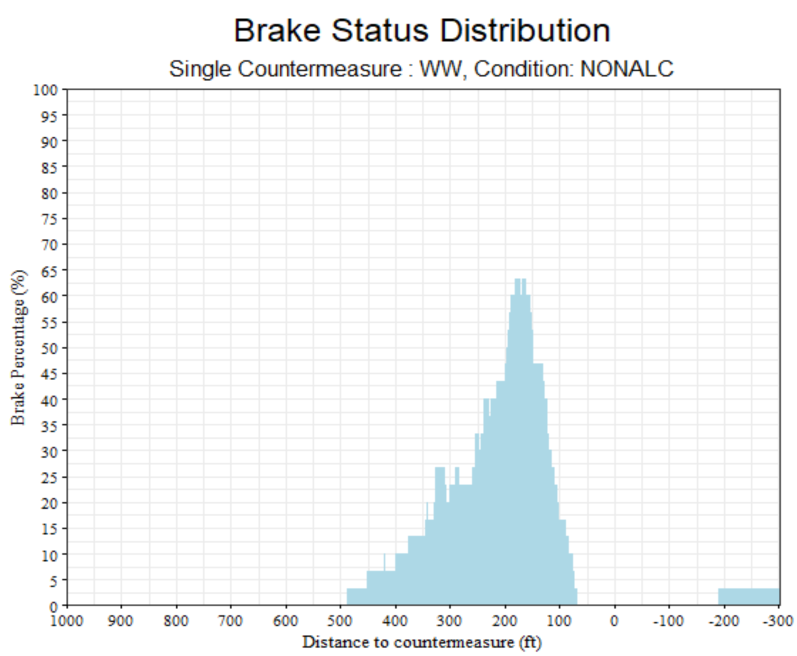
-100
-200
-300


Brake Status Distribution
Single Countermeasure : WW, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)
100
95
90
85
80
75
70
65
60
55
50
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40
35
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25
20
15
10
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1000
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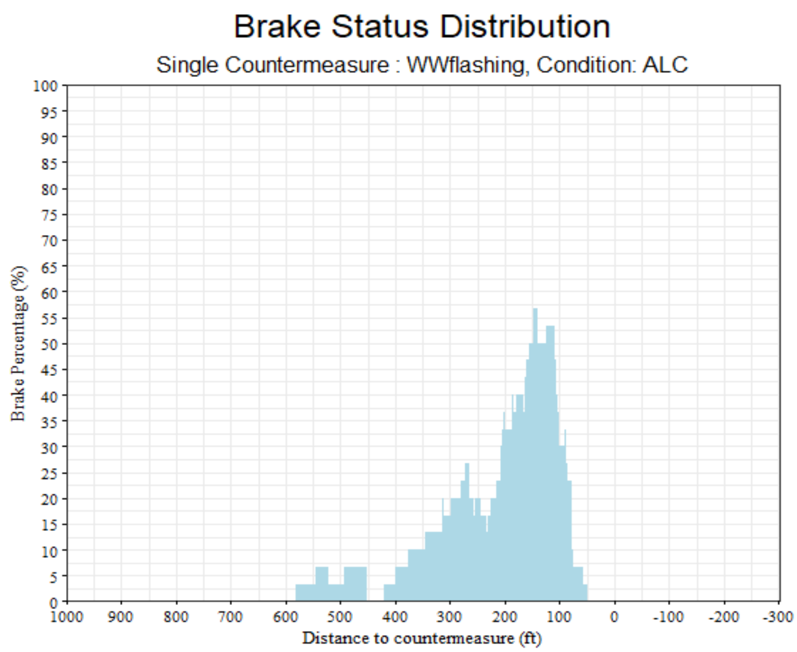
100
0
-100
-200
-300


