GEORGIA DOT RESEARCH PROJECT 19-12

FINAL REPORT

COGNITIVE ATTENTION AND ITS APPLICATION IN COUNTERMEASURES ON A CURVE SECTION

Georgia Department of Transportation

OFFICE OF PERFORMANCE-BASED MANAGEMENT AND RESEARCH

600 WEST PEACHTREE STREET NW
ATLANTA, GA 30308

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7. Authors: Junan Shen (PI), Ph.D. (https://orcid.org/0000-0001-6069-4313); Weinan Gao (co-PI), Ph.D. (https://orcid.org/0000-0001-7921-018X); Mohammad Ahad, Ph.D.; Yunfeng Chen (co-PI), Ph.D. (https://orcid.org/0000-0002-0108-8484); Hongyue Wu (https://orcid.org/0000-0003-2252-4078); and Osahon Iroghama		8. Performing Organization Report No.: RP 19-12
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16. Abstract:

To reduce crashes and improve traffic safety on roads, this project explored a methodology of evaluating the safety countermeasures based on cognitive attention and driving performance with eye-tracking and driving simulation technologies and comprehensive analysis of eye movements, driving performance, and short-term memory. An experiment for data collection of cognitive response and driving performance to 11 countermeasures was designed with two weather conditions (clear and foggy) and two traffic flows (light and heavy) in a rural road curve section with a right and a left turn. Four combinations of the weather conditions and traffic flow were formed. Four sequence groups of the combinations were followed to eliminate the bias in data collection. Data of 60 participants were collected. Analysis of variance (ANOVA) tests indicated that countermeasures, weather conditions, and traffic flow impacted the drivers' cognitive attention, driving behavior, and short-term memory. Dividing participants into groups with different sequences of simulation combinations was useful to improve the bias for a limited sample size, while different starting time points of the combinations did not cause significant differences in the data collected. Finally, regression analyses using machine learning technology indicated that edge line pavement marking, shoulder rumble strips, flexible delineator posts, curve warning sign, and increased shoulder width are effective countermeasures that can attract drivers' attention and maintain the proper level of cognitive workload and visual information to reduce traffic crashes and improve the traffic safety. The effectiveness of the countermeasures from the regressions that considered the cognitive properties was much closer to what is expected compared to those that did not consider the cognitive properties. The proposed methodology using both eye tracker and driving simulator was found to be a useful way to evaluate the effectiveness of countermeasures to improve traffic safety.

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Final Report

COGNITIVE ATTENTION AND ITS APPLICATION IN COUNTERMEASURES ON A CURVE SECTION

By

Junan Shen, Ph.D.
Professor, Civil Engineering & Construction, Georgia Southern University

Weinan Gao, Ph.D.
Assistant Professor, Mechanical and Civil Engineering, Florida Institute of Technology

Mohammad Ahad, Ph.D.
Associate Professor, Electrical and Computer Engineering, Georgia Southern University

Yunfeng Chen, Ph.D.
Assistant Professor, Construction Management Technology, Purdue University

Georgia Southern University Research and Service Foundation, Inc

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

One of the leading reasons for premature death in Georgia (GA) is motor vehicle crashes, and lack of attention for drivers is a critical reason for traffic crashes. To reduce crashes and improve traffic safety, this project explored the relationship between cognitive attention between safety countermeasures and drivers' performance in a typical rural area in GA with high incidences of crashes through a comprehensive analysis of eye movements, driving performance, and self-reported short-term memory. An experiment was designed to simulate the selected rural road curve section on Cypress Lake Road in Statesboro, GA, with both horizontal and vertical curves, 11 different countermeasures, 4 combinations of weather conditions (foggy and clear) with 2 different traffic flows (light and heavy traffic volume). Eye movements and short-term memory were collected by an eye tracker and questionnaires, respectively, and were used to evaluate drivers' cognitive attention, while the driving simulator was used to measure driving performance. Sixty drivers participated in the experiment for data collection. The analysis of variance (ANOVA) method was then used to test the differences between drivers' cognitive attention, driving performance, and short-term memory between countermeasures and combinations of weather and traffic. Next, heat maps were used to achieve the visualization of attention distribution and intensity. Finally, regression analysis was performed to evaluate the relationships between countermeasures, drivers' cognitive attention, and traffic safety.

The findings of the project include the following:

1. The countermeasures had significant impacts on drivers' cognitive attention and driving performance according to the ANOVA tests. Specifically, there were significant differences in drivers' cognitive workload, attention shifts, level of interests, and difficulty of information extraction and understanding, as well as the number of crashes, vehicle speed, acceleration and deceleration, lateral acceleration, steering wheel angle, and lateral lane position between countermeasures.
2. The results of the regression analysis between cognitive attention, traffic crash, and countermeasures indicated that the following countermeasures were effective, meaning they can attract drivers' attention and maintain the proper level of cognitive workload and visual information to reduce traffic crashes and improve traffic safety in the two-lane rural curve section:
    a. Edge line pavement marking ($B \times D_{attention\ shifts} = -0.0007$, $B \times D_{interest} = 0.1247$, and $B \times D_{difficulty} = -0.1078$)[1].
    b. Shoulder rumble strips ($B \times D_{workload} = -0.1397$ and $B \times D_{difficulty} = -0.1075$).
    c. Flexible delineator posts ($B \times D_{workload} = -0.1411$ and $B \times D_{interest} = 0.1220$).

[1] *B*: significance parameter between countermeasures and drivers' cognitive attention;
D: significance parameter between drivers' cognitive attention and traffic crash;
B×*D*: significance parameter showing the relationships between countermeasures and traffic crash based on the drivers' cognitive attention.

d. Curve warning sign ($B \times D_{attention\ shifts}$ = −0.0009 and $B \times D_{interest}$ = 0.1240).

e. Increased shoulder width ($B \times D_{attention\ shifts}$ = −0.0007 and $B \times D_{interest}$ = 0.1181).

3. There were significant differences in drivers' cognitive attention, driving performance, and short-term memory between the weather conditions and traffic flows according to the ANOVA results, including the cognitive workload ($p < 0.05$), attention patterns ($p < 0.05$), attention shifts ($p < 0.01$), level of interests ($p < 0.01$), vehicle speed ($p < 0.01$), acceleration and deceleration ($p < 0.01$), lateral acceleration ($p < 0.01$), lateral lane position ($p < 0.01$), and ability to control attention ($p < 0.05$). Foggy weather with heavy traffic flow was the most dangerous scenario that caused the most crashes, while the scenario with clear weather and light traffic flow was a safer combination that led to the smallest number of crashes.

4. The results of regression analyses between crashes and countermeasures indicated that edge line pavement marking, flexible delineator posts, curve speed warning sign, posted speed sign, and increased curve grade countermeasures were effective to improve traffic safety by adding them to the road along with the basic centerline pavement marking. In particular, the countermeasures of posted speed sign (W = 0.0333)[2] and increased curve grade (W = 0.0333) were the most effective countermeasures based on the existing centerline and edge line markings

[2] *W*: significance parameter between countermeasures and number of crashes.

in reducing the number of crashes in the selected two-lane rural road curve section.

5. There were significant differences for 12 out of 17 indicators of eye movements, driving performance, and short-term memory among different sequences of combinations of weather and traffic flow. Dividing the 60 participants into 4 sequences of combinations of different weather conditions and traffic flow was useful to reduce the bias within a limited sample size. On the contrary, the order of each combination did not impact the majority of indicators (15 out of 17). Different starting time points of each combination did not cause a significant difference between eye movements and driving performance.
6. The proposed methodology using both the eye tracker and driving simulator together was an effective tool to evaluate the effectiveness of the countermeasures, based on a comprehensive analysis of cognitive attention and driving performance to improve traffic safety. Considering drivers' cognition in the regressions between the countermeasure and crash was capable of achieving more realistic results compared with those without cognitive properties.

CHAPTER 1. INTRODUCTION

OVERVIEW

Over 403,000 traffic crashes occurred in Georgia (GA) in 2019 (Georgia Department of Transportation [GDOT] 2021a). Specifically, fatality crashes increased from 1,180 in 2013 to 1,506 in 2019 in Georgia (GDOT 2021a). In particular, driver attention is important for studying how to reduce traffic accidents. About 70–90 percent of traffic crashes are correlated with human error, especially visual attention, which is considered the most critical source of accidents and incidents (Konstantopoulos et al. 2010, Petrillo and De Felice 2011). To reduce traffic crashes, researchers have proposed approaches and models to assess and estimate human failures and visual attention in the transportation area (Dia 2001, Petrillo and De Felice 2011). The role and impact of attention in road safety, especially in countermeasures, have been investigated with different measures (i.e., driving performance, eye movements, self-assessment, and memory), conditions (i.e., focused driving and distracted driving), areas (e.g., perceptual speed countermeasures, distraction countermeasures, and impaired driving countermeasures), and settings (i.e., field research and laboratory simulations). However, there has been limited study of attention through the collection and analysis of eye movements data with a high-precision eye tracker, which tracks drivers' attention at high temporal and spatial resolutions.

Some studies have discussed the role of attention in speed selection for different perceptual countermeasures based on driving performance (Charlton 2007, Khan 2010). However, the empirical evidence of visual performance is missing. Also, existing studies tracked the driving performance and eye movements of drivers with video cameras to identify the attention allocation patterns and relationships between drivers' inattention and crash risk in lead-vehicle pre-crash scenarios (Victor et al. 2015, Wong and Huang 2013). The results provide valuable insights into the impact of inattention and glancing behavior of drivers in real-world situations. However, the quality and processing of data are limited and inherently somewhat "messy" and prone to errors with low sampling rates and manually annotated glance location data. Other studies employed eye-tracking data, driving performance, and self-reporting to study drivers' attention (Caird et al. 2008, Castro 2008). However, practical solutions or comparison of countermeasures were not provided. For example, the Texas Department of Transportation (TxDOT) sponsored a study to identify relationships between drivers' performance and information load with eye movements and heart rate/electrocardiogram wave (Tsyganov et al. 2005). But there is a lack of analysis on drivers' performance under different countermeasures.

One of four leading reasons for premature death in Georgia is motor vehicle crashes. To reduce crashes and improve road safety, it is critical to know the causes of those crashes. It has been found that more than 90 percent of traffic crashes are due to human error (Petrillo and De Felice 2011). Additionally, more than 90 percent of these crashes are related to problems with visual information processing (Castro 2008). More significantly, a majority of explanations given by the drivers were related to attention-related issues such as inattention, distracted attention, and "looked but failed to see" (Konstantopoulos et al. 2010). Attention is a primary cognitive requirement for safe driving performance. To improve road safety and reduce crashes, it is necessary to develop and set effective countermeasures through evaluating the existing road environment of interest by monitoring drivers' driving performance and eye movements. The countermeasures may include adding, removing, and adjusting any components in the road environment.

RESEARCH OBJECTIVE AND SCOPE

This project's objective was to develop a methodology of evaluating countermeasures based on cognitive attention and driving simulation, i.e., to study the feasibility of explaining the drivers' performance by their eye movements. This was conducted via a thorough and more recent study of drivers' attention to countermeasures in a typical rural area of a curve section in a two-lane, two-way road in GA with a comprehensive analysis of eye movements, driving performance, and self-reported short-term memory.

The scope of the study included testing whether there are significant differences in (1) drivers' performance; (2) drivers' eye movements; and (3) short-term memory between 11 countermeasures on a curve section of both a *right* and a *left turn* under two weather conditions of *clear* and *fog* and two traffic flows of *heavy* and *low*. Data of driving performance, eye movements, and short-term memory were collected for 60 participants with valid driving licenses under different ages, ethnicities, and genders.

CHAPTER 2. LITERATURE REVIEW

This study included a detailed literature review that provides insights into current issues, causes, simulations, solutions, and countermeasures for traffic crashes. In particular, indicators of demographics, driving performance, eye movements, and short-term memory were identified through the literature review.

TRAFFIC CRASHES

Traffic crashes are incidents such as collisions among road users, which can be caused by a lack of driver attentiveness. This section summarizes the rate of traffic crashes related to drivers' attention and on-going research related to it. Latest statistics indicated that there was 9.9% increase in fatalities in distraction-affected crashes (National Highway Traffic Safety Administration [NHTSA] 2020). Over the years, research has been done on drivers' attention in order to identify factors that lead to traffic crashes. Distractions were seen to play a major part in decreasing drivers' attention, which further leads to traffic crashes. "The Role of Driver Distraction in Traffic Crashes" was a major study funded by the American Automobile Association (AAA) Foundation for Traffic Safety in 1999. This 3-year study aimed to identify sources of distraction while driving that would lead to traffic crashes based on data from the previous 5 years (Stutts and Hunter 2003).

DRIVING SIMULATION

Driving simulation is an immerging technology that makes it possible to record, supervise, and analyze data of drivers' performance under different conditions in a real-time setting. Due to the advancement of this technology, it has been possible to identify difficulties in real road situations that drivers face without putting a driver in harm's way (Mohellebi et al. 2007). This section summarizes previous research performed with driving simulation in relation to drivers' attention and performance. The use of driving simulation has made it possible for many situations to be measurable, such as fitness to drive (Shechtman 2010). It makes it possible to test many challenging/dangerous conditions and scenarios that may not be presented during on-road testing in a standardized setting. Moreover, many advantages make this approach a promising alternative to both neuropsychological and on-road testing for a safe assessment procedure, as well as for cost-cutting, time efficiency, and reliability (de Winter et al. 2009, Lew et al. 2005, Mayhew et al. 2011, Shechtman 2010). These advantages also make it possible for a large amount of data and variables to be collected and analyzed. On the other hand, the major shortcomings of driving simulation seem to be: (1) difficulty in comparing research findings adopting different driving simulators because of how parameters are collected and how driving simulator performance is quantified (Jacobs et al. 2017); (2) participant sickness, dizziness, nausea, vomiting, and sweating associated with simulations (Brooks et al. 2010, Domeyer et al. 2013); and (3) simulator cannot let drivers have the "real" driving experiences because there may be a lack of force being experienced as the driver operates the vehicle. More advanced driving simulator can work better to provide the near-reality driving experiences.

DEMOGRAPHIC INDICATORS

Demographic and situational factors are both related to drivers' attention, which is an important potential cause of crashes (Stutts et al. 2001). This section summarizes operators' demographic information that can affect their driving performance, as shown in table 1.

Table 1. Demographic indicators.

Indicators	References
Age	Andrews and Westerman (2012)
Gender	Yan et al. (2009)
Visual Abilities	Ackerman et al. (2008)
Marital Status	Sagaspe et al. (2010)
Driving Experience	Lehtonen et al. (2014)
Smoking Habit	Colrain et al. (1992)
Alcohol Consumption	Behnood and Mannering (2017)

Age affects driving performance for multiple reasons. With increasing age, cognitive and visual ability and short-term memory decrease, which further results in poor performance when the drivers are involved in multiple tasks (Andrews and Westerman 2012). Lee et al. (2003) also indicated that the driving performance of older drivers is negatively associated with age due to several factors, including loss of visual processing ability on the periphery, deficits due to medical conditions, cognitive decrements, and sensory impairment. Thus, older drivers are more likely to be at-fault because they may have perceptual difficulty when facing traffic flow (McGwin and Brown 1999). *Gender* also impacts drivers' performance. For example, male drivers have a greater chance to be involved in car crashes than female drivers because female drivers are better at memorizing the correct traffic signs (Sagaspe et al. 2010). Also, a previous study has found that young males have shorter brake response time (Yan et al. 2009). Moreover, the *visual ability* of drivers has an impact on drivers' driving performance; poor vision is the factor that most commonly affects driving performance (Ackerman et al. 2008). In addition, the *marital status* of a driver can also impact driving performance. It was reported that unmarried drivers' driving performance was worse than married drivers' driving performance based on the available statistics (Sagaspe et al. 2010). In addition, past *driving experience* can also impact driving behaviors. The current research showed that experienced drivers allocate a greater part of their visual attention in curve driving (Lehtonen et al. 2014). Finally, *smoking* and *alcohol* consumption habits are also key factors (Behnood and Mannering 2017, Colrain et al. 1992). Drivers with smoking and alcohol consumption habits are indicated to be more likely to be involved in crashes (Behnood and Mannering 2017, Colrain et al. 1992).

EYE MOVEMENTS

Measurement of eye movements is an important part of examining the information processing cycle and controlling task performance (Cornelissen et al. 1992), such as comprehension of language, memory, decision-making, and even more complex tasks (Richardson and Spivey 2004b, 2004a). For drivers, use of eye movements data is a common way to assess their mental workload (Brookhuis and de Waard 2010, Recarte and Nunes 2000, Recarte et al. 2008). Many parameters characterizing eye movements have been studied in relation to the drivers' mental workload, such as eye fixation, saccade, and pupillometry (Marquart et al. 2015); these indicators are provided in table 2.

Table 2. Eye movements indicators.

Factor	Definition	Indicators	References
Fixation	Eye movements located within a spatially limited region for a minimum period of time	Fixation duration/Total fixation time	Costa et al. ((2019), de Greef et al. (2009), Vignali et al. (2019)
		Number of fixations/Fixation counts	Najar and Sanjram (2018)
Saccade	Fast eye movements between different fixation points	Saccade durations	Desmet and Diependaele (2019)
		Number of saccades	Takeda et al. (2016)
		Saccade distance	Brookhuis and de Waard (2010), de Greef et al. (2009)
		Saccade speed	Brookhuis and de Waard (2010), de Greef et al. (2009)
Pupillometry	Diameter of pupil	Changes of pupil diameter	de Greef et al. (2009), Marshall (2002)
		Average pupil diameter	de Greef et al. (2009)

Fixation indicates eye movements that are located within a spatially limited region (about 0.5°) for a minimum period of time (Nyström and Holmqvist 2010). Number of fixations is calculated as the number of times (counts) the drivers fixated on the areas of interest (AOI), and is also called *fixation counts* (Najar and Sanjram 2018). The fixation duration means the period of time when the eyes are relatively stable and fixating on the AOIs; it is usually represented in seconds (Costa et al. 2019). Number of fixations in a specific area indicates the level of interest, while fixation duration measures the difficulty of information extraction and information understanding (Hill et al. 2003, de Greef et al. 2009, Najar and Sanjram 2018, Vignali et al. 2019). Previous studies show that an increase in cognitive workload results in increased fixation duration, as well (de Greef et al. 2009).