Brake Status Distribution
Single Countermeasure : WWflashing, Condition: ALC
Brake Percentage (%)
100
95
90
85
80
75
70
65
60
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15
10
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0
1000
900
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700
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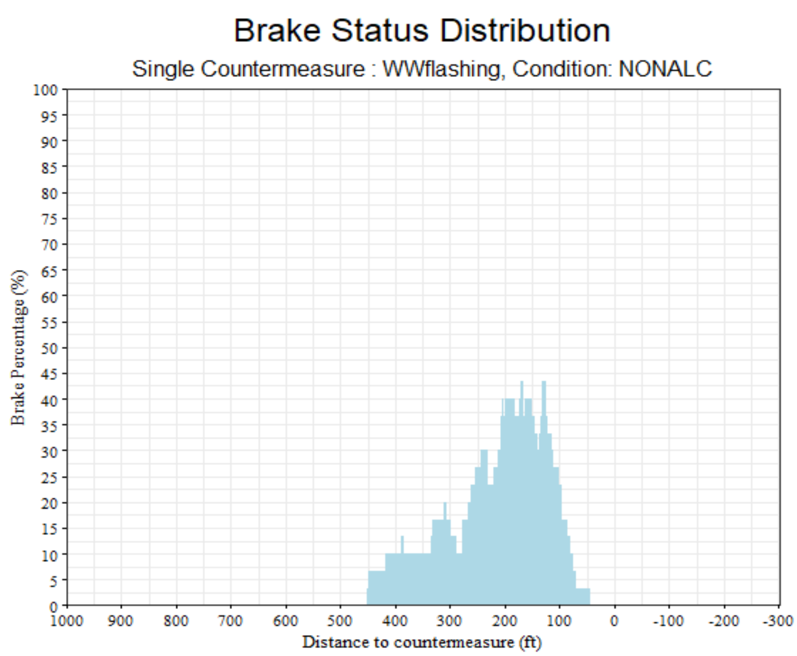
500
400
300
200
100
0
-100
-200
-300
Distance to countermeasure (ft)


Brake Status Distribution
Single Countermeasure : WWflashing, Condition: NONALC
Brake Percentage (%)
100
95
90
85
80
75
70
65
60
55
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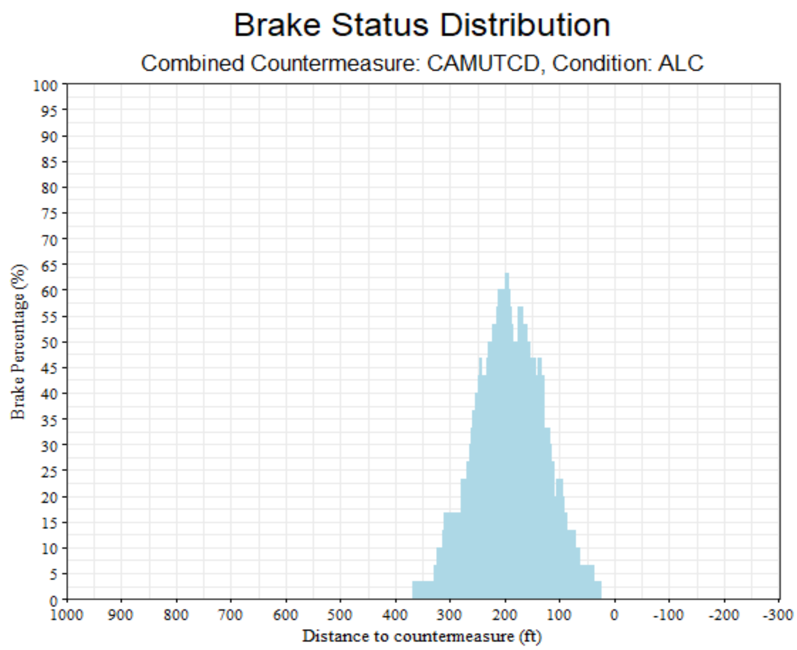
-100
-200
-300
Distance to countermeasure (ft)

Scenario 2



Brake Status Distribution
Combined Countermeasure: CAMUTCD, Condition: ALC
Brake Percentage (%)
100
95
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60
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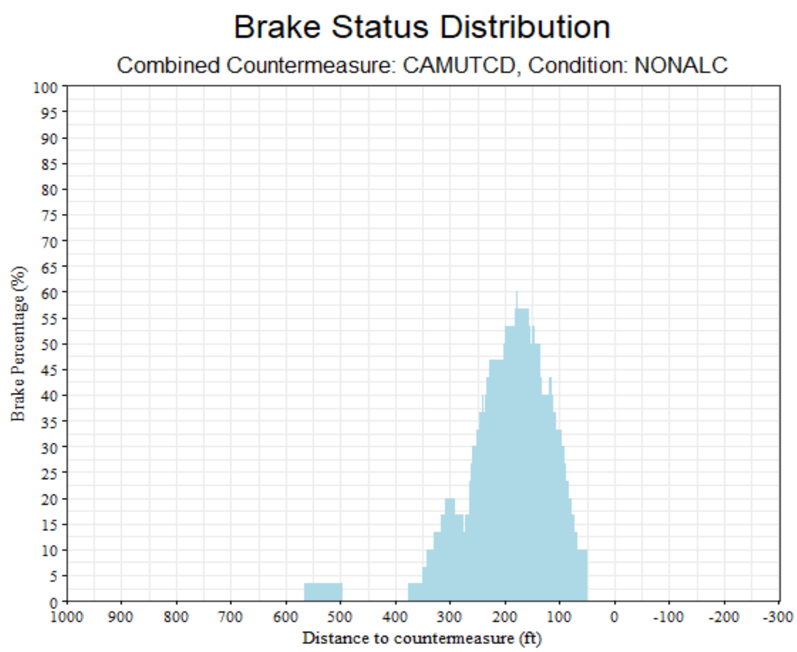
100
0
-100
-200
-300
Distance to countermeasure (ft)



Brake Status Distribution
Combined Countermeasure: CAMUTCD, Condition: NONALC
Brake Percentage (%)
100
95
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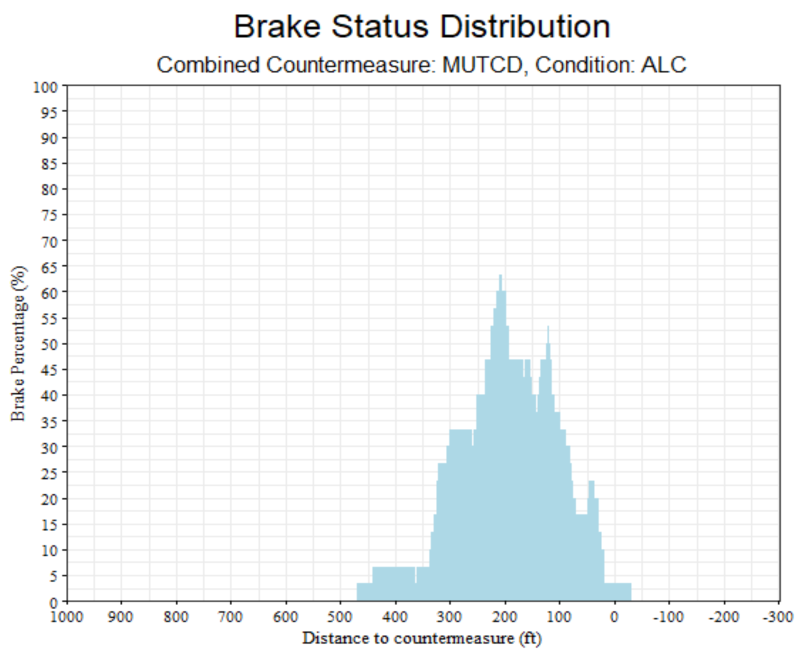
-100
-200
-300
Distance to countermeasure (ft)