Saccade means fast eye movements between different fixation points (Di Stasi et al. 2010). Saccade duration measures drivers' eye movements speed from one fixation point to another point. Longer saccade time means a more dispersed fixation pattern (Desmet and Diependaele 2019). In the driving task, saccades could be shorter than 200 ms (Kapitaniak et al. 2015). The saccade distance and angles also show the drivers' attention (de Greef et al. 2009, Jiao et al. 2020). In addition, the saccade speed is the saccade distance divided by the saccade duration, which can be used to measure the attention shifts (Kapitaniak et al. 2015). Number of saccades also measures the frequency of attention shifts (Takeda et al. 2016).

Pupillometry, which means the pupil diameter, is used in relation to cognitive workload. The changes in the pupil diameter can reveal whether a person is experiencing cognitive workload (de Greef et al. 2009, Marshall 2002). The average pupil diameter is larger in the overload scenarios, while the average pupil diameter is lower in the underload scenarios (de Greef et al. 2009).

DRIVING PERFORMANCE

Driving performance indicates the drivers' speed, lane position, and other factors that can accommodate the severity of the curve (Hallmark 2012). This section summarizes driving performance indicators, as shown in table 3.

Table 3. Driving performance indicators.

Category	Indicators	References
Crash	Number of any contact with an object	Guo et al. (2013), Lee et al. (2011)
Speed	Vehicle speed	Whitmire et al. (2011)
	Acceleration and deceleration	Birrell and Young (2011), Vignali et al. (2019)
	Lateral acceleration	Reymond et al. (2001)
Other	Lateral position	Fisher et al. (2011)
	Steering wheel angle	Reed and Green (1999)

Crash indicates the number of any contact with an object by the vehicle, which is the core indicator showing the driving performance (Guo et al. 2013, Lee et al. 2011). Moreover, the vehicle *speed*, including acceleration, can be used to evaluate the driving performance. Previous studies compared speed before and within work zones to evaluate whether drivers comply with the speed limit (Whitmire et al. 2011). After knowing the speed from different points, the acceleration and deceleration can be calculated to evaluate the driving performance, including acceleration and deceleration of the vehicle and lateral acceleration (Birrell and Young 2011, Reymond et al. 2001, Vignali et al. 2019). Particularly, average speed reduction can be used to evaluate the effectiveness of traffic signs (Vignali et al. 2019). *Lateral position* (lane keeping) means the position of a vehicle on the road in relation to the center of the lane. Mean lateral position is the most commonly used indicator to measure the lateral position (Fisher et al. 2011). Finally, *steering wheel angle* indicates the movement of the steering wheel to measure whether the driver controls the vehicle appropriately (Reed and Green 1999).

SHORT-TERM MEMORY

Short-term memory indicates the temporary working memory of drivers (Reimer et al. 2012). It indicates faculties of the human mind that can hold a limited amount of information in a very accessible state temporarily (Cowan 2008). The system is specialized for the temporary storage of information within particular informational domains (St Clair-Thompson 2010). The maximum length of short-term memory is 60 s (Shao 2010). Three aspects of short-term memory are shown in table 4.

Table 4. Short-term memory indicators.

Indicators	Definitions	References
Ability to Control Attention	The ability to inhibit irrelevant information	Hasher et al. (1999)
Recall Ability	Retrieval of past information	St Clair-Thompson (2010)
Speed of Item Identification and Item Processing	The ability to identify and process an item	Case et al. (1982)

The *ability to control attention* indicates to what extent the drivers can inhibit any activated but goal-irrelevant information (Hasher et al. 1999). It requires cognitive engagement to prevent interference (Espy and Bull 2005). The irrelevant information indicates meaningful information that may distract drivers (Kane et al. 2001). *Recall ability* aims to measure how much the drivers can retrieve past information (St Clair-Thompson 2010). It is often measured by recall tasks about vision following the experiment procedure (Averbach and Coriell 1961, Reimer et al. 2012). *Speed of item identification and processing* means the drivers' ability to identify and process the items when testing their short-term memory (Case et al. 1982).

CHAPTER 3. DATA COLLECTION

The data collection process of this project can be divided into the following parts:

1. Identify a rural road curve section with a high risk of crashes as the case study in the project.
2. Identify the countermeasures that can impact traffic safety in rural road curve areas to be the key independent variables in the project.
3. Prepare the driving simulation and scenario modeling using a driving simulator to simulate the selected case and countermeasures
4. Model the scenarios with different weather conditions and traffic flows.
5. Identify the population and sample of the experiment.
6. Clarify the experiment procedure and prepare all the materials (e.g., questionnaires, driving simulator, eye tracker, etc.) to collect data during the experiment, including demographic information, eye movements, driving performance, and short-term memory.
7. Invite the possible participants and perform the data collection process.

CASE STUDY

The rural road is a significant part of the transportation system in the United States (Eason et al. 1955). Curves on rural roads are recognized as one of the most dangerous types of road section. Horizontal curves are changes in the alignment or direction of the road including right and left turn, while vertical curves are a change in the slope including sag curves and crest curves. Although horizontal-curve road sections only account for a small portion of the roadway, almost 25 percent of all fatal highway crashes occur at horizontal curve sections (Mauriello et al. 2018).

McLean (1981) investigated the driver speed behavior, showing that most drivers traverse the curve section exceeding the design speed. Also, an experiment by Lehtonen et al. (2012) showed that drivers look at the occlusion point when driving on the rural road curve section, where working memory load leads to a significant decrease in visual anticipation. Run-off-the-road and head-on crashes are two main crash types, which account for 87 percent of the fatal crashes at horizontal curves (Wang et al. 2018). On the road curve section, drivers' behaviors will be impacted by the characteristics of the road curve section, including the radius of curve, length of curve, and presence of a shoulder (Zwahlen and Schnell 1996). In addition, the historical crash data in GA (Cotton et al. 2010, GGOHS 2017) showed that roads in rural counties had the highest risk; state and county roads were the road types with the highest number of vehicle fatalities in GA. This project is devoted to a segment of rural road, i.e., Cypress Lake Road, Statesboro, GA, with both horizontal and vertical curves, as shown in figure 1.

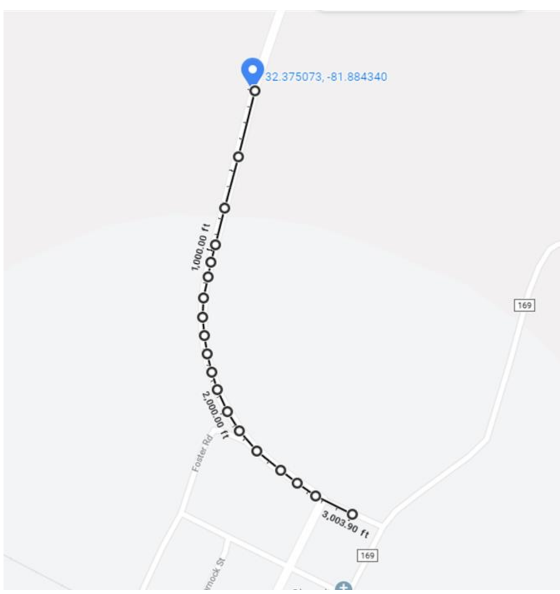


Figure 1. Map. Cypress Lake Road, Statesboro, GA.

The road segment is around 3,000 ft (0.57 mile) long. It has a 30-ft difference in elevation between the starting and ending points for a length of 0.4 mile, i.e., a grade of about 1.3 percent, as shown in figure 2. From north to south, the curve is in a left turn; it is a right turn when driving from south to north.

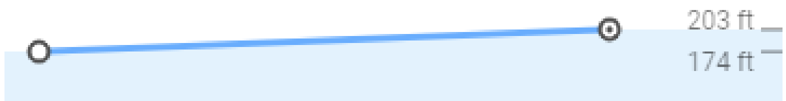


Figure 2. Diagram. Road grade of Cypress Lake Road.

To consider a more common situation of rural road curve section, both left and right turns were included in this study. In the simulation, the testing section was created by connecting a left turn and right turn, i.e., a curve from north to south followed by a curve from south to north, as shown in figure 3.

Figure 3. Map. Scenario road setup showing both left and right curves.

Thus, the total length of the simulated road section was about 6,000 ft, with a left turn of 3,000 ft followed by a right turn with the same parameters. In addition, two different traffic flows (i.e., *light* and *heavy*) and two different weather conditions (i.e., *clear* and *foggy*) were selected in the case study (Alexander et al. 20022002, Rizzo et al. 2003). The foggy weather included limited visibility. Rain was not selected as a weather condition simply due to the limitation of the simulator used for this study.

COUNTERMEASURES

Several countermeasures have been used in previous studies to improve curve safety. Using the GDOT road design policy (GDOT 2021b), a matrix of countermeasures was selected, as shown in table 5.

Table 5. Summary of countermeasures used for this project.

Number	Countermeasures	Curve Type	Category	References	MUTCD Code
#1	Centerline Pavement Marking	HC	Pavement Marking	Charlton (2007)	Section 3B.01-C (Two-direction no-passing zone markings)
#2	Edge Line Pavement Marking	HC	Pavement Marking	Charlton (2007)	Section 3B.06-A
#3	Shoulder Rumble Strips	HC	Pavement Marking	Räsänen (2005)	Section 3J.01
#4	Flexible delineator posts	HC	Pavement Marking	Zhao et al. (2020)	Section 3B.11
#5	Posted Speed Sign	HC	Signage	Charlton (2007), Zwahlen (1987)	Section 2C.08; W13-1P
#6	Curve Warning Sign	HC	Signage	Charlton (2007), Zwahlen (1987)	Section 2C.07; W1-2
#7	Curve Speed Warning Sign	HC	Signage	Charlton (2007), Zwahlen (1987)	W1-2+ W13-1P
#8	Increased Shoulder Width	HC	Roadway Improvement	Charlton (2007), Gross et al. (2009)	N/A
#9	Changed Horizontal Curve Curvature	HC	Roadway Improvement	Saleem and Persaud (2017)	N/A
#10	Decreased Curve Grade on Negative Grade	VC	Roadway Improvement	Bauer and Harwood (2013)	N/A
#11	Increased Curve Grade on Positive Grade	VC	Roadway Improvement	Bauer and Harwood (2013)	N/A

Notes: HC: Horizontal curve; VC: Vertical curve

There are three categories of curve section road countermeasures: pavement marking, signage, and roadway improvement. First, *pavement markings* (countermeasures #1–4) impact drivers' behaviors by providing separation between lanes, as well as enhancing lane-keeping ability (Charlton 2007, Lenné et al. 2011, Räsänen 2005, Zhao et al. 2020). Pavement markings include centerline and edge line, shoulder rumble strips, and flexible delineator posts. They are effective countermeasures to reduce traffic crashes and improve safety. Second, *signage* (countermeasures

#5–7) reminds drivers by providing road information in advance of the curve. Both speed limit signs and curve warning signs have effects on drivers' eye scanning and performance (Charlton 2007, Zwahlen 1987). Signage includes posted speed signs, curve warning signs, and curve speed warning signs. For the pavement markings and signages, the standard designs from the driving simulation system were directly used without any modification. Third, the *roadway improvement* category (countermeasures #8–11) covers the physical changes to the curve, including the shoulder width, horizontal curve curvature, and curve grades. Increasing shoulder width makes curves more forgiving to improve traffic safety (Charlton 2007, Gross et al. 2009). Also, the horizontal curve curvature significantly impacts the crash reduction rate (CRR) (Saleem and Persaud 2017). In addition, curve grade is a critical factor for traffic safety in rural two-lane highways (Bauer and Harwood 2013). This study aimed to further explore drivers' responses to these countermeasures through a simulator experiment.

DRIVING SIMULATION SETUP AND MODELING PLAN

STISIM Drive® was the driving simulator used in this study. This system makes it possible to achieve a very close simulation to real driving and also provides real-time data when in use. It is a system designed to give a high-level simulation performance with a 60-degree field of the driver's vision. The system provides for a realistic detailed road environment with little to no programming experience needed, and its manual is very detailed regarding the programming of the scenarios. An eye tracker, Tobii Eye Tracker 4C, was used for this project. This eye tracker was originally limited to certain data, but the Pro upgrade key made it possible to access the Tobii Pro lab or any Tobii Pro software for advanced analysis and access to extended data set information.

This portable eye tracker is centralized and attached to the lower frame of the monitor and connected to the simulator computer by a single USB cable. Figure 4 shows the combined system of the eye tracker and the driving simulator that was used to collect data. The driving simulation was done in the Transportation Safety Research lab, which means the distractions can be reduced as limited people were given access to the lab during the social distancing protocol of pandemic period. A Next level Racing GT Simulator Cockpit was used for the drivers to adjust the position so that a close to realistic driving experience can obtained. A 27-inch monitor was used as the simulation display unit. A Logitech driving force racing wheel was used as the driver steering wheel. It has dimensions (Width x Height x Depth) of Wheel unit 10.24 x 10.63 x 10.94" (260 x 270 x 278 mm) and Pedals unit 16.87 x 6.57 x 12.24" (428.5 x 167 x 311 mm). The driving simulator displayed the road scenario on a display monitor. The eye tracker then recorded images of users' eye movements and patterns through cameras with the help of image processing algorithms to determine the eyes' position and gaze point on the driving simulator display screen. This process is described in the flowchart in figure 5.

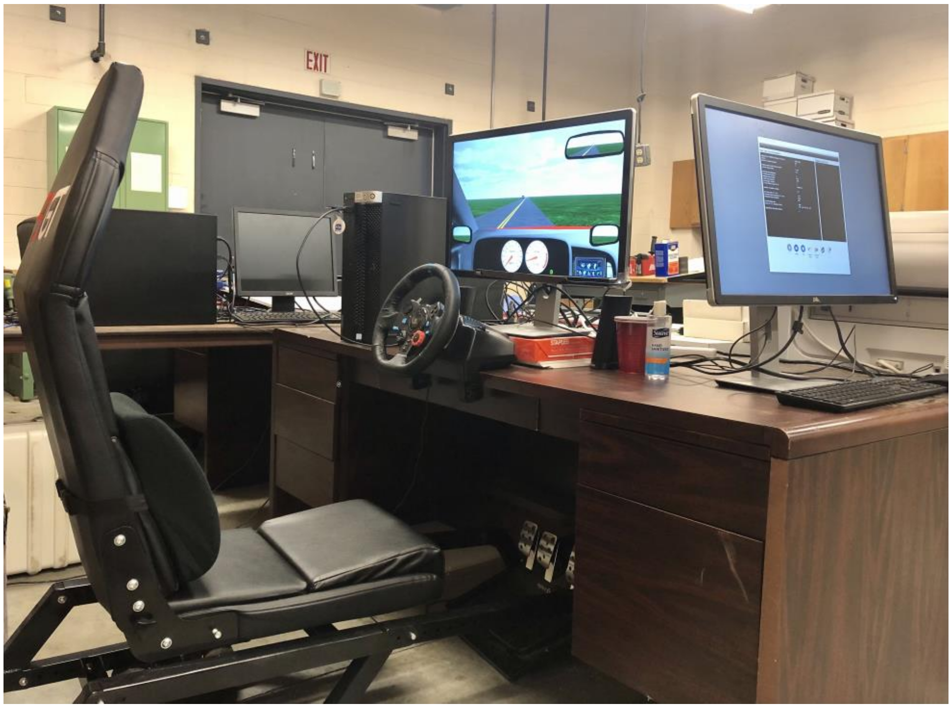


Figure 4. Photo. Combined driving simulator and eye tracker system.

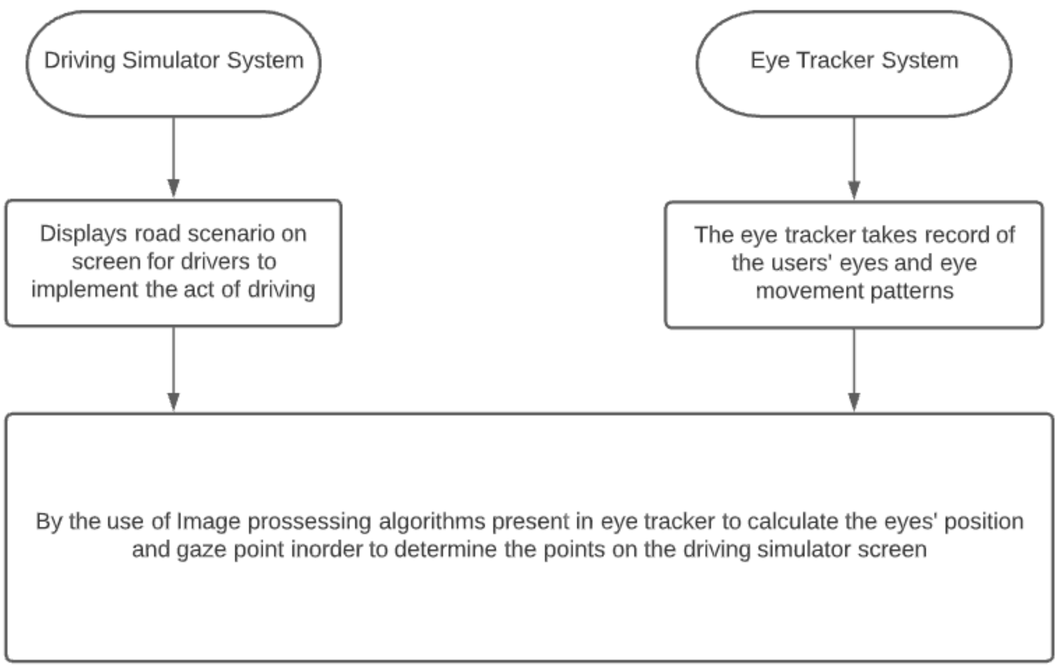


Figure 5. Flowchart. How the combined system worked.

Before this system could accomplish the goal, a model plan was necessary for proper and exact implementation of the simulation in order to match the required scenarios, i.e., the combination of weather condition and traffic flow. Figure 6 is the simulation model plan made by the research team. In the model plan, 11 countermeasures were to be implemented over different major scenarios of weather and traffic flow. Based on this model plan for implementation, the simulation was split into four combinations of two weather conditions and two traffic flows to achieve the entire plan. Each section of the simulation is listed below:

- Combination 1 – Light traffic flow with clear weather
- Combination 2 – Light traffic flow with foggy weather
- Combination 3 – Heavy traffic flow with clear weather
- Combination 4 – Heavy traffic flow with foggy weather

As the names imply, each combination had a varying control scenario, but all the countermeasures were kept the same. Due to the varying control scenarios of different weather conditions and traffic flows, the time duration of the simulation needed was, in most cases, different as the scenario varied. This is because driving will be easier for light traffic flow than for heavy traffic. All four simulation combinations had the same road distance setting and all countermeasures, with only the different control setting scenarios. For combination 1 and combination 2, which had a light traffic setting, an average time of 18 minutes was required to complete the simulation combinations. Due to the presence of heavy traffic flow in combination 3 and combination 4, the average time to complete those simulations rose by 10 minutes, taking the average time to 28 minutes.

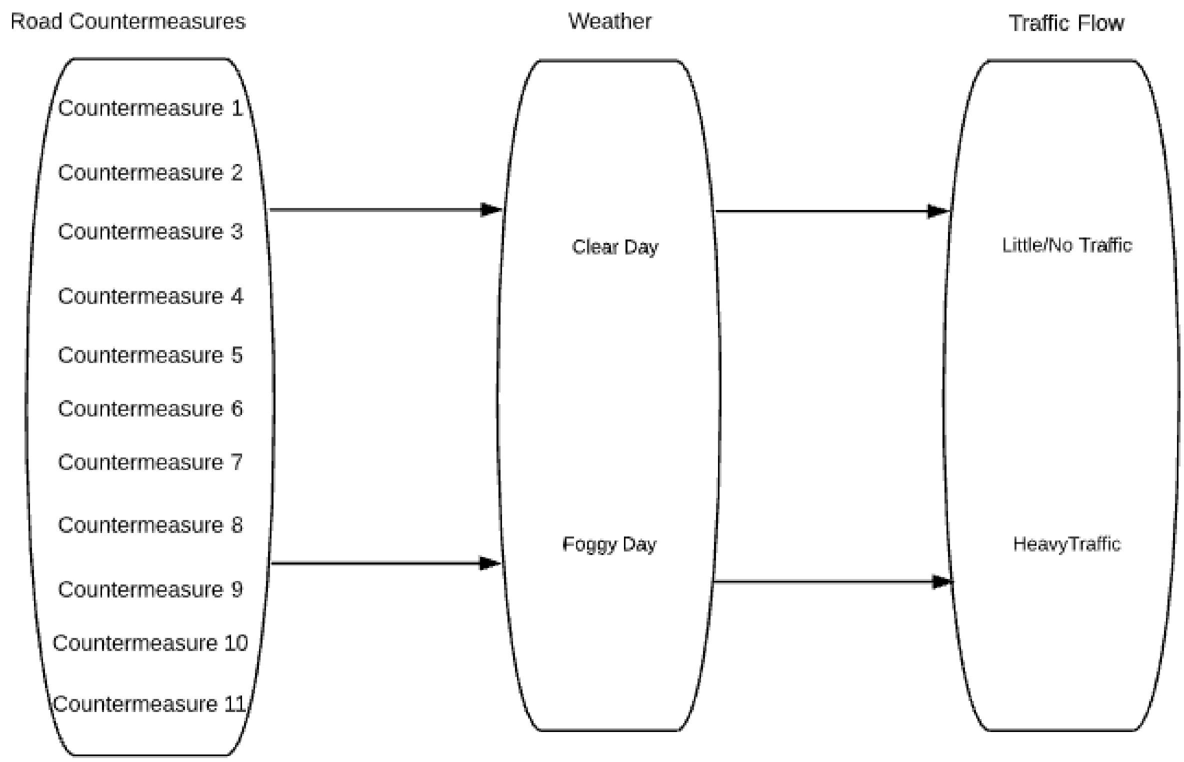


Figure 6. Diagram. Simulation model plan.

SCENARIO MODELING

For this system, the 11 countermeasures selected to be implemented in the driving simulator are shown in table 5. For the simulation, a total of 11 runs were created in each simulation combination. Each run consisted of a combination of countermeasures that were tested. Table 6 shows the various runs and the countermeasures present for each run. From table 6, countermeasure 1 (centerline pavement marking of a solid double yellow line with a width of 6 inches) is the basic one that existed in each run. Also, countermeasure 2 (edge line pavement marking of a solid white line with a width of 6 inches) was added as another basic countermeasure for runs 2 to 11. This was necessary because of the off-road and lane position data that the system collects in order to evaluate driving performance at each run. Then, countermeasures 3 – 11 were added based on the basic two countermeasures respectively to test the impact of each countermeasure.

Table 6. Runs and countermeasures for each combination.

Runs Present in Each Combination (Run=R)	Countermeasures Present in Each Run (Countermeasure=C)	Note: Countermeasures
R1	C1	C1=Centerline Pavement Marking
R2	C1, C2	C2=Edge Line Pavement Marking
R3	C1, C2, C3	C3=Shoulder Rumble Strips
R4	C1, C2, C4	C4=Flexible delineator posts
R5	C1, C2, C5	C5=Posted Speed Sign
R6	C1, C2, C6	C6=Curve Warning Sign
R7	C1, C2, C7	C7=Curve Speed Warning Sign
R8	C1, C2, C8	C8=Increased Shoulder Width
R9	C1, C2, C9	C9=Changed Horizontal Curve Curvature
R10	C1, C2, C10	C10=Decreased Curve Grade on Negative Grade
R11	C1, C2, C11	C11=Increased Curve Grade on Positive Grade

Creating a scenario using this simulator required descriptive programming. In descriptive programming, the user calls together already-provided files in order to give the required output. For example, in order to implement the scenario in figure 7, all components were already provided by the software in a file; what was required was to locate the file address and arrange the scenario based on how the components were to be displayed. In figure 7, a total of five components were called: (1) the roadway, which can be set to different types based on preference. The roadway in this case is referred to the road and its major feature like how many lanes it would have or what type of road either a rough sandy road or a tar road depending on the requirement; (2) the road sign, which in this case was a curve ahead speed limit sign. Many road signs can be implemented as long as the sign can be found in the model library; (3) the weather condition, which was set to be foggy; (4) an incoming road vehicle; and (5) the roadway lines, which includes the edge line and centerline markings on the road. All these components can be changed to match different preferences, but all the possible models are located in the model library, which can be found accompanied by the software file.[1]

Figure 8 and figure 9 show the left and right turns simulated in the project. Figure 10–figure 13 show the different combinations for the full simulations: Figure 10 and figure 12 show the simulation parts that dealt with clear weather and different traffic flow types, while figure 11 and figure 13 show the simulation parts that dealt with foggy weather with the different traffic flows. Following those, figure 14–figure 21 show the countermeasures that were implemented on the horizontal curve, which include the centerline pavement marking, edge line pavement marking, shoulder rumble strips, flexible delineator posts, posted speed sign, curve warning sign, curve speed warning sign and increased shoulder width. For all the countermeasures, the researcher selected standard designs in the driving simulation system. In implementing the shoulder rumble strips scenario from figure 16, rumble strips were not very visible, and the vibration feedback that is felt from the actual shoulder rumble was not possible to achieve. As a close alternative, the shoulder region of the road was changed to a sand setting and a noise effect alone was used. In figure 18, the speed sign scenario involved a change in set posted speed. The speed limit for the simulation was set at 45 mph, but in this scenario the speed limit was changed by decreasing the set limit by 10 mph on the sign. Countermeasures such as the change in curve curvature and the increase or decrease in curve grade, which are vertical curve countermeasures, could not be illustrated in figure form due to the inability to properly capture the desired change.

[1] Although all scenarios were implementable, the STISIM Drive available for this study was a basic version. For future studies, the simulator could be easily updated, and those studies using a higher version would be capable of much more than with the basic version. The higher version would give access to open modules that make it possible to implement a custom design for the roadway setting and even create a dynamic event. It also would provide a wider view of the road setting compared to the view seen in figure 7.

Figure 7. Screenshot. Basic scenario model example.

Figure 8. Screenshot. Left turn in the simulation.

Figure 9. Screenshot. Right turn in the simulation.

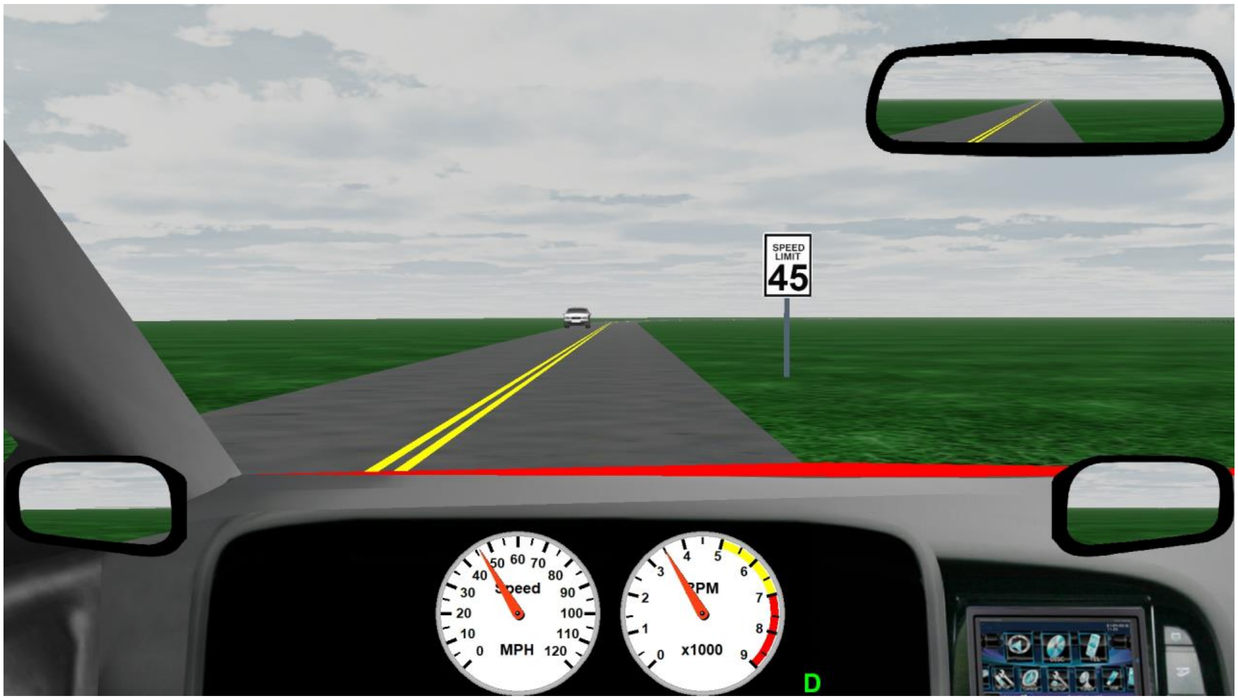


Figure 10. Screenshot. Combination 1 – Light traffic flow with clear weather.

Figure 11. Screenshot. Combination 2 – Light traffic flow with foggy weather.

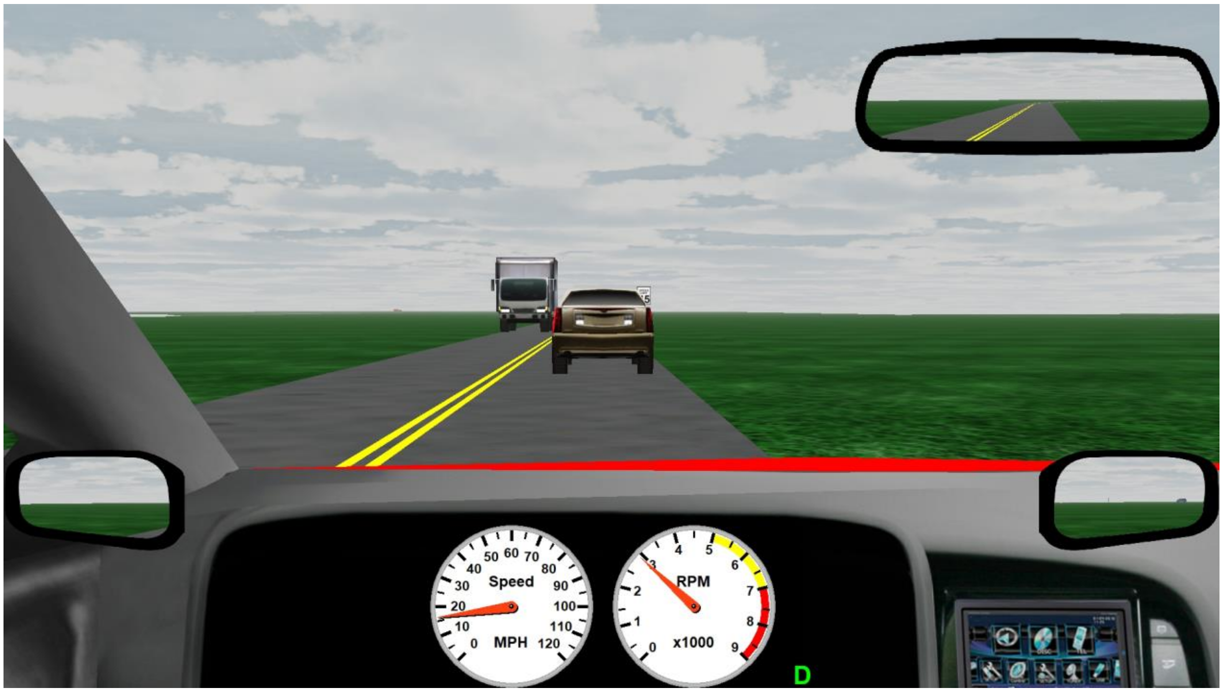


Figure 12. Screenshot. Combination 3 – Heavy traffic flow with clear weather.

Figure 13. Screenshot. Combination 4 – Heavy traffic flow with foggy weather.

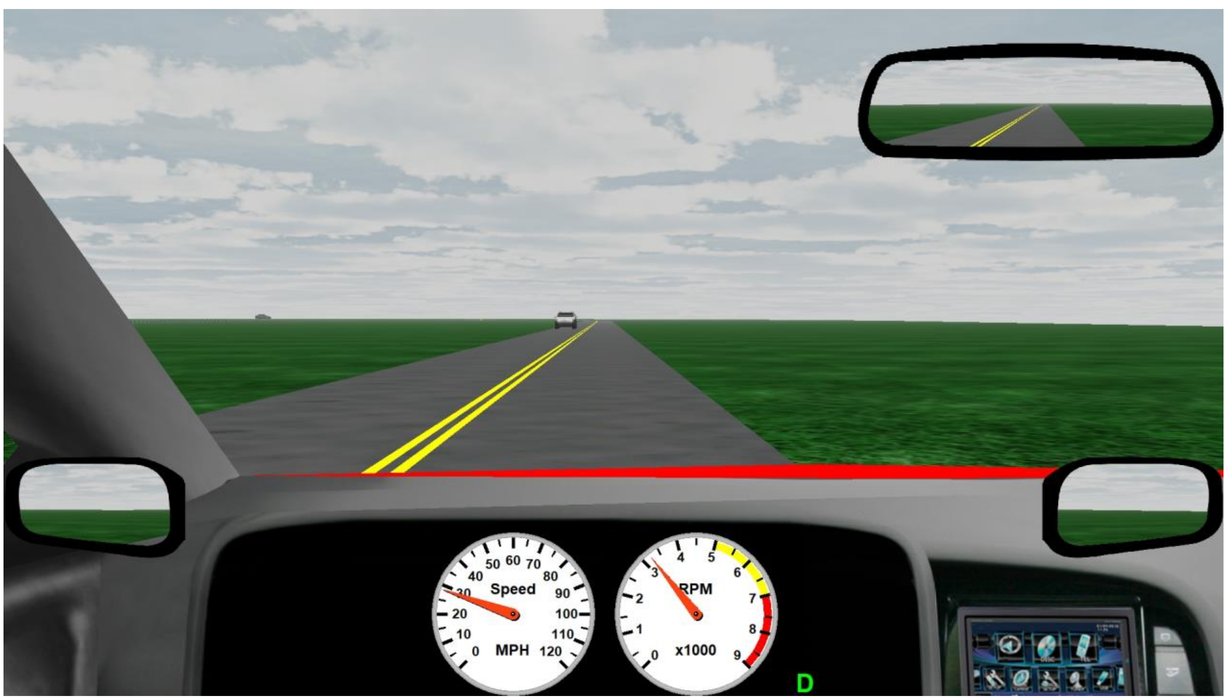


Figure 14. Screenshot. Countermeasure 1 – Centerline pavement marking.

Figure 15. Screenshot. Countermeasure 2 – Edge line pavement marking.

Figure 16. Screenshot. Countermeasure 3 – Shoulder rumble strips.

Figure 17. Screenshot. Countermeasure 4 – Flexible delineator posts.

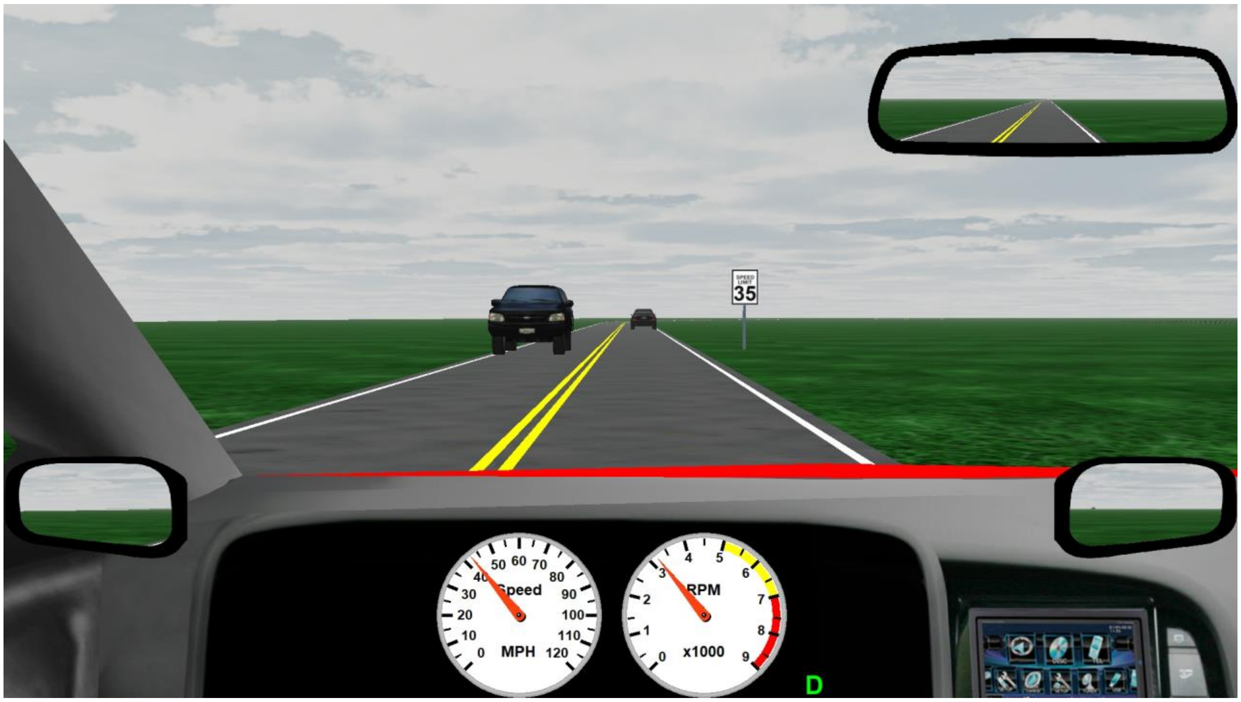


Figure 18. Screenshot. Countermeasure 5 – Posted speed sign.