Brake Status Distribution
Combined Countermeasure: MUTCD, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)
100
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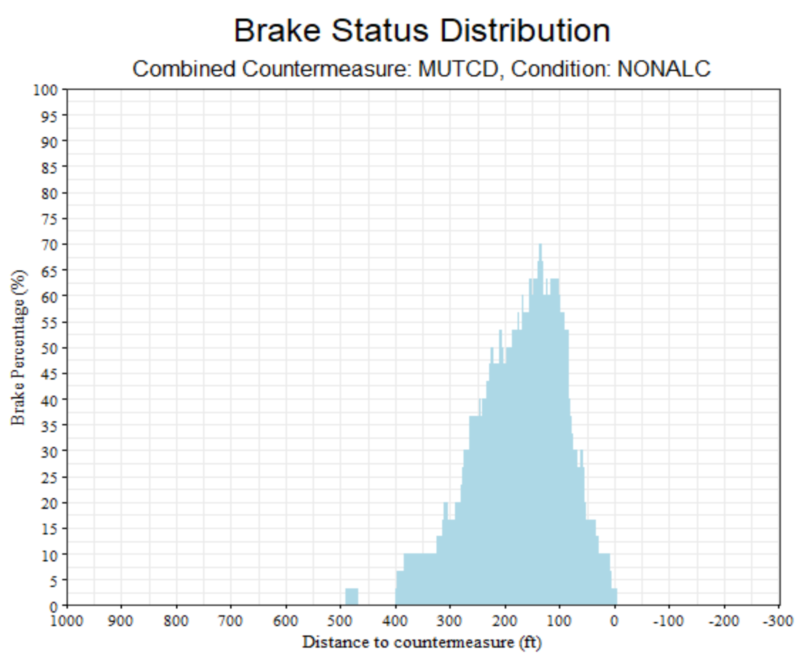
Brake Status Distribution
Combined Countermeasure: MUTCD, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)
100
95
90
85
80
75
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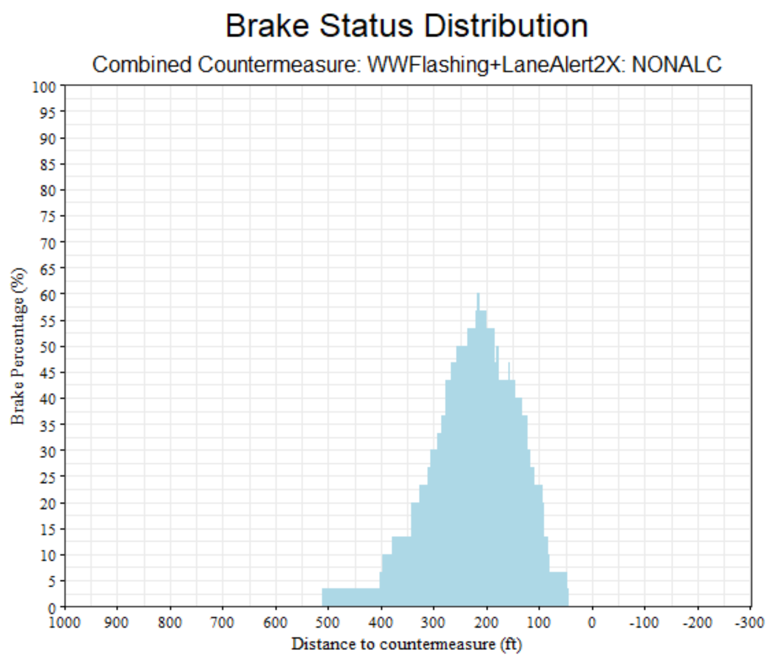
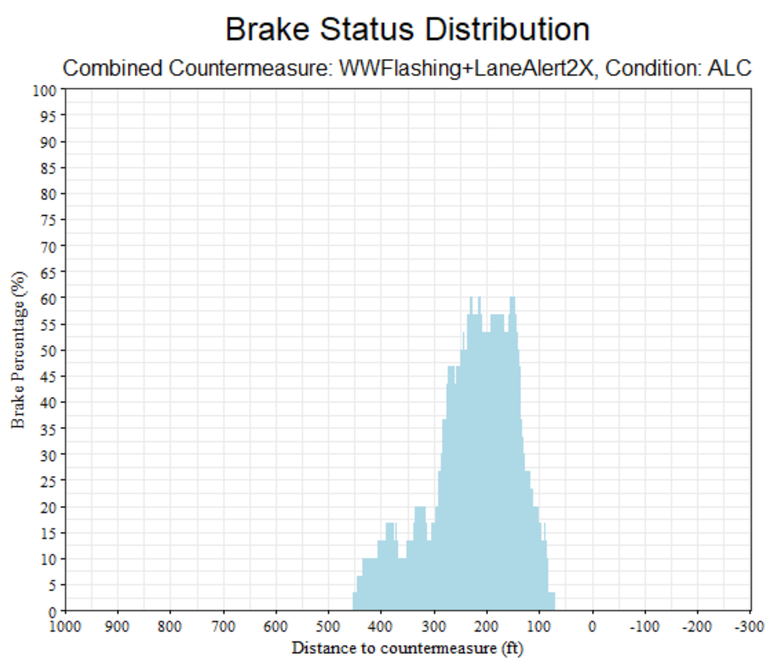
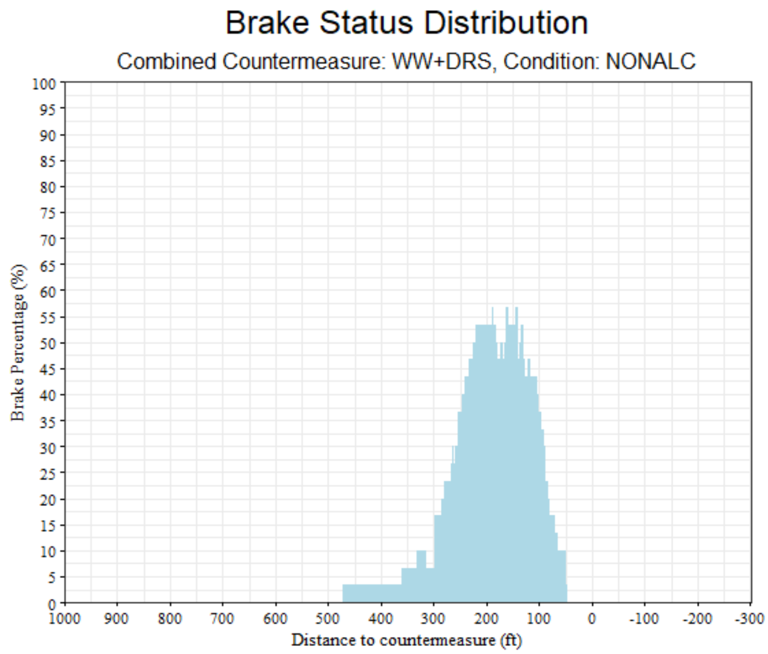
Scenario 3