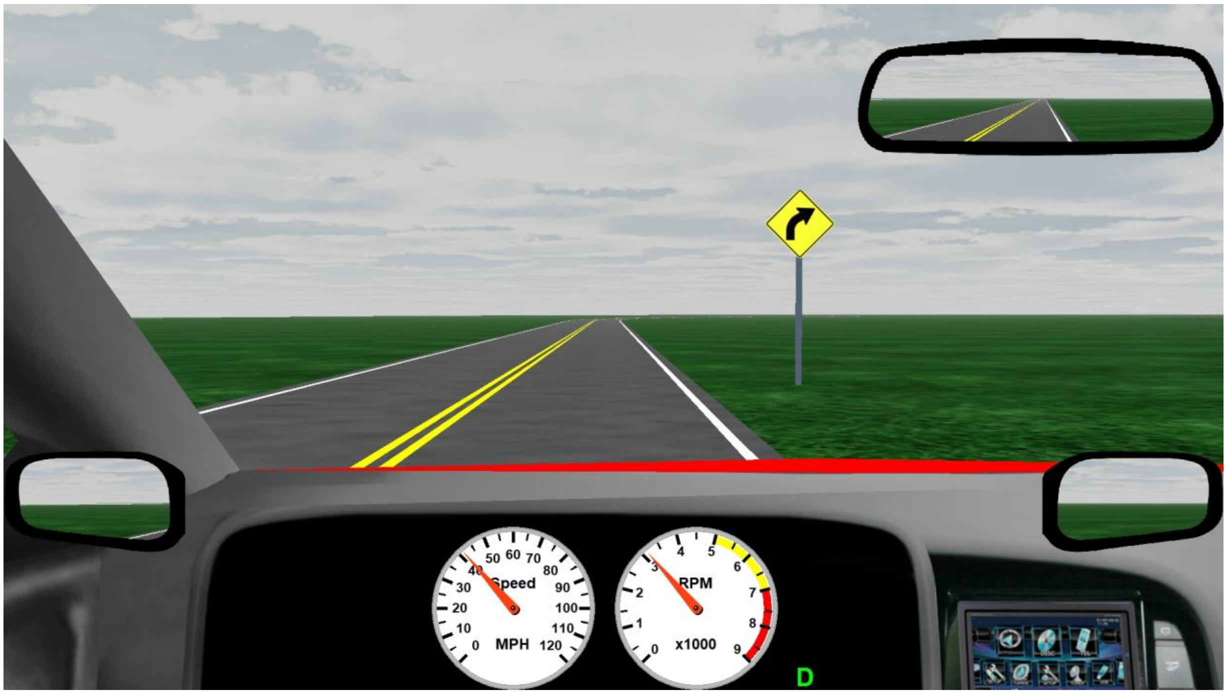


Figure 19. Screenshot. Countermeasure 6 – Curve warning sign.

Figure 20. Screenshot. Countermeasure 7 – Curve speed warning sign.

Figure 21. Screenshot. Countermeasure 8 – Increased shoulder width.

POPULATION AND SAMPLE

A total of 60 participants were chosen as the set sample size for the simulation experiment in order to collect data. The 60 participants were required to match different demographic distribution designs, including age, ethnicity, marital status, etc., as discussed in the demographic indicators section in chapter 2. Due to the lengthy time of the simulations, the performance of the driver could vary between the very beginning and the end of the experiment. Thus, to reduce the bias of the data that favored one combination of the simulation, participants were split into four sets with a different sequence of simulation combinations. The trial phase of the simulation showed that participants usually experienced dizziness due to staring at a screen for a long period of time, which affected the drivers' performance such that they would be active at the first section of the simulation and upon reaching the last part, their activity levels would drop, causing a decline in driver performance. This issue led to the grouping of the participants to attain an even set of data that is well balanced. In grouping the participants, each group took a different set of arrangements for the simulation. They are as follows:

Sequence 1 = Combination 1—Combination 3—Combination 4—Combination 2

Sequence 2 = Combination 3—Combination 2—Combination 1—Combination 4

Sequence 3 = Combination 2—Combination 4—Combination 3—Combination 1

Sequence 4 = Combination 4—Combination 1—Combination 2—Combination 3

The four sequences can contribute to reduce the impact of the different starting time of each combination. The driving simulator system, which is the STISIM Drive, can collect data based on the participant's drive. The specific data collected by the driving simulator for this study were the following 38 indicators:

- Elapsed time (s) since the beginning of the run.
- Longitudinal acceleration (ft/s^2 or m/s^2) of the driven vehicle.
- Lateral acceleration (ft/s^2 or m/s^2) of the driven vehicle.
- Longitudinal velocity (ft/s or m/s) of the driven vehicle.
- Lateral velocity (ft/s or m/s) of the driven vehicle.
- Total longitudinal distance traveled (ft or m) by the driven vehicle since the beginning of the run.
- Lateral lane position (ft or m) of the driven vehicle with respect to the roadway dividing line, positive to the right.
- Vehicle curvature (1/ft or 1/m), the curved path the driven vehicle is following based on the driver's steering and speed.
- Current roadway curvature (1/ft or 1/m).

- Vehicle heading angle (°).
- Steering wheel angle input (°).
- For the simple dynamics: longitudinal acceleration due to throttle (ft/s^2 or m/s^2).
- For the simple dynamics: longitudinal acceleration due to the brakes (ft/s^2).
- Running compilation of driver crashes.
- Minimum time to collision (s) (TTC) for the current simulation frame. During each simulation frame, the TTC for each vehicle traveling in the driver's initial direction[2] will be computed and the lowest overall value of TTC will be used.
- Driver vehicle speedometer value (mph or km/hr).
- Vehicle yaw rate (rad/s).
- Current transmission gear.
- Steering input counts. Actual raw steering wheel input directly from the steering wheel.
- Gas pedal input counts. Actual raw input directly from the gas pedal.
- Brake pedal input counts. Actual raw input directly from the brake pedal.
- Total pitching angle (rad), includes both ground slope and vehicle motion.
- Total rolling angle (rad), includes both ground slope and vehicle motion.
- Steering wheel angular rate (rad/s).
- Minimum TTC (s) between the driver's vehicle and all vehicles in the driver's direction.
- Minimum range (ft or m) between the driver's vehicle and all vehicles in the driver's direction.
- Minimum TTC (s) between the driver's vehicle and all vehicles opposing the driver's direction.

[2] This does not work correctly if the driver does a U-turn.

- Minimum range (ft or m) between the driver’s vehicle and all vehicles opposing the driver’s direction.
- Driver’s response time (s) to any divided attention tasks.
- Current speed limit (ft/s or m/s).
- Current speed limit (mph or km/hr).
- Engine revolutions per minute (RPM) value.
- Minimum TTC (s) between the driver’s vehicle and all cross-traffic vehicles in the driver’s direction.
- Minimum range (ft or m) between the driver’s vehicle and all cross-traffic vehicles in the driver’s direction.
- Minimum TTC (s) between the driver’s vehicle and all pedestrians that are within the extents of the driver’s vehicle.
- Minimum range (ft or m) between the driver’s vehicle and all pedestrians that are within the extents of the driver’s vehicle.
- Absolute value of lateral acceleration (ft/s^2 or m/s^2).
- Absolute value of steering wheel angle (°).

METHODOLOGY AND MATERIALS

The design of the experimental procedure is shown in figure 22. The steps below were followed:

1. When inviting participants, an introduction and explanation were provided to briefly introduce the experiment and project.
2. Before the experiment, the demographic information was collected by questionnaire.

3. During the driving simulation, the eye movements and driving performance data were collected by the eye tracker and driving simulator.
4. After each combination of the experiment, the participants' short-term memory was measured via questionnaires.
5. After the experiment, a post-survey was conducted to record participants' experiences and comments.

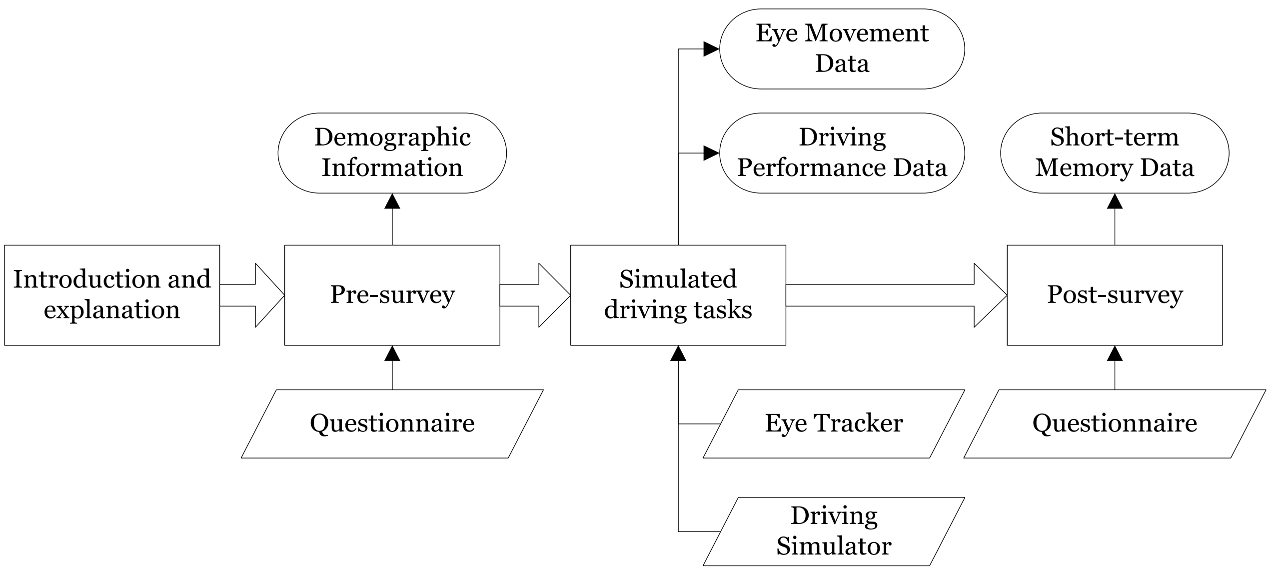


Figure 22. Flowchart. Experiment procedure.

Demographic Information

A pre-experiment survey collected participants' demographics. According to the indicators mentioned in the literature review, the pre-survey questionnaire covered three parts: basic information, household status and habits, and driving experience. First, the basic information covered the location, ethnicity, gender, age, education, and occupation of participants to record the basic demographics. Then, the household status and habits covered the marital status, annual household income, visual ability, glasses-wearing habit, smoking habit, and alcohol consumption habit. For the annual household income, data had indicated that the median household income of Georgia was $58,765 in 2018, and the highest share was 75K–100K (ACS 2018). Thus, the research team set the ranges of choices for this question according to that data. Finally, the driving experience portion asked about the driving experiences, average driving hours per week, and past crash or ticket record. The pre-survey questionnaire is attached in the appendix A: pre-survey.

Eye Movements and Driving Performance

The participants' eye movements were collected by eye tracker during the driving simulation. The indicators included pupillometry, saccade, and fixation to measure the cognitive workload, attention pattern and shifts, level of interests, and the difficulty of information extraction and understanding, as shown in table 7.

Table 7. Factors of eye movements.

Category	Definition	Indicators	Meaning	Measurement/Unit
Pupillometry	Diameter of pupil	Changes of pupil diameter	Cognitive workload	Variance of pupil diameter left and right (mm^2)
		Average pupil diameter	Cognitive workload	Mean of pupil diameter left and right (mm)
Saccade	Fast eye movements between different fixation points	Saccade duration	Attention pattern (dispersed)	Mean of saccade durations (ms)
		Number of saccades	Attention shifts	Number of saccades
		Saccade distance	Attention shifts	Mean of movement distance of the eye between fixation points (pixel)
		Saccade speed	Attention shifts	Mean of speed of movement of the eye between fixation points (pixel/ms)
Fixation	Eye movements located within a spatially limited region for a minimum period	Number of fixations	Level of interest	Number of fixations
		Fixation duration	Difficulty of information extraction and understanding	Mean of fixation duration (ms)

Meanwhile, the participants' driving performance was collected using a driving simulator. There were 38 indicators collected by the driving simulator in the experiment. The factors that were used in the study to measure driving performance, including crash, speed, steering wheel angle, and lateral lane position, are shown in table 8.

Table 8. Factors of driving performance.

Category	Indicators	Measures	Scale/unit
Crash	Number of any contact with an object	Running compilation of driver crashes	Number
Speed	Vehicle speed	Driver vehicle speedometer value	m/hr
	Acceleration and deceleration	Absolute value of longitudinal acceleration	ft/s^2
	Lateral acceleration	Absolute value of lateral acceleration	ft/s^2
Others	Steering wheel angle	Absolute value of steering wheel angle	degrees (°)
	Lateral lane position	Lateral lane position of the driven vehicle to the roadway dividing line, positive to the right	ft

Note: Six types of crashes can be collected by the simulator: 1 = Vehicle collisions; 2 = Off-road collisions; 3 = Collisions with pedestrians; 4 = Collisions with lane markers (e.g., barrels, cones, etc.); 5 = Collisions with Jersey barriers; 6 = Collisions with collision blocks.

Short-term Memory

The participants' short-term memory was collected by a questionnaire survey after each combination of the different weather conditions and traffic flows. The indicators included recall ability, the ability to control attention, and speed of item identification and processing, as shown in table 9. The survey is attached in the appendix B: short-term memory questionnaire.

To gauge the *recall ability*, the pictures of nine countermeasures that could be seen in the simulation were presented, such as the curve warning sign, centerline pavement marking, etc. The picture included the sign or marking itself rather than the whole scenario to ensure no additional information was available to remind the participants. Participants were asked to check the countermeasures they remembered in order to evaluate their recall ability immediately after driving. Then, for measurement of the *ability to control attention*, the questionnaire displayed pictures of cars to allow the participants to check whether they had noticed those cars during the experiment; the vehicles were meaningful but irrelevant objects around the countermeasures. The survey covered four questions in different difficulty levels. The first question asked the participants to randomly select two cars from five completely different cars. Then, the second question used the same cars with different colors. The third question covered different cars of the same color. The last question asked for the sequence of the cars' appearance during the experiment. These survey questions were able to check whether other information distracted the drivers' attention. Finally, for the *speed of item identification and processing*, the 5-point Likert scale was used to let the participants self-evaluate.

Table 9. Factors of short-term memory.

Indicators	Definitions	Measurement
Ability to Control Attention	Ability to inhibit irrelevant information	Whether participant noticed the cars during the simulation
Recall Ability	Retrieval of past information	Whether participant saw the countermeasures during the simulation
Speed of Item Identification and Processing	Ability of identifying and processing an item	How confident is the participant in ability to identify the countermeasures quickly and accurately (5-point Likert scale)?

Post-survey

Finally, a post-survey was conducted to measure the experiences of participants. The questions covered the dizziness or other symptoms, the effect of taking breaks or not, the experiences of using the eye tracker, whether the incentive encouraged them to participate in the experiment, and the helpfulness of the research team. The survey is attached in the appendix C: post-survey.

DATA COLLECTION PROCESS

Collecting data from 60 participants requires planning and organization. This was not an easy task, as the issues arising—such as special safety protocols for COVID-19, participant rescheduling due to cancellation, or even failure to show up. In figure 23, a detailed flowchart of the data collection process is provided.

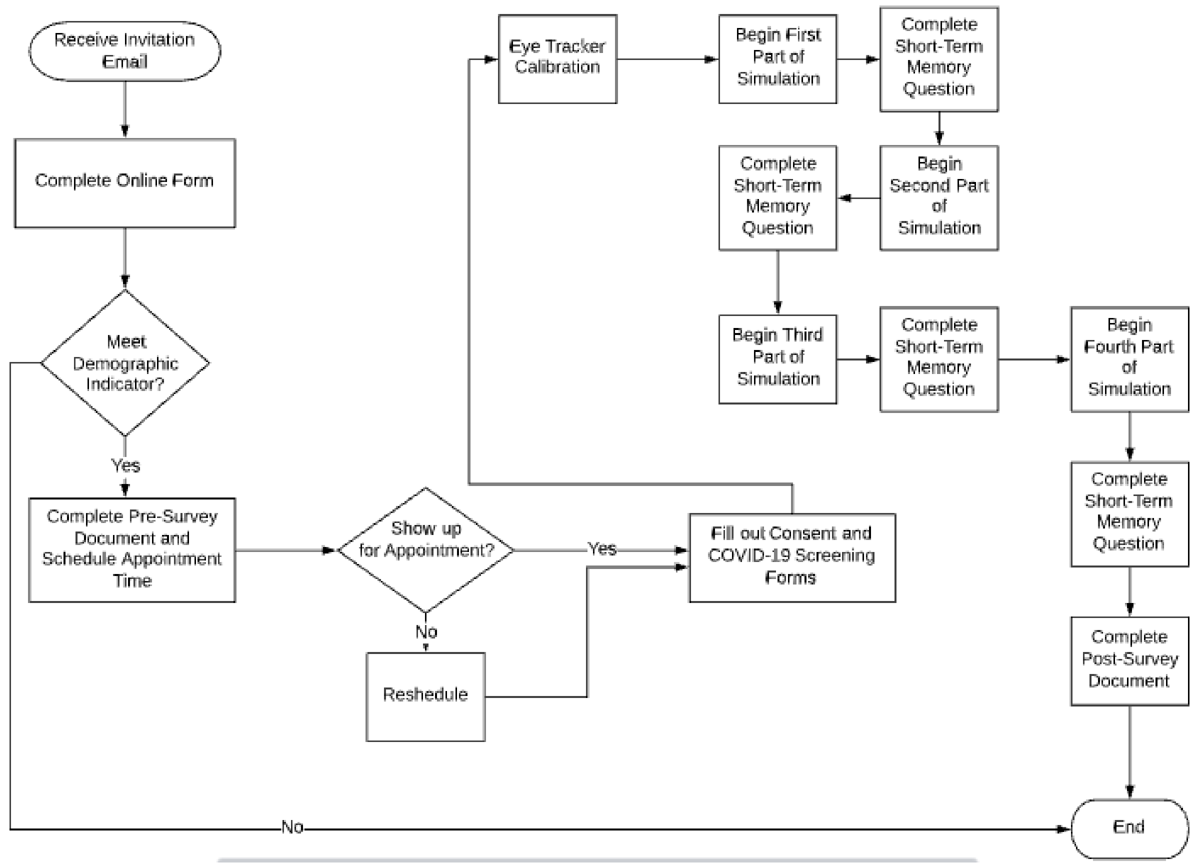


Figure 23. Flowchart. Data collection process.

To start the process, an invitation letter was sent by email, out to the residents of the populating region. Within this invitation letter was a link to a form to fill out online, making it possible to select participants carefully in order to match the demographic indicators set. The research team reached out to selected participants in order to schedule an appointment to come in, as well as to complete the pre-survey document. Participants who were not able to make their appointment were given the option to reschedule. Those who did come in were then given a consent form and a COVID-19 screening form to go over. Hand sanitizer was then passed out to participants and the driving simulator equipment was sanitized between participants. Each participant was given a number based on the 60 required participants. After all the forms were filled and the participant was settled at the simulator, the participant would undergo an eye calibration test, which then began the driving simulation's official data collection. The simulation sequence would be determined based on the participant's number and, according to that sequence, the first simulation combination of weather and traffic would begin for that participant. After the first simulation combination of weather and traffic, a short-term memory questionnaire was given to the participant based on that simulation combination. After completing the questionnaire, the participant was given the option to go on a short break or continue. After the opportunity for a break, the participant went on to the next combination, which would follow another short-term memory question based on that simulation combination and another break session, if desired. The same process went on until the last simulation combination, after which the participant took the short-term memory questionnaire and also filled out a post-survey document. That concluded the data collection for that participant. All data were then saved into a file based on the participant's number.

CHAPTER 4. RESULTS AND DISCUSSIONS

Data analysis was conducted for four different purposes with four various mathematic tools/methods, as shown in figure 24. Combining all the results, a comprehensive discussion was used to further explain and summarize all the findings, as follows:

1. Descriptive analysis was conducted to summarize the demographic information of the 60 participants and the short-term memory data from the questionnaires.
2. Analysis of variance (ANOVA) tests were applied to compare the eye movements, driving performance, and short-term memory among the countermeasures, combinations of weather and traffic, sequence of different combinations, and order of each combination. Specifically, how the countermeasures impact the eye movements indicators and driving performance indicators were discussed.
3. Heat maps and gaze plots were used to achieve the visualization of attention distribution and intensity of drivers.
4. Machine learning was used to examine the relationships between the countermeasures, cognition indicators, and traffic safety. The relationships can be divided into three parts: regression model between countermeasures and traffic safety (number of crashes), regression model between countermeasures and drivers' cognition (eye movements indicators), and regression model between drivers' cognition and traffic crashes.

This chapter presents the results of these analyses, as well as their discussions.

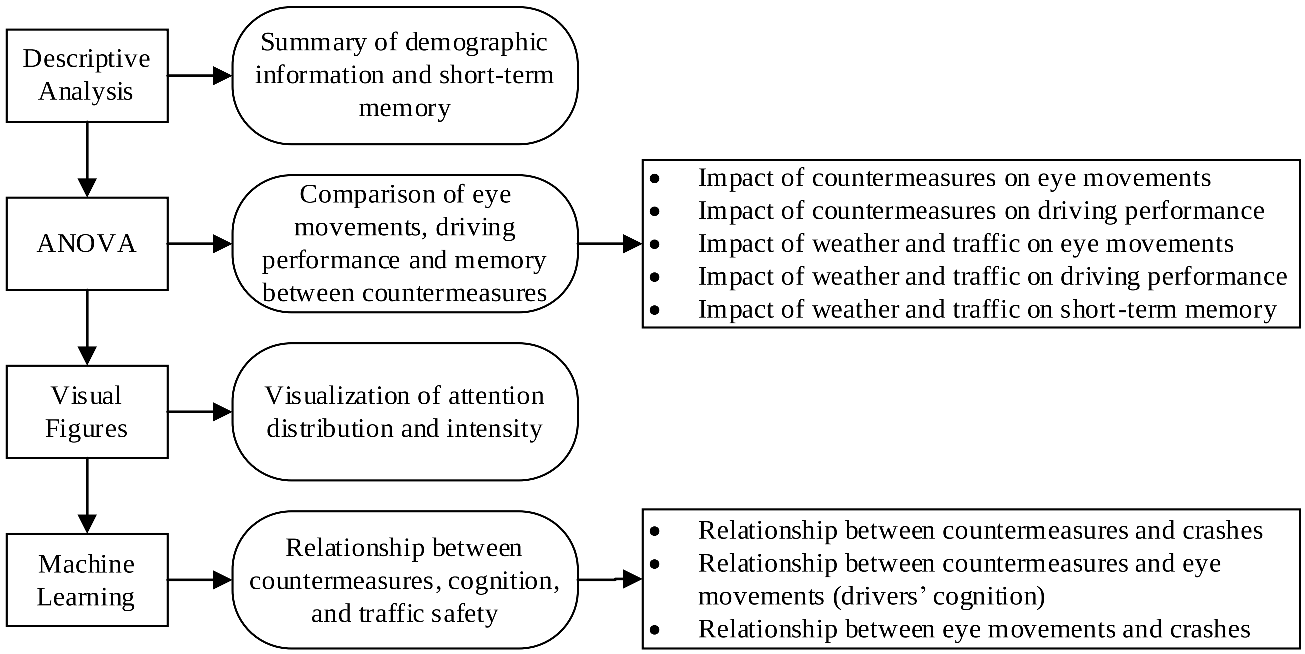


Figure 24. Flowchart. Data analysis process.

DESCRIPTIVE ANALYSIS

Based on the demographic data and the short-term memory data, charts were used to represent the distribution or note significant changes. In this section, as the name implies, a summary of the statistical analysis is displayed, i.e., an analysis of the basic features of the data in this study.

Demographic Data Analysis

Based on the data of demographic indicators from the 60 participants, a chart analysis was done. Figure 25 shows the gender breakdown of all participants; a total of 35 males and 25 females participated. Figure 26 and figure 27 show the ethnicity breakdown of all participants. The data display that the white ethnicity was a major ethnic group for both male and female genders among the participants. The next demographic indicator is the distribution of the age of the participants, as shown in figure 28. The majority of participants were in the ages between 25 to 34; however, a further breakdown of the age groups according to the common practice for traffic safety analysis is presented in figure 28. Due to the COVID-19 pandemic, the research team faced difficulties in recruiting senior participants as planned, leading to a huge percent of young group. The next demographic breakdown (figure 29) is participants' driving experience grouped based on fewer or greater than 5 years. The majority were experienced drivers, as they had more than 5 years of driving experience. Finally, Table 10 is the breakdown of participant data based on smoking habits and alcohol consumption. No participant was identified as a frequent smoker and frequent consumer of alcohol, but a large number of participants identified as consuming alcohol occasionally. In the case of smoking, more participants identified under the class of not smoking at all than those who identified as occasional smokers.

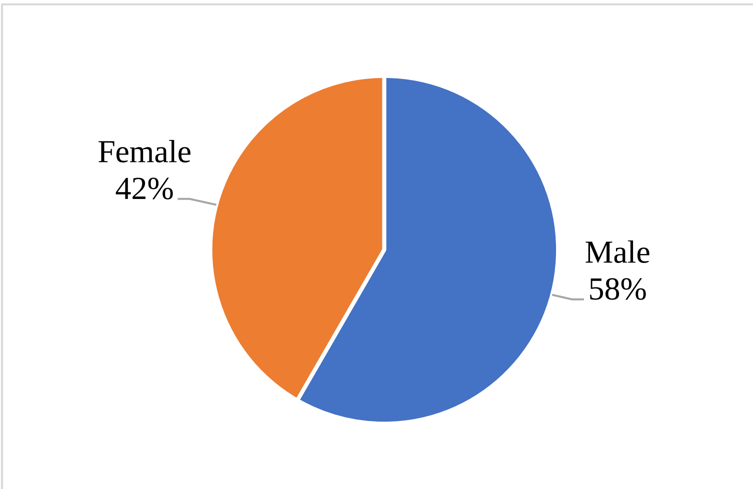


Figure 25. Pie graph. Breakdown of participants by gender.

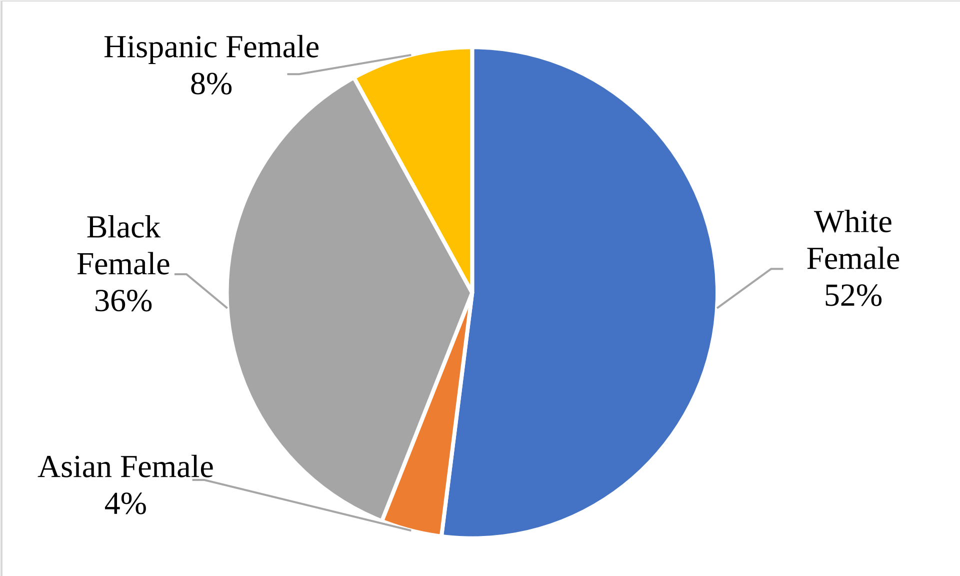


Figure 26. Pie graph. Breakdown of female participants by ethnicity.

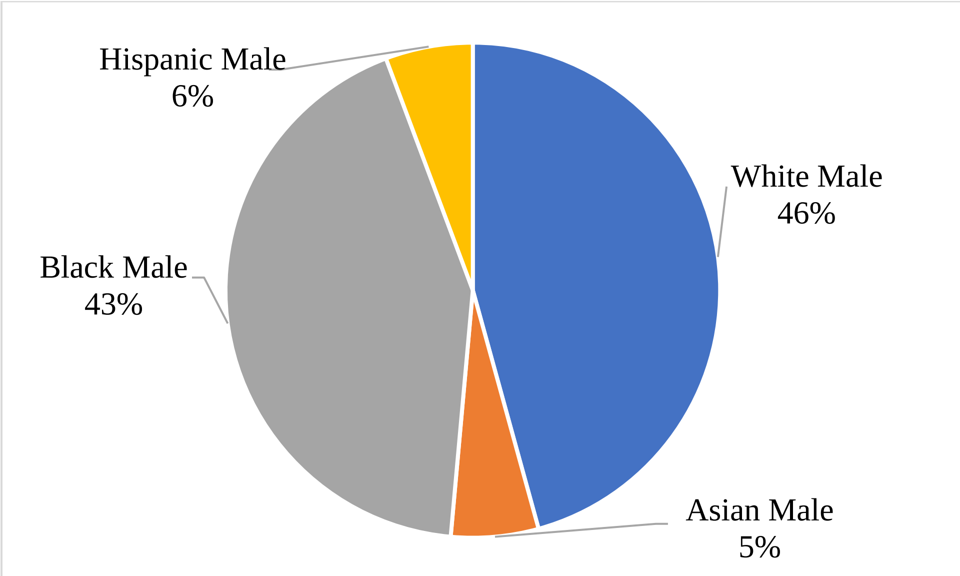


Figure 27. Pie graph. Breakdown of male participants by ethnicity.

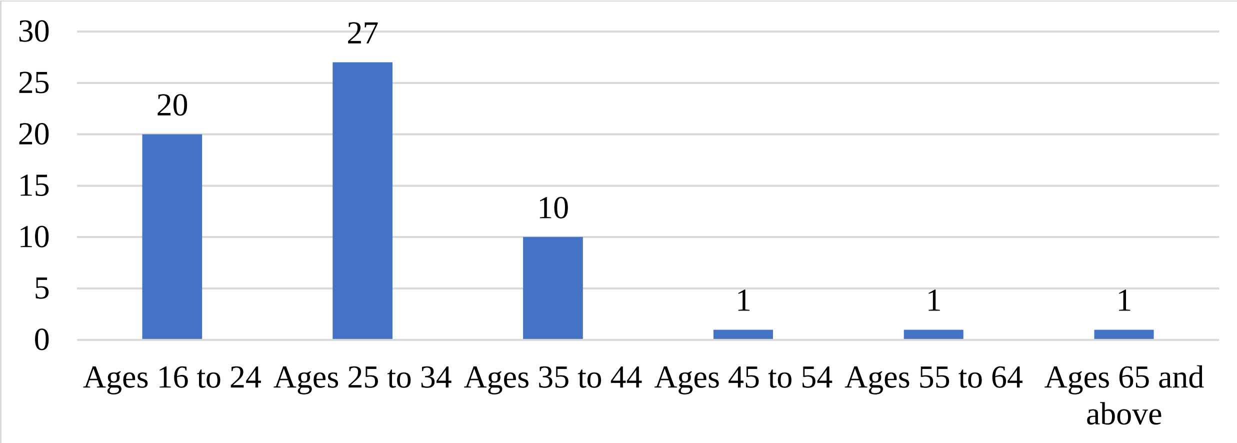


Figure 28. Pie graph. Breakdown of participants by age.

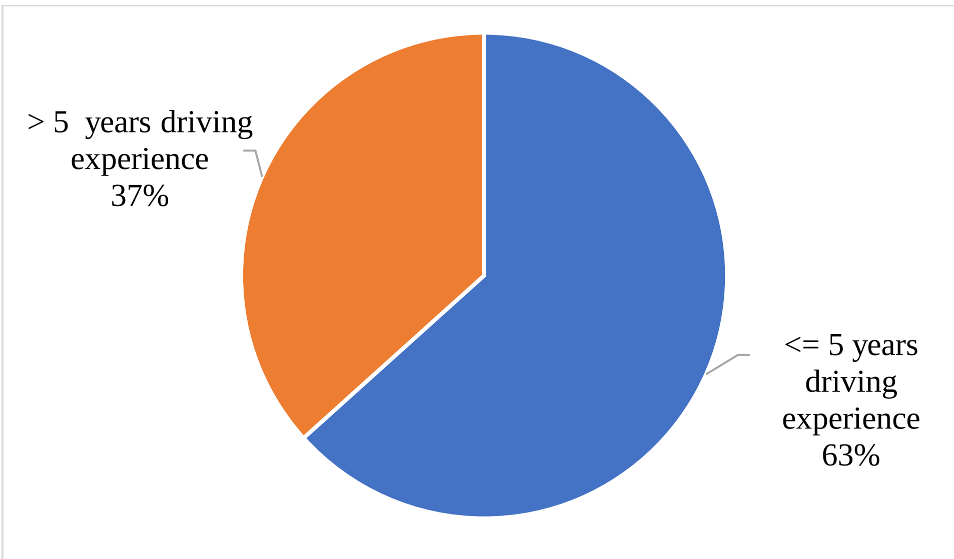


Figure 29. Pie graph. Breakdown of participants by driving experience.

Table 10. Breakdown of participants by smoking and alcohol consumption.

Indicator	Frequently (%)	Occasionally (%)	Not at All (%)
Alcohol	0.0	73.0	27.0
Smoking	0.0	47.0	53.0

Short-term Memory Data Analysis

A chart analysis was performed based on the short-term memory questions given to the participants at the end of each simulation. This analysis was centered on the three tests that the short-term memory questions aimed to investigate (see the appendix B: short-term memory questionnaire). For each short-term memory questionnaire, images of the countermeasures were presented. These images were used to test the preciseness of their recall ability. In the first three parts of the short-term memory questions, a set of five cars was displayed on the survey forms from which the participants were to select. Only two of the five cars actually appeared in each combination of the simulation. The participants were asked to identify the two vehicles that had appeared. The last part was a test of the drivers' pattern identification ability, as participants were required to recall the order in which a set of cars drove past them in the simulation.

Table 11 shows the mean, median, and mode values of all participants for each simulation combination; these were used to assess the accuracy of the recall test from the short-term memory questions. The mean values showed that participants' recall ability was lower in the simulation combination of heavy traffic and clear weather. More participants could successfully recall all images except in the simulation combination of light traffic with clear weather, this is because as seen from table 11, the mode for the other three combinations is higher (i.e. 100%) compared to that of the combination of light traffic with clear weather (i.e. 88.89).

Table 11. Breakdown of recall test for all participants.