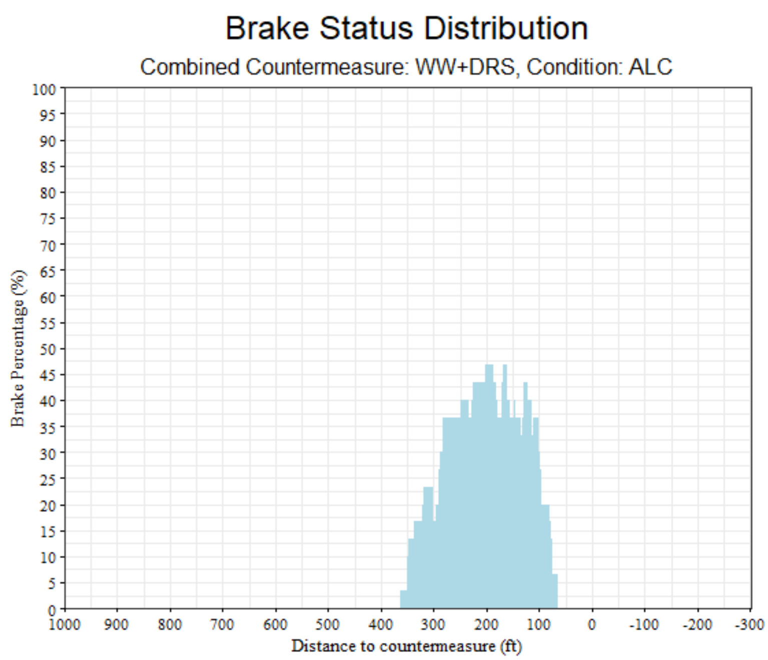


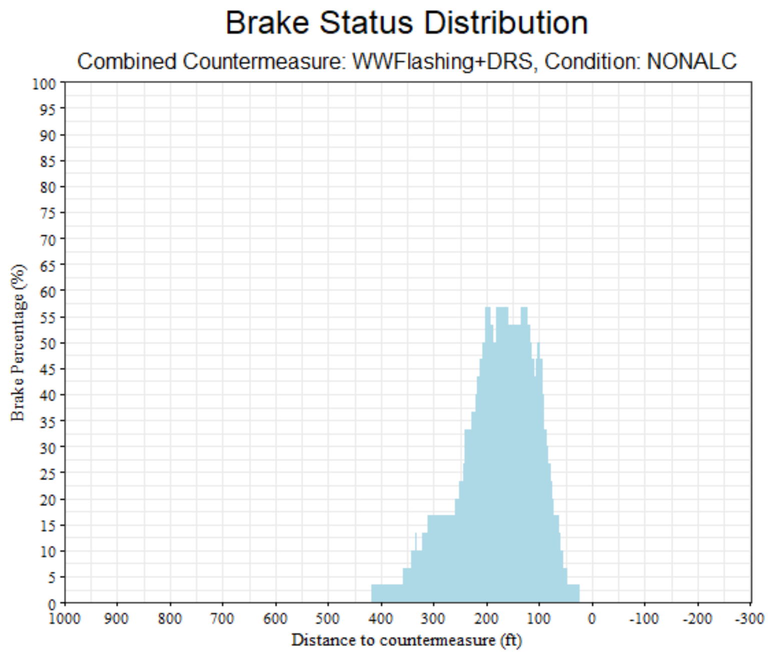
Brake Status Distribution
Combined Countermeasure: WWFlashing+LaneAlert2X: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)