Combinations	Mean (%)	Median (%)	Mode (%)
Light Traffic with Clear Weather	88.15	88.89	88.89
Light Traffic with Foggy Weather	89.08	88.89	100.00
Heavy Traffic with Clear Weather	86.11	88.89	100.00
Heavy Traffic with Foggy Weather	86.67	100.00	100.00

Figure 30 to figure 32 are pie graphs of the item identification ability for the first three simulation combinations. As shown in these figures, more participants got all items correct in combination 1, but then combination 2 had the lowest number of participants who got none correct. As shown in figure 31, participants had more problems identifying the items in this situation, as it recorded the lowest number of correct answers. Figure 33 shows the number of participants who got the pattern identification placed properly in the short-term memory question for combination 4. Half of the participants were able to identify the correct pattern.

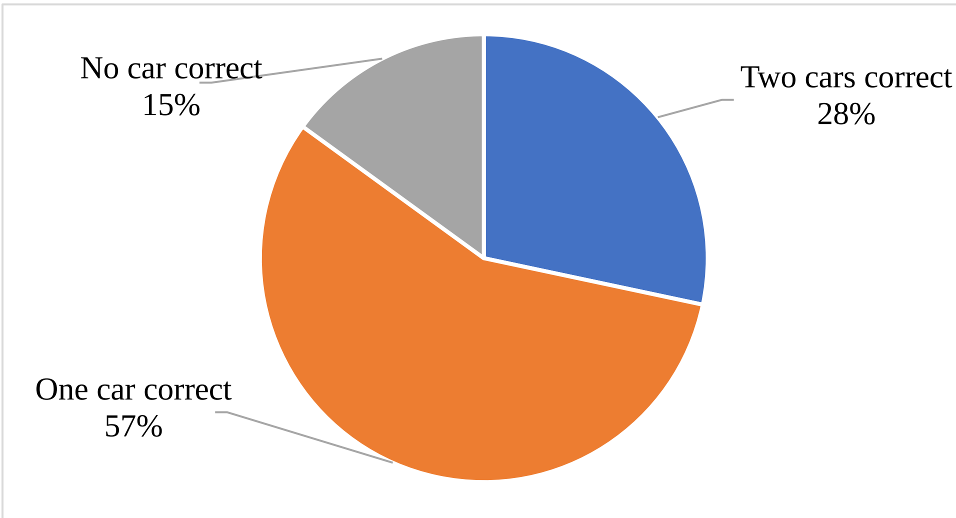


Figure 30. Pie graph. Item identification analysis breakdown for combination 1.

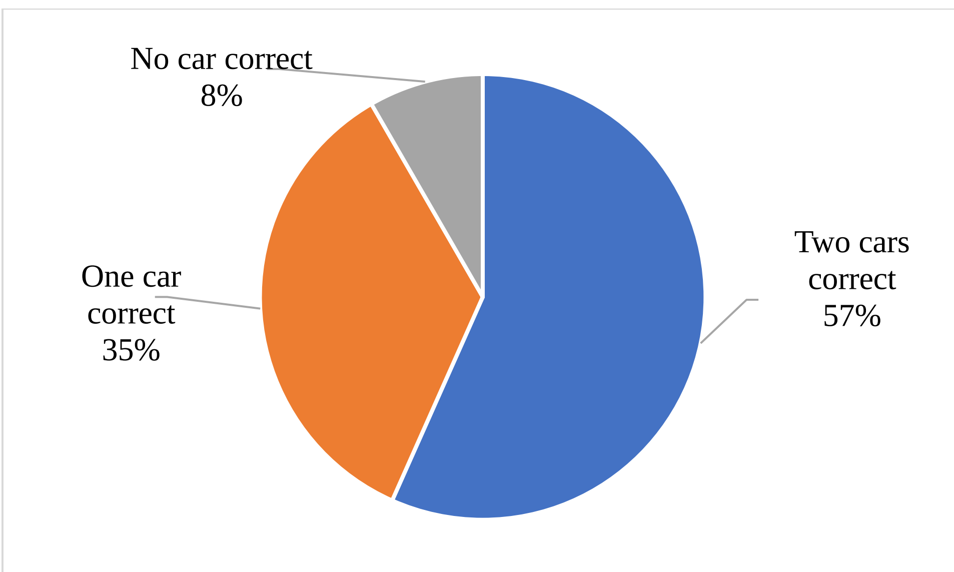


Figure 31. Pie graph. Item identification analysis breakdown for combination 2.

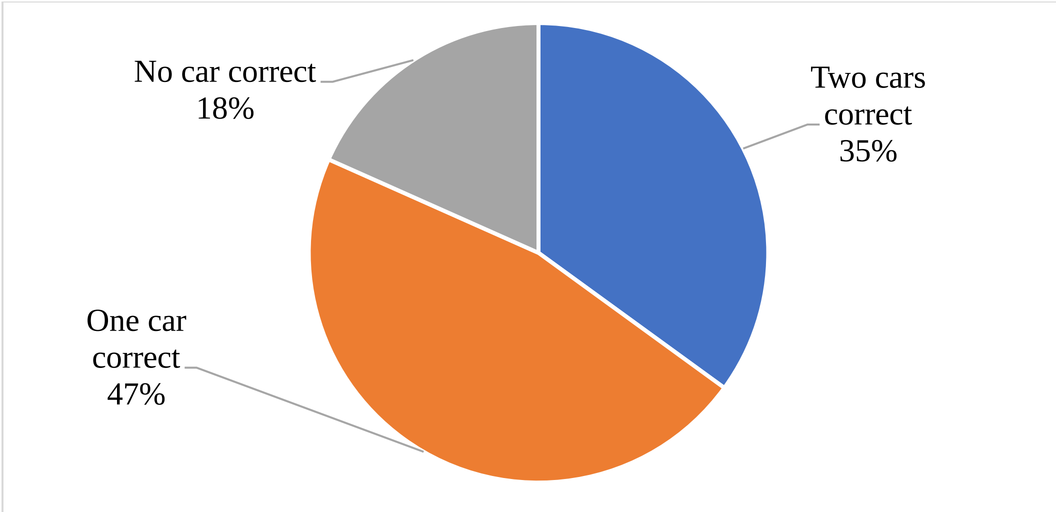


Figure 32. Pie graph. Item identification analysis breakdown for combination 3.

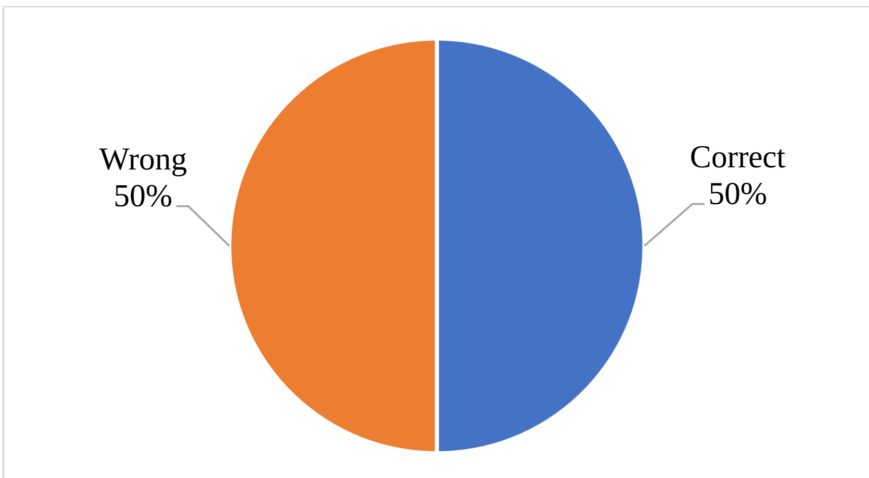


Figure 33. Pie graph. Pattern identification analysis breakdown for combination 4.

ANOVA TEST FOR EYE MOVEMENTS, DRIVING PERFORMANCE, AND MEMORY

To determine whether there were significant differences in drivers' eye movements, driving performance, and short-term memory capacities among the 11 different countermeasures, a one-way ANOVA analysis was performed. RStudio® and SAS® software were applied to conduct the statistical analysis of the collected data. The analysis results can provide a better insight into this methodology and empirical evidence to the effectiveness of different countermeasures, which can help engineers to select the optimal countermeasures in similar locations, to reduce crashes and increase road safety. Also, the ANOVA test was applied to evaluate whether significant differences existed between the four simulation combinations of different weather conditions and traffic flows.

To explain the ANOVA test, the hypothesis for examining the impact of countermeasures on the number of crashes (which is one indicator for driving performance) is listed below as an example.

> *Ho*: drivers had the same number of crashes under all the countermeasures: $\mu_1 = \mu_2 = \mu_3 = \cdots = \mu_{11} = c$
>
> *Ha*: at least one of the group means of crashes was different from the others: $\mu_i \neq c$

In the results, when $p > 0.05$, *Ho* is accepted. Thus, there was no significant difference in the number of crashes between the 11 countermeasures. On the contrary, if $p < 0.05$, *Ha* is accepted, which means at least one countermeasure had a different number of crashes than the others.

Where,

> μ_i is the group mean value for countermeasure i.
>
> c is a constant value.
>
> p is the p-value of the ANOVA test.

Based on the settings of 11 countermeasures in 11 experiment runs as explained in table 6 (page 25), ANOVA tests were divided into two parts: (1) comparison between the first (centerline) and the second run to test the impact of the edge line pavement marking (countermeasure 2); and (2) comparisons between the second and the remaining nine runs to examine the impacts of countermeasures 3–11. Here, the impact of countermeasure 1 (centerline pavement marking) was not compared because it is regarded as a basic countermeasure. Then, for the four combinations of weather conditions and traffic flow, an ANOVA test was performed using the four combinations as the independent variable. Eye movements, driving performance, and short-term memory indicators were used as dependent variables, respectively.

Eye Movements

Eye Movements Between Countermeasures

Table 12 shows the results of ANOVA tests for the eight eye movements indicators. Countermeasure 2 (edge line pavement marking) did not have significant impact on the number of saccades ($p = 0.10$) and saccade duration ($p = 0.17$); however, all the other six indicators were significantly impacted by this countermeasure ($p < 0.01$). Then, for the impacts of countermeasures 3–11, average pupil diameter ($p = 0.97$), number of saccades ($p = 0.13$), and saccade duration ($p = 0.76$) did not have significant differences, while the other five eye movements indicators had significant differences.

Table 12. Results of ANOVA tests for eye movements and countermeasures.

Variables	ANOVA Test					
	Impact of Countermeasure 2					
	Source	***Df***	***Sum Sq***	***Mean Sq***	***F value***	***Pr (>F)***
Changes of Pupil Diameter	Model	1	0.88	0.88	196.54	<0.01
	Error	474	2.13	0.00		
Average Pupil Diameter	Model	1	5.88	5.88	31.98	<0.01
	Error	474	87.18	0.18		
Saccade Duration	Model	1	146.13	146.13	2.78	0.10
	Error	474	24,955.32	52.65		
Number of Saccades	Model	1	250,522.26	250,522.26	1.86	0.17
	Error	474	63,885,400.74	134,779.33		
Saccade Distance	Model	1	839,224.83	839,224.83	257.76	<0.01
	Error	474	1,543,245.40	3,255.79		
Saccade Speed	Model	1	3,419.30	3,419.30	359.09	<0.01
	Error	474	4,513.47	9.52		
Number of Fixations	Model	1	71,115.43	71,115.43	10.14	<0.01
	Error	474	3,324,832.26	7,014.41		
Fixation Duration	Model	1	260,246.32	260,246.32	21.55	<0.01
	Error	474	5,722,912.88	12,073.66		
	Impact of Countermeasures 3–11					
	Source	***Df***	***Sum Sq***	***Mean Sq***	***F value***	***Pr (>F)***
Changes of Pupil Diameter	Model	9	0.07	0.01	4.93	<0.01
	Error	2344	3.70	0.00		
Average Pupil Diameter	Model	9	0.53	0.06	0.32	0.97
	Error	2344	429.97	0.18		
Saccade Duration	Model	9	323.01	35.89	0.64	0.76
	Error	2362	132,329.75	56.02		
Number of Saccades	Model	9	2,017,188.00	224,132.00	1.53	0.13
	Error	2362	346,463,032.00	146,682.10		
Saccade Distance	Model	9	367,326.59	40,814.07	9.46	<0.01
	Error	2359	10,181,355.32	4,315.96		
Saccade Speed	Model	9	943.25	104.81	9.47	<0.01
	Error	2359	26,117.70	11.07		
Number of Fixations	Model	9	649,739.49	72,193.28	8.48	<0.01
	Error	2362	20,114,438.36	8,515.85		
Fixation Duration	Model	9	377,142.58	41,904.73	3.23	<0.01
	Error	2362	30,653,506.79	12,977.78		

Table 13 shows the mean values and standard deviations of indicators under each run. The eight eye movements indicators and their meanings will be discussed individually.

Table 13. Summary of eye movements under countermeasures.

Countermeasures	Variables (unit)							
	Changes of Pupil Diameter (mm^2)		Average Pupil Diameter (mm)		Saccade Duration (ms)		Number of Saccades	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
1	0.13	0.09	3.44	0.43	28.30	6.65	484.66	309.63
1&2	0.04	0.04	3.22	0.43	27.19	7.82	530.54	417.16
1&2&3	0.04	0.04	3.22	0.42	27.01	7.71	519.71	402.35
1&2&4	0.04	0.03	3.21	0.42	26.75	7.22	548.15	453.44
1&2&5	0.05	0.04	3.21	0.42	26.85	7.43	524.03	405.97
1&2&6	0.05	0.05	3.20	0.42	27.08	7.60	519.34	370.09
1&2&7	0.05	0.04	3.19	0.44	26.98	7.15	527.16	370.89
1&2&8	0.05	0.03	3.19	0.44	27.38	7.84	503.68	368.19
1&2&9	0.05	0.04	3.19	0.43	26.94	7.48	489.67	344.08
1&2&10	0.05	0.04	3.21	0.44	26.25	7.16	505.48	372.80
1&2&11	0.06	0.04	3.23	0.43	26.15	7.40	436.09	305.76
	Saccade Distance (pixel)		Saccade Speed (pixel/ms)		Number of Fixations		Fixation Duration (ms)	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
1	259.06	55.82	14.78	3.30	235.38	73.63	314.68	76.83
1&2	175.09	58.28	9.42	2.85	259.83	92.85	361.45	135.26
1&2&3	171.12	61.56	9.21	2.75	254.69	89.21	355.69	118.77
1&2&4	172.80	61.67	9.42	3.20	256.05	88.74	341.67	111.87
1&2&5	180.00	60.03	9.74	3.17	252.71	91.26	337.27	107.03
1&2&6	183.52	61.13	9.95	3.10	252.83	96.58	342.50	112.67
1&2&7	180.45	62.93	9.88	3.47	255.22	88.82	337.15	108.70
1&2&8	180.41	66.91	9.61	3.24	247.85	96.67	352.74	117.85
1&2&9	179.23	68.45	9.69	3.36	243.73	89.30	347.59	105.46
1&2&10	179.84	67.41	10.03	3.67	234.64	96.01	347.45	114.60
1&2&11	217.79	84.64	11.60	4.23	200.70	92.89	313.25	103.75

Note: SD: Standard deviation

First, the change of pupil diameter was measured by the average value of variances of left pupil diameters and right pupil diameters in equation 1:

$$Changes\ of\ pupil\ diameter = \frac{var(left\ pupil\ diameter) + var(right\ pupil\ diameter)}{2} \tag{1}$$

Second, the average pupil diameter was measured by the average value of the left pupil diameter and the right one. Both indicators measure drivers' cognitive workload. The higher the values of the changes of pupil diameter and average pupil diameter, the higher the cognitive workload. The mean values indicated that only centerline pavement marking had the largest changes of pupil diameter and average pupil diameter, which means the highest cognitive workload compared to the other combined countermeasures. Thus, adding the other 10 countermeasures reduced the cognitive workload significantly. The centerline and edge line markings (1&2), adding shoulder rumble strips (1&2&3) and adding flexible delineator posts (1&2&4) had the lowest level of cognitive workload. A countermeasure with cognitive workload that is too low indicates that the countermeasure may receive less attention from drivers, and vice versa. However, a heavy cognitive workload might decrease driving performance because drivers may feel stress and fatigue easily due to the increased needs for cognitive resources (de Greef et al. 2009, Palinko and Kun 2012). An adequate level of cognitive workload is desirable and can improve driving performance (Brookhuis and de Waard 2010).

Then, the third indicator was saccade duration, which ranged from 26.15 ms to 28.30 ms. The higher saccade duration indicated a more dispersed attention pattern of drivers, meaning drivers' attentions were less focused, which may result in worse driving performance (Desmet and Diependaele 2019). No statistically significant difference was identified for the attention pattern between the countermeasures discussed.

The fourth indicator was the number of saccades, which ranged from 436.09 to 548.15 on average for the countermeasures. The fifth indicator, saccade distance, was the distance in pixels between fixations (de Greef et al. 2009), which can also be measured in degrees (Reyes and Lee

2008). Because the driving simulator recorded the fixation point X and Y in pixels, the saccade distance in pixels can be calculated as in equation 2:

$$Saccade\ distance\ = \sqrt{\Delta X^2 + \Delta Y^2} \quad (2)$$

Where, ΔX and ΔY indicate the horizontal and vertical changes of fixation points at the beginning and end of the saccade.

The sixth indicator was saccade speed, which was defined as the saccade distance divided by the saccade duration (de Greef et al. 2009, Reyes and Lee 2008) as in equation 3:

$$Saccade\ distance\ = Saccade\ distance\ /\ Saccade\ duration \quad (3)$$

All three indicators were used to measure attention shifts of drivers. The higher the number of saccades, saccade distance, and saccade speed, the more frequently drivers obtained visual information from new locations (Takeda et al. 2016). According to the mean values, adding the other countermeasures based on centerline pavement marking reduced the attention shifts significantly because the saccade distance and speed decreased. Among countermeasures 3–11, adding shoulder rumble strips (1&2&3) had the fewest attention shifts, while adding increased curve grade on positive curve (1&2&11) had the most attention shifts. Fewer attention shifts indicated less information obtained for the driving task, which may result in the underload and reduce the alertness of drivers (Takeda et al. 2016). On the contrary, more attention shifts indicated the higher difficulties of driving tasks and overload of drivers (Jin et al. 2014), which may decrease the driving performance. A proper level of attention shifts can improve driving performance.

The greater number of fixations indicated the higher level of interests within the area (Vignali et al. 2019). Edge line pavement marking can increase the level of interest significantly. Then, among countermeasures 3–11, adding increased curve grade on positive grade based on countermeasures 1 and 2 (1&2&11) had the lowest mean level of interests, while adding flexible delineator posts (1&2&4) had the highest mean level of interests. The high level of interest indicated the increase of drivers' visual attention during driving (Vignali et al. 2019), which may reduce crashes.

The final indicator was fixation duration. The larger the fixation duration, the higher the level of difficulty of information extraction and understanding (Costa et al. 2018). Edge line and centerline pavement marking (1&2) had the highest difficulty level of information extraction and understanding, while increased curve grade on positive grade based on countermeasures 1 and 2 (1&2&11) had the lowest difficulty level. The increasing level of difficulty of information extraction and understanding may decrease the driving performance (Costa et al. 2018).

Overall, the countermeasures had impacts on the drivers' cognitive workload, attention shifts, level of interest, and difficulty of information extraction and understanding. The relationships between the cognition and attention of drivers and their driving performance will be discussed in the regressions between countermeasures, cognitive attention, and crash using machine learning section.

Eye Movements Between Combinations of Weather Conditions and Traffic Volume

For the four simulation combinations of clear and foggy weather conditions and heavy and light traffic flows, ANOVA tests were applied to examine the differences. Table 14 shows that only fixation duration did not have significant differences between the four combinations (p = 0.10), while the other seven indicators were significantly impacted by the weather conditions and traffic flows ($p < 0.05$).

Table 14. Results of ANOVA tests for eye movements and combinations.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Changes of Pupil Diameter	Model	3	0.03	0.01	3.49	0.02
	Error	2589	6.94	0.00		
Average Pupil Diameter	Model	3	2.02	0.67	3.61	0.01
	Error	2589	483.99	0.19		
Saccade Duration	Model	3	659.31	219.77	4.01	0.01
	Error	2607	142,964.92	54.84		
Number of Saccades	Model	3	6,668,405.10	2,222,801.70	15.89	<0.01
	Error	2607	364,771,898.30	139,920.20		
Saccade Distance	Model	3	66,227.23	22,075.74	4.59	<0.01
	Error	2604	12,513,131.29	4,805.35		
Saccade Speed	Model	3	246.42	82.14	6.17	<0.01
	Error	2604	34,670.27	13.31		
Number of Fixations	Model	3	1,256,673.94	418,891.31	52.45	<0.01
	Error	2607	20,821,433.21	7,986.74		
Fixation Duration	Model	3	78,258.73	26,086.24	2.09	0.10
	Error	2607	32,539,804.59	12,481.70		

Table 15 summarizes the eye movements for each combination. First, the changes of pupil diameter were higher for combinations 3 and 4, which means the cognitive workload was higher for heavy traffic flow with both clear and foggy weather. Traffic flow was the major reason impacting this indicator. However, the mean values of average pupil diameter showed that drivers experienced a higher workload (i.e., larger average pupil diameter) for clear weather with both light traffic flow and heavy traffic flow. Thus, weather conditions also contributed to the differences in cognitive workload. Next, drivers showed the most frequent attention shifts under heavy traffic flow with foggy weather. Moreover, combinations 3 and 4 had a larger number of fixations, which means heavy traffic flow with both clear and foggy weather had a higher level of interest. Finally, fixation duration did not have significant differences, which indicates that the difficulty of information extraction and understanding were similar for all the weather conditions and traffic flows.

Table 15. Summary of eye movements under combinations.

Variables (unit)	Combinations of Weather and Traffic							
	1		2		3		4	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Changes of Pupil Diameter (mm^2)	0.05	0.05	0.05	0.06	0.06	0.05	0.06	0.05
Average Pupil Diameter (mm)	3.27	0.43	3.21	0.44	3.23	0.42	3.20	0.43
Saccade Duration (ms)	27.87	7.67	26.76	7.32	26.80	7.29	26.58	7.36
Number of Saccades	474.90	417.43	446.61	330.39	532.65	361.69	576.44	383.31
Saccade Distance (pixel)	190.61	68.35	181.40	65.21	189.00	67.60	195.35	75.66
Saccade Speed (pixel/ms)	10.07	3.43	10.00	3.52	10.37	3.59	10.78	4.02
Number of Fixations	225.89	85.58	220.31	80.48	261.47	97.06	270.97	93.26
Fixation Duration (ms)	345.49	122.19	347.03	107.05	338.14	113.09	333.60	104.16

Note: SD: Standard deviation

Driving Performance

Driving Performance with Different Countermeasures

Similar ANOVA tests were performed for driving performance indicators with different countermeasures. Table 16 shows the results of the ANOVA tests for the six indicators of driving performance. For the impact of edge line pavement marking, three driving performance indicators—crash, acceleration and deceleration, and lateral lane position—showed significant differences ($p < 0.01$), while vehicle speed, lateral acceleration, and steering wheel angle were not impacted. For the differences among countermeasures 3–11, three driving performance indicators—crash ($p = 0.58$), acceleration and deceleration ($p = 1.00$), and lateral lane position

(p = 0.49)—did not show significant differences, while vehicle speed, lateral acceleration, and steering wheel angle were significantly impacted. Table 17 shows the mean values and standard deviations of each variable under countermeasures.

Table 16. Results of ANOVA tests for driving performance and countermeasures.

Variables	ANOVA Test					
	Impact of Countermeasure 2					
	Source	***Df***	***Sum Sq***	***Mean Sq***	***F value***	***Pr (>F)***
Crash	Model	1	1.20	1.20	14.66	<0.01
	Error	478	39.13	0.08		
Vehicle Speed	Model	1	128.73	128.73	2.46	0.12
	Error	478	25,027.06	52.36		
Acceleration and Deceleration	Model	1	25.25	25.25	29.28	<0.01
	Error	478	412.21	0.86		
Lateral Acceleration	Model	1	4.17	4.17	2.38	0.12
	Error	478	838.92	1.76		
Steering Wheel Angle	Model	1	0.74	0.74	0.09	0.77
	Error	478	4,011.89	8.39		
Lateral Lane Position	Model	1	20.94	20.94	54.47	<0.01
	Error	478	183.74	0.38		
	Impact of Countermeasures 3–11					
	Source	***Df***	***Sum Sq***	***Mean Sq***	***F value***	***Pr (>F)***
Crash	Model	9	0.31	0.03	0.84	0.58
	Error	2390	98.70	0.04		
Vehicle Speed	Model	9	1,108.39	123.15	1.90	<0.05
	Error	2390	155,295.83	64.98		
Acceleration and Deceleration	Model	9	0.77	0.09	0.09	1.00
	Error	2390	2,214.55	0.93		
Lateral Acceleration	Model	9	1,487.70	165.30	99.00	<0.01
	Error	2390	3,990.64	1.67		
Steering Wheel Angle	Model	9	61,823.53	6,869.28	1,386.61	<0.01
	Error	2390	11,840.08	4.95		
Lateral Lane Position	Model	9	3.99	0.44	0.93	0.49
	Error	2390	1,135.41	0.48		

Table 17. Summary of driving performance under countermeasures.

Counter measures	Variables (unit)					
	Crash (number)		Vehicle Speed (M/hr)		Acceleration and Deceleration (ft/s^2)	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***
1	0.14	0.36	37.93	5.35	1.58	0.88
1&2	0.04	0.19	36.89	8.72	1.12	0.98
1&2&3	0.05	0.31	36.39	8.18	1.12	0.99
1&2&4	0.02	0.16	35.85	7.71	1.13	0.99
1&2&5	0.03	0.16	34.34	7.08	1.14	0.99
1&2&6	0.03	0.17	35.37	7.42	1.11	0.94
1&2&7	0.01	0.11	35.53	7.56	1.13	0.94
1&2&8	0.03	0.19	35.93	8.70	1.09	0.85
1&2&9	0.04	0.19	36.34	9.13	1.10	0.90
1&2&10	0.04	0.33	35.26	7.65	1.15	1.07
1&2&11	0.01	0.11	36.12	8.20	1.14	0.96
	Lateral Acceleration (ft/s^2)		**Steering Wheel Angle (°)**		**Lateral Lane Position (ft)**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***
1	3.69	1.01	21.82	3.12	5.52	0.61
1&2	3.50	1.58	21.90	2.66	5.10	0.63
1&2&3	3.43	1.53	21.78	2.31	5.09	0.66
1&2&4	3.31	1.39	21.73	2.19	5.02	0.71
1&2&5	3.03	1.30	21.51	3.10	5.06	0.66
1&2&6	3.24	1.31	21.51	1.96	5.05	0.72
1&2&7	3.20	1.25	21.34	1.90	5.09	0.68
1&2&8	1.35	0.87	9.08	2.06	5.05	0.86
1&2&9	1.34	0.79	8.90	1.25	5.11	0.75
1&2&10	3.24	1.27	21.80	2.13	5.12	0.57
1&2&11	3.37	1.39	21.79	2.22	4.98	0.62

Note: SD: Standard deviation

First, regarding crash, there were 37 vehicle collisions and 65 off-road collisions in total. Of the 60 participants, 24 did not have any crashes. The mean value of crash with only countermeasure 1 (centerline pavement marking) is the highest at 0.14. Similarly, those of the other performance indicators are mostly the highest for countermeasure 1. However, these results do not mean that the countermeasure of centerline pavement marking is the least effective since this countermeasure is compared with the combination of other countermeasures. This result of the single countermeasure was used as a base countermeasure when others were examined.

Adding the countermeasure of the edge line pavement marking to the road section with the centerline pavement marking (1&2) reduced the crashes significantly, while the effectiveness of further adding other countermeasures (1&2&3–1&2&11) did not show significant differences. Second, the value of the vehicle speedometer showed the exact speed. When only the centerline pavement marking countermeasure was applied on the road, the average speed was the highest. Then, adding countermeasures on the road reduced the average speed. Specifically, adding the posted speed sign countermeasure resulted in the lowest average speed. Third, the absolute value of the longitudinal acceleration of the vehicle represented the acceleration and deceleration. It showed that when centerline pavement marking (countermeasure 1) only was applied on the road, the mean acceleration and deceleration value was the highest, indicating that drivers had more speed changes. Adding edge line pavement marking on the road (1&2) reduced the acceleration and deceleration significantly, while adding other countermeasures (1&2&3–1&2&11) did not show significant changes in this indicator.

The fourth indicator was the absolute value of the lateral acceleration of the vehicle. Adding countermeasures in general reduced the lateral acceleration. When countermeasures 8 and 9, i.e., increased shoulder width and changed horizontal curve curvature, were applied on the existing centerline and edge line (1&2&8, 1&2&9), lateral accelerations were the smallest among all of the countermeasures 3–11.

The fifth indicator of the mean angle of the steering wheel ranged from 8.90° to 21.90°. Drivers had fewer moving angles of the steering wheel under countermeasures of increased shoulder width and changed horizontal curve curvature. Finally, the last indicator was the lateral lane position of the driven vehicle to the roadway dividing line, which is positive to the right. The vehicle had the largest distance from the roadway dividing line under only centerline pavement marking, which means the vehicle was closer to the centerline of the road. Adding edge line pavement marking (1&2) made the vehicles move further to the centerline of the road, which may improve safety.

Driving Performance with Different Combinations of Weather and Traffic Conditions

Considering the four combinations of different weather conditions and traffic flows, table 18 shows the results of the ANOVA tests for the six driving performance indicators between those four combinations. Vehicle speed, acceleration and deceleration, lateral acceleration, and lateral lane position had significant differences between the four combinations ($p < 0.01$), while the combinations did not have significant impacts on crashes and steering wheel angle. Also, table 19 shows the summary of driving performance under each combination of weather condition and traffic flow.

Table 18. Results of ANOVA tests for driving performance and combinations.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Crash	Model	3	0.20	0.07	1.33	0.26
	Error	2636	131.86	0.05		
Vehicle Speed	Model	3	90,863.55	30,287.85	1,088.18	<0.01
	Error	2636	73,369.05	27.83		
Acceleration and Deceleration	Model	3	15.99	5.33	5.78	<0.01
	Error	2636	2,429.17	0.92		
Lateral Acceleration	Model	3	1,804.83	601.61	391.21	<0.01
	Error	2636	4,053.69	1.54		
Steering Wheel Angle	Model	3	168.93	56.31	1.92	0.12
	Error	2636	77,395.65	29.36		
Lateral Lane Position	Model	3	35.81	11.94	25.46	<0.01
	Error	2636	1,235.86	0.47		

Table 19. Summary of driving performance under combinations.

Variables (unit)	Combinations of Weather and Traffic							
	1		2		3		4	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Crash (number)	0.03	0.18	0.05	0.27	0.04	0.19	0.04	0.24
Vehicle Speed (m/hr)	41.51	4.42	42.18	5.23	30.68	5.85	29.61	5.49
Acceleration and Deceleration (ft/s^2)	1.04	0.88	1.25	1.09	1.20	0.89	1.16	0.96
Lateral Acceleration (ft/s^2)	3.73	1.33	3.86	1.36	2.24	1.15	2.05	1.11
Steering Wheel Angle (°)	19.45	5.59	19.75	5.84	19.24	5.00	19.08	5.20
Lateral Lane Position (ft)	5.25	0.54	5.20	0.63	4.97	0.75	5.02	0.79

Note: SD: Standard deviation

First, the mean values of the crash were similar among the four combinations. Specifically, combination 2 (foggy and light traffic flow) had the most crashes (34 crashes), while combination 1 (clear and light traffic flow) had the smallest number of crashes (18 crashes). However, the difference was not statistically significant. Second, the average speed of both foggy weather and light traffic flow, and clear weather and light traffic flow was larger than the speed of foggy weather and clear weather with traffic flow. Thus, light traffic flow led to a higher speed. Third, the acceleration and deceleration were highest for foggy weather and light traffic flow, while it was lowest under clear weather and light traffic flow. Therefore, the weather condition was the major factor impacting acceleration and deceleration. Drivers changed their speed more often in foggy weather, which means they were more cautious to control their speed. Fourth, lateral acceleration was larger for foggy weather and light traffic flow and clear weather and light traffic flow, while the mean values were smaller for both foggy weather and clear weather with heavy traffic flows. Thus, traffic flow was the major source impacting lateral acceleration. Vehicles had higher lateral acceleration in the curve when there was light traffic flow. Fifth, the mean angle of the steering wheel ranged from 19.08° to 19.75° for the four combinations without a statistically significant difference. Finally, the vehicles under clear weather and traffic flow had the smallest distance from the roadway dividing line, while clear weather and light traffic flow had the largest lateral lane position. Traffic flow was a more critical factor influencing this indicator. Vehicles were closer to the centerline of the road when there was light traffic flow. Overall, drivers showed bolder driving performance when there was light traffic flow.

Short-term Memory

The three short-term memory indicators were compared between the combinations of weather and traffic. Table 20 shows that only ability to control attention showed significant differences between different weather and traffic flow, while both recall ability and speed of item identification and processing were not impacted by the combinations. According to table 21, drivers identified more cars that appeared during the simulation. The possible reason is that drivers were very attentive to all the information that appeared on the screen when there was limited visibility.

Table 20. Results of ANOVA tests for short-term memory and combinations.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Recall Ability	Model	3	331.38	110.46	0.49	0.69
	Error	236	53,276.79	225.75		
Ability to Control Attention	Model	3	1.89	0.63	4.23	0.01
	Error	236	35.06	0.15		
Speed of Item Identification and Processing	Model	3	0.41	0.14	0.32	0.81
	Error	236	100.25	0.42		

Table 21. Summary of short-term memory under combinations.

Variables (unit)	Combinations of Weather and Traffic							
	1		2		3		4	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Recall Ability (%)	88.15	10.99	89.08	12.01	86.11	16.57	86.67	19.06
Ability to Control Attention (correct rate)	0.57	0.33	0.74	0.33	0.58	0.36	0.50	0.50
Speed of Item Identification and Processing (5-point scale)	4.05	0.62	4.10	0.63	4.00	0.66	4.00	0.69

Note: SD: Standard deviation

ANOVA TEST FOR SEQUENCE AND ORDERS

To reduce the impacts of sequences of conducting each combination of weather and traffic during the experiment, the 60 participants were divided into four different sequences of the combinations of weather and traffic flow, as shown in table 22. The four combinations covered two weather conditions (clear and foggy weather) and two traffic flows (light and heavy traffic), which were discussed in detail in driving simulation setup and modeling plan. Then, as introduced in the data collection section (population and sample), each row of table 22 indicates the different sequences of combinations that appeared in the driving simulation task. For example, for participants of sequence 1, their experiment procedure started with combination 1, followed by combinations 3 and 4, and then ended with combination 2. Finally, the order (i.e., each column of table 22) indicates the different starting time points for each combination. For example, order 1 indicated the combination that started at the beginning, which was combination 1 for sequence 1, combination 3 for sequence 2, combination 2 for sequence 3, and combination 4 for sequence 4. The driving performance, eye movements, and short-term memory were compared between sequences of combinations of weather and traffic and orders of each combination to explore the differences.

Table 22. Four sequences with different order of combinations.

Sequences	Orders			
	1	**2**	**3**	**4**
Sequence 1	Combination 1	Combination 3	Combination 4	Combination 2
Sequence 2	Combination 3	Combination 2	Combination 1	Combination 4
Sequence 3	Combination 2	Combination 4	Combination 3	Combination 1
Sequence 4	Combination 4	Combination 1	Combination 2	Combination 3

Comparison Between Sequences of Combinations of Weather Condition and Traffic Flow

Eye Movements

For eye movements indicators, ANOVA tests (see table 23) showed that only numbers of fixation did not have significant differences between sequences (p = 0.11), while the other seven indicators were impacted significantly by the sequences (p < 0.01). Table 24 presents the summary of the eight indicators.