Brake Status Distribution
Combined Countermeasure: WWFlashing+LaneAlert2X, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)


Brake Status Distribution
Combined Countermeasure: WW+DRS, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)


Brake Status Distribution
Combined Countermeasure: WW+DRS, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)


Brake Status Distribution
Combined Countermeasure: WWFlashing+DRS, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)
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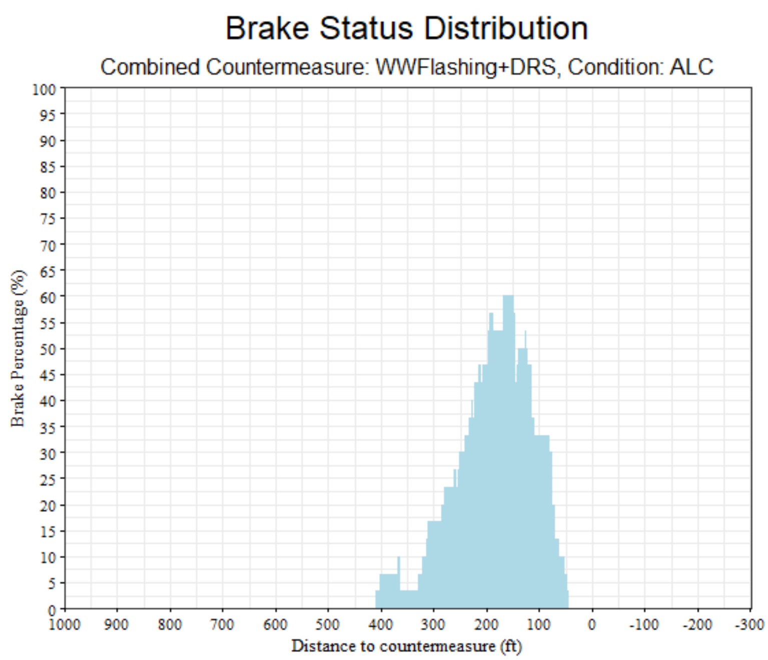
Brake Status Distribution
Combined Countermeasure: WWFlashing+DRS, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)
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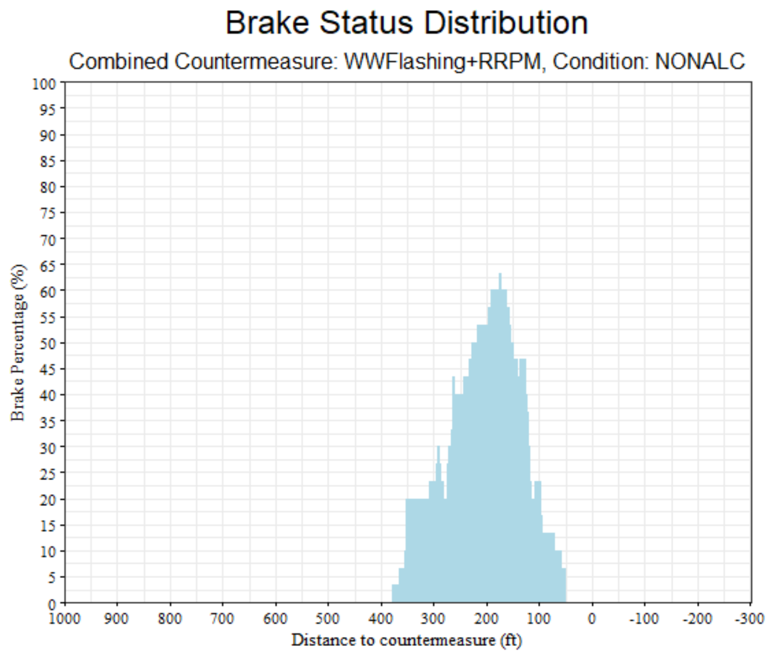
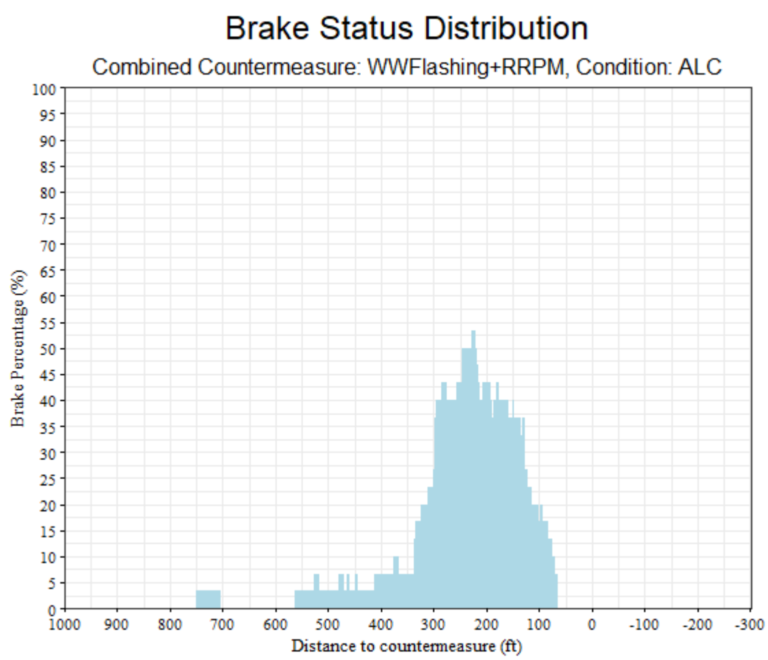
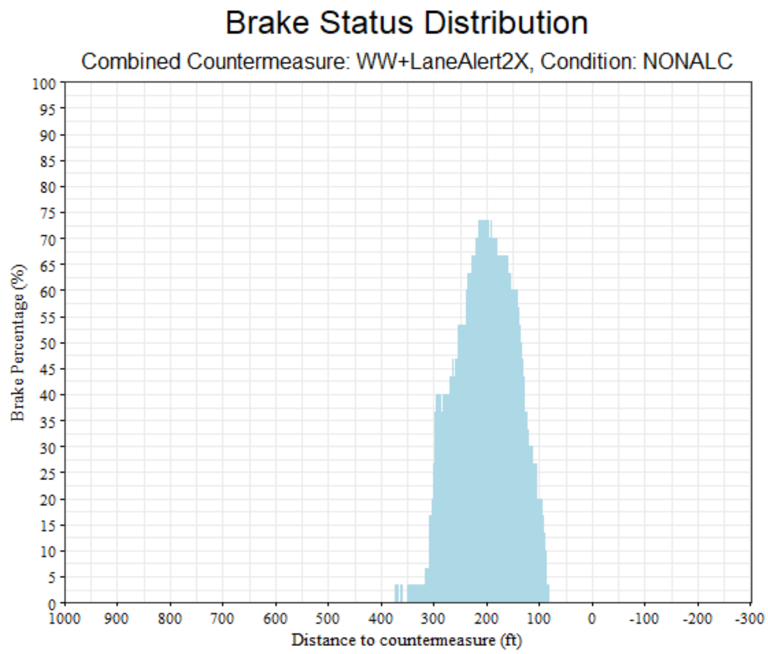

Brake Status Distribution
Combined Countermeasure: WWFlashing+RRPM, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)


Brake Status Distribution
Combined Countermeasure: WWFlashing+RRPM, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)


Brake Status Distribution
Combined Countermeasure: WW+LaneAlert2X, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)
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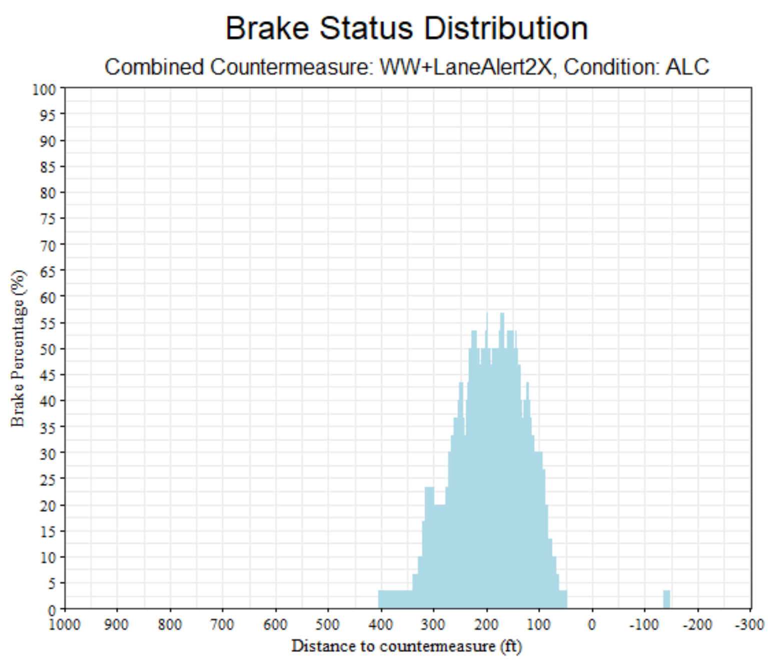
Brake Status Distribution
Combined Countermeasure: WW+LaneAlert2X, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)
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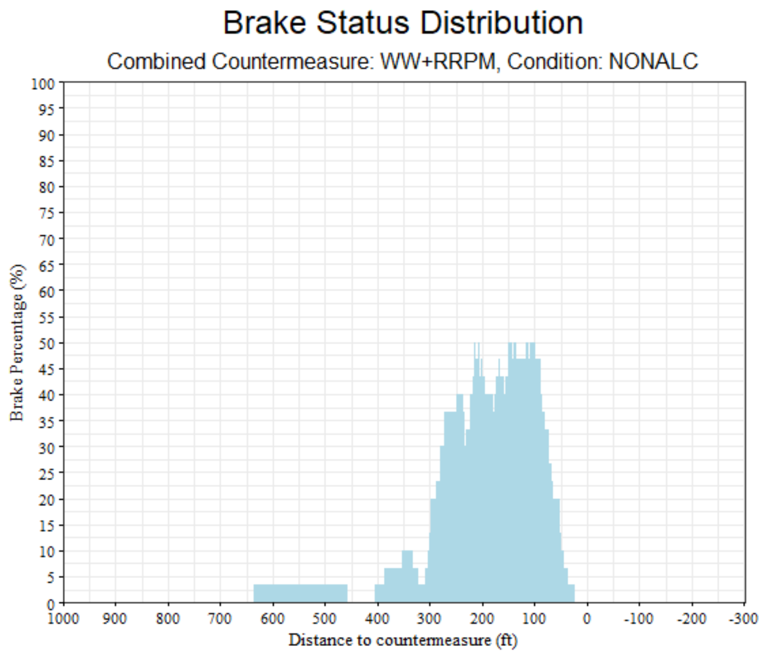
Brake Status Distribution
Combined Countermeasure: WW+RRPM, Condition: NONALC
Brake Percentage (%)
Distance to countermeasure (ft)
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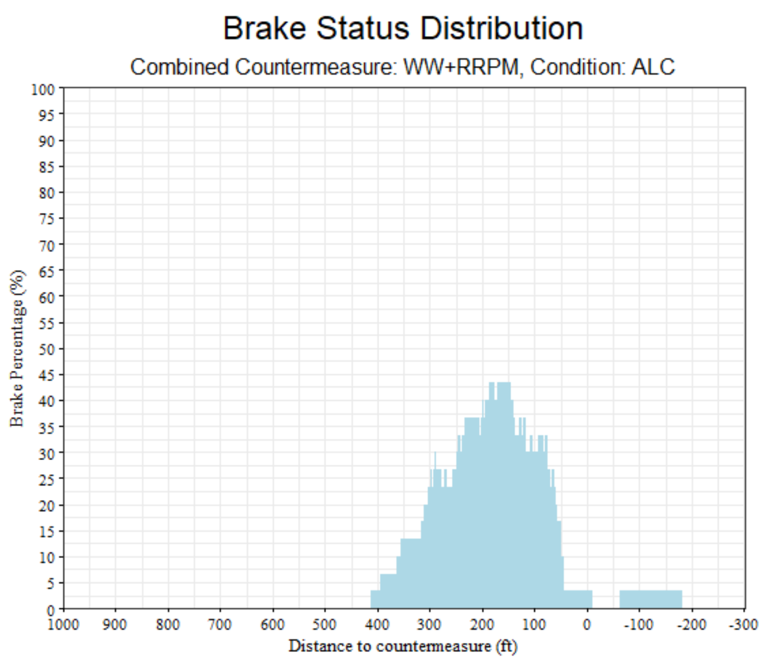
Brake Status Distribution
Combined Countermeasure: WW+RRPM, Condition: ALC
Brake Percentage (%)
Distance to countermeasure (ft)
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