Table 23. Results of ANOVA tests for eye movements and sequences.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Changes of Pupil Diameter	Model	3	0.11	0.04	13.46	<0.01
	Error	2589	6.86	0.00		
Average Pupil Diameter	Model	3	24.85	8.28	46.51	<0.01
	Error	2589	461.16	0.18		
Saccade Duration	Model	3	7,901.74	2,633.91	50.59	<0.01
	Error	2607	135,722.49	52.06		
Number of Saccades	Model	3	18,495,317.80	6,165,105.90	45.54	<0.01
	Error	2607	352,944,985.60	135,383.60		
Saccade Distance	Model	3	239,639.60	79,879.87	16.86	<0.01
	Error	2604	12,339,718.91	4,738.76		
Saccade Speed	Model	3	458.59	152.86	11.55	<0.01
	Error	2604	34,458.09	13.23		
Number of Fixations	Model	3	144,038.71	48,012.90	5.71	0.11
	Error	2607	21,934,068.44	8413.53		
Fixation Duration	Model	3	705,781.86	235,260.62	19.22	<0.01
	Error	2607	31,912,281.46	12,241.00		

Table 24. Summary of eye movements under sequences.

Variables	Sequences of Combinations of Weather and Traffic							
	1		2		3		4	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Changes of Pupil Diameter	0.05	0.05	0.05	0.04	0.06	0.07	0.06	0.04
Average Pupil Diameter	3.08	0.37	3.20	0.41	3.32	0.41	3.32	0.49
Saccade Duration	28.80	6.70	24.13	7.20	27.56	7.03	27.51	7.88
Number of Saccades	394.75	174.16	630.49	473.18	490.10	367.73	515.66	389.26
Saccade Distance	189.11	68.42	175.20	66.23	202.24	72.82	189.86	67.73
Saccade Speed	9.72	3.69	10.29	3.45	10.91	3.74	10.31	3.66
Number of Fixations	239.98	84.33	257.63	92.01	241.15	97.57	240.50	92.53
Fixation Duration	366.23	98.42	366.23	98.42	338.30	100.53	339.46	111.79

Note: SD: Standard deviation

Driving Performance

Table 25 indicates that the crash, vehicle speed, acceleration and deceleration, and lateral acceleration indicators had significant differences ($p < 0.05$), while the steering wheel angle and lateral lane position were not influenced by the different sequences ($p > 0.05$).

Table 25. Results of ANOVA tests for driving performance and sequences.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr. (>F)**
Crash	Model	3	0.60	0.20	4.00	0.01
	Error	2636	131.46	0.05		
Vehicle Speed	Model	3	824.77	274.92	4.43	<0.01
	Error	2636	163407.83	61.99		
Acceleration and Deceleration	Model	3	13.59	4.53	4.91	<0.01
	Error	2636	2431.56	0.92		
Lateral Acceleration	Model	3	37.87	12.62	5.72	<0.01
	Error	2636	5820.64	2.21		
Steering Wheel Angle	Model	3	95.58	31.86	1.08	0.35
	Error	2636	77469.00	29.39		
Lateral Lane Position	Model	3	3.66	1.22	2.54	0.06
	Error	2636	1268.01	0.48		

Table 26 shows the mean values and standard deviations of each indicator for every sequence. The results indicate that the setting of different sequences was useful to increase the diversity within the limited sample.

The average speed of driving in the simulator was about 35.4-36.7 mile/hr. These speeds look like lower than real driving speeds in a road with a speed limit 35 m/hr. to 45 m/hr. The reasons causing the low speed of driving a simulator are probably the following: 1) the simulator was not able to create a driving environment close to the real driving, 2) participants tried to drive prudently since they knew they were part of data collection.

Table 26. Summary of driving performance under sequences.

Variables	Sequences of Combinations of Weather and Traffic							
	1		2		3		4	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Crash	0.04	0.23	0.02	0.13	0.04	0.19	0.06	0.31
Vehicle Speed	36.43	7.88	35.41	7.22	35.48	7.18	36.66	9.07
Acceleration and Deceleration	1.18	0.88	1.05	0.74	1.19	0.75	1.24	1.34
Lateral Acceleration	3.05	1.48	2.85	1.37	2.86	1.35	3.12	1.72
Steering Wheel Angle	19.47	5.36	19.07	5.18	19.41	5.30	19.58	5.81
Lateral Lane Position	5.14	0.79	5.05	0.61	5.14	0.63	5.11	0.74

Note: SD: Standard deviation

Short-term Memory

Finally, table 27 shows that only the speed of item identification and processing variable was significantly different between sequences ($p < 0.01$). Both recall ability and ability to control attention were not significantly impacted by the different sequences. Table 28 summarizes the data under each sequence of combinations. Thus, the set of four sequences did not contribute to major differences for short-term memory.

Table 27. Results of ANOVA tests for short-term memory and sequences.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Recall Ability	Model	3	1,145.79	381.93	1.72	0.16
	Error	236	52,462.38	222.30		
Ability to Control Attention	Model	3	0.29	0.10	0.61	0.61
	Error	236	36.66	0.16		
Speed of Item Identification and Processing	Model	3	13.91	4.64	12.62	<0.01
	Error	236	86.75	0.37		

Table 28. Summary of short-term memory under sequences.

Variables	Sequences of Combinations of Weather and Traffic							
	1		2		3		4	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Recall Ability	87.22	18.51	86.30	13.31	91.11	13.69	85.37	13.49
Ability to Control Attention	0.65	0.38	0.57	0.42	0.61	0.35	0.57	0.43
Speed of Item Identification and Processing	4.18	0.60	4.25	0.57	3.63	0.58	4.08	0.67

Note: SD: Standard deviation

Comparison Between Orders of Each Combination of Weather Condition and Traffic Flow

As shown in Table 22, the order (i.e., each column of table 22) indicates the different starting time points for each combination. The followings are the results about eye movements, driving performance, and short-term memory respectively.

Eye Movements

For the eye movements indicator, table 29 indicates that only saccade speed had a significant difference between orders (p = 0.02). The other seven indicators were not impacted by the order (p > 0.05). Then, table 30 shows the summary of each indicator for different sequences. Overall, the results also indicated that the order did not impact the eye movements of drivers.

Table 29. Results of ANOVA tests for eye movements and orders.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Changes of Pupil Diameter	Model	3	0.01	0.00	0.75	0.52
	Error	2589	6.96	0.00		
Average Pupil Diameter	Model	3	0.23	0.08	0.42	0.74
	Error	2589	485.78	0.19		
Saccade Duration	Model	3	113.32	37.77	0.69	0.56
	Error	2607	143,510.91	55.05		
Number of Saccades	Model	3	459,692.30	153,230.80	1.08	0.36
	Error	2607	370,980,611.00	142,301.70		
Saccade Distance	Model	3	23,849.75	7,949.92	1.65	0.18
	Error	2604	12,555,508.76	4,821.62		
Saccade Speed	Model	3	125.69	41.90	3.14	0.02
	Error	2604	34,790.99	13.36		
Number of Fixations	Model	3	10,798.88	3,599.63	0.43	0.73
	Error	2607	22,067,308.27	8,464.64		
Fixation Duration	Model	3	7,948.41	2,649.47	0.21	0.89
	Error	2607	32,610,114.91	12,508.67		

Table 30. Summary of eye movements under orders.

Variables	Orders of Each Combination of Weather and Traffic							
	1		**2**		**3**		**4**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Changes of Pupil Diameter	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.05
Average Pupil Diameter	3.24	0.43	3.23	0.44	3.22	0.42	3.22	0.43
Saccade Duration	27.17	7.16	27.23	7.92	26.81	7.44	26.76	7.13
Number of Saccades	505.69	366.97	495.86	360.08	530.03	420.90	500.04	356.85
Saccade Distance	192.12	68.13	186.03	69.23	192.04	72.36	186.03	67.91
Saccade Speed	10.45	3.47	9.99	3.43	10.56	4.05	10.22	3.64
Number of Fixations	245.34	83.71	244.11	93.49	247.76	92.11	242.16	98.13
Fixation Duration	338.57	113.66	342.58	108.44	342.76	111.56	340.18	113.60

Note: SD: Standard deviation

Driving Performance

After learning the impacts of different sequences, ANOVA tests were performed between different orders of each combination of weather and traffic. For the driving performance, table 31 shows that only the lateral lane position was significantly impacted by the order, while the other five indicators did not have a significant difference.

Table 31. Results of ANOVA tests for driving performance and orders.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Crash	Model	3	0.15	0.05	0.98	0.40
	Error	2636	131.91	0.05		
Vehicle Speed	Model	3	311.90	103.97	1.67	0.17
	Error	2636	163,920.71	62.19		
Acceleration and Deceleration	Model	3	4.97	1.66	1.79	0.15
	Error	2636	2,440.19	0.93		
Lateral Acceleration	Model	3	10.02	3.34	1.51	0.21
	Error	2636	5,848.49	2.22		
Steering Wheel Angle	Model	3	18.55	6.18	0.21	0.89
	Error	2636	77,546.02	29.42		
Lateral Lane Position	Model	3	8.32	2.77	5.79	<0.01
	Error	2636	1,263.36	0.48		

Table 32 shows the summary of each order. The order did not cause major differences in driving performance. Thus, the experiment time duration did not cause a decrease in driving performance.

Table 32. Summary of driving performance under orders.

Variables	Order of Combinations of Weather and Traffic							
	1		2		3		4	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Crash	0.05	0.27	0.03	0.18	0.04	0.23	0.03	0.21
Vehicle Speed	35.94	7.74	35.61	7.65	36.55	7.98	35.88	8.16
Acceleration and Deceleration	1.15	1.04	1.16	0.99	1.12	0.93	1.24	0.89
Lateral Acceleration	2.97	1.48	2.90	1.45	3.07	1.53	2.95	1.50
Steering Wheel Angle	19.50	5.59	19.27	5.32	19.41	5.51	19.34	5.27
Lateral Lane Position	5.02	0.74	5.11	0.68	5.12	0.70	5.18	0.64

Note: SD: Standard deviation

Short-term Memory

Finally, table 33 shows that all three indicators of short-term memory did not have significant differences between orders ($p > 0.05$). Table 34 summarizes the short-term memory data by orders. Thus, the order also did not influence the short-term memory of drivers.

Table 33. Results of ANOVA tests for short-term memory and orders.

Variables	ANOVA Test					
	Source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Recall Ability	Model	3	928.04	309.35	1.39	0.25
	Error	236	52,680.12	223.22		
Ability to Control Attention	Model	3	0.18	0.06	0.38	0.77
	Error	236	36.77	0.16		
Speed of Item Identification and Processing	Model	3	0.01	0.00	0.01	1.00
	Error	236	100.65	0.43		

Table 34. Summary of short-term memory under orders.

Variables	Orders of Combinations of Weather and Traffic							
	Order 1		Order 2		Order 3		Order 4	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Recall Ability	90.37	12.69	85.19	17.32	86.30	15.36	88.15	14.00
Ability to Control Attention	0.59	0.41	0.56	0.39	0.61	0.39	0.63	0.39
Speed of Item Identification and Processing	4.03	0.66	4.03	0.66	4.03	0.61	4.05	0.67

Note: SD: Standard deviation

Summary of ANOVA Results

Table 35 lists the summaries of all the ANOVA test results performed for this project, which is discussed further as follows:

First, the results indicate that different countermeasures caused significant differences in the driving performances, including the number of crashes, speed, acceleration and deceleration, lateral acceleration, steering wheel angle, and lateral lane position, which are in accordance with the existing literature (Bauer and Harwood 2013, Charlton 2007, Gross et al. 2009, Lenné et al. 2011, Räsänen 2005, Saleem and Persaud 2017, Zhao et al. 2020, Zwahlen 1987). Also, the countermeasures significantly impacted drivers' cognition by influencing pupillometry, saccade, and fixation. Drivers had different cognitive workloads, frequency of attention shifts, level of interest, and difficulty of information extraction and understanding among countermeasures. The results can be supported by previous work (Hill et al. 2003, de Greef et al. 2009, Kapitaniak et al. 2015, Marshall 2002, Najar and Sanjram 2018, Vignali et al. 2019). Drivers' cognitive attention was influenced by the signs, pavement markings, and roadway improvements.

Second, different weather conditions and traffic flow did not impact crash significantly, although crash is the major indicator of traffic safety (Guo et al. 2013, Lee et al. 2011). But weather conditions and traffic flow did impact the other drivers' performance indicators in the study as reported, which was also supported by previous studies (Birrell and Young 2011, Fisher et al. 2011, Reymond et al. 2001, Vignali et al. 2019, Whitmire et al. 2011). Next, the drivers' cognitive properties were significantly different among the different combinations of weather and traffic flows. Finally, for short-term memory, the weather and traffic flow impacted drivers' ability to control attention, i.e., identifying cars that appeared in the experiment. However, the recall ability and speed of item identification and processing were not significantly influenced.

Third, for the experiment design, on one hand, the different sequences of four combinations of weather and traffic in the experiment showed significantly different results in driving performance, eye movements, and short-term memory. Therefore, the experiment design of dividing 60 participants into four sequences was useful to improve the bias within a limited sample size. On the other hand, the order of each combination of weather and traffic did not impact the majority of indicators (15 out of 17). The different starting time of each combination of weather and traffic was not an influencing factor in the experiment, supporting the reliability of the experiment of this study.

Table 35. Summary of ANOVA test results.

Meaning	Indicators	Countermeasures	Combinations	Sequences	Orders
Cognitive Workload	Changes of Pupil Diameter	√	√	√	×
	Average Pupil Diameter	√	√	√	×
Attention Pattern	Saccade Durations	×	√	√	×
Attention Shifts	Number of Saccades	×	√	√	×
	Saccade Distance	√	√	√	×
	Saccade Speed	√	√	√	√
Level of Interest	Number of Fixations	√	√	×	×
Difficulty of Information Extraction and Understanding	Fixation Duration	√	×	√	×
Driving Performance	Crash	√	×	√	×
	Speed	√	√	√	×
	Acceleration and Deceleration	√	√	√	×
	Lateral Acceleration	√	√	√	×
	Steering Wheel Angle	√	×	×	×
	Lateral Lane Position	√	√	×	√
Short-term Memory	Recall Ability	-	×	×	×
	Ability to Control Attention	-	√	×	×
	Speed of Item Identification and Processing	-	×	√	×

Note: √ indicates significant difference; × means non-significant difference; - indicates the impacts were not examined.

VISULIZATION OF ATTENTION DISTRIBUTION AND INTENSITY

In this section, the heat maps for all the participants are compared by the eye-tracking software to generate a general heat map image. This heat map is the representation of all drivers' gazes based on colors. The more they gaze at a spot, the more the color changes, i.e., from a green to yellow and finally to red; the color ranges from light green all the way to red. Figure 34 shows the heap map generated from all the participants with the help of the eye tracker, which also excluded irrelevant gaze areas that participants did not focus on. Most participants' focus and attention can be seen to be primarily on the roadway; however, other regions of interest can be seen, as well. One area that had a significant amount of participant gaze was the dashboard of the vehicle at the speedometer. Figure 35 shows the heat map for the first 10 participants. These participants paid good attention to not only the road but the speed at which they were moving. Comparing the two heat maps generated by different participants, more attention is shown on the road from the heat map of all the participants.

Figure 36 and figure 37 show the gaze plots of two simulation parts for just one of the first few participants. They are examples of the gaze numbers and sequences. From the gaze plots, this participant had a lot of fixations on the road as well as on the dashboard area for the simulation. Greater amounts of fixation signify a high level of interest in these regions by the participants. Also, by comparing more heat maps, it can be observed that more participants tend to not focus to a greater extent on the speedometer on the dashboard, which would cause the change in intensity that the colors represent. More participants were focused on the road, causing the intensity on the road to increase in that area of interest.

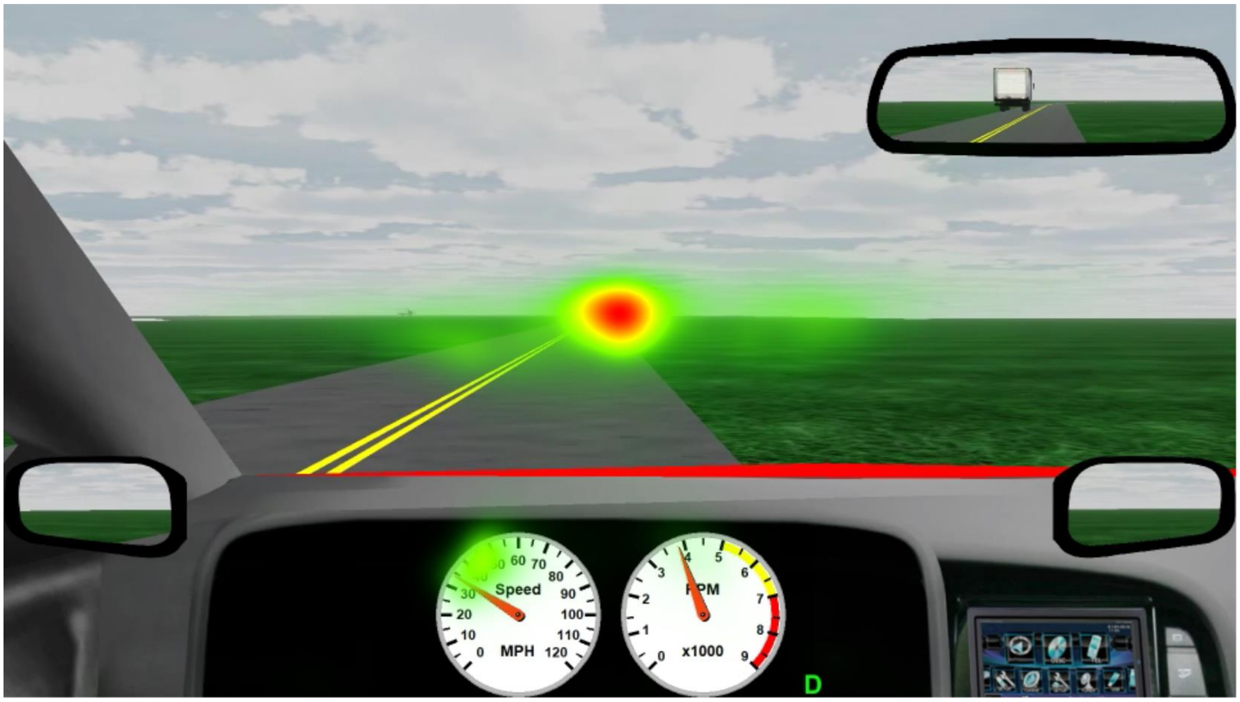


Figure 34. Screenshot. Heat map image for all 60 participants.

Figure 35. Screenshot. Heat map image for first 10 participants.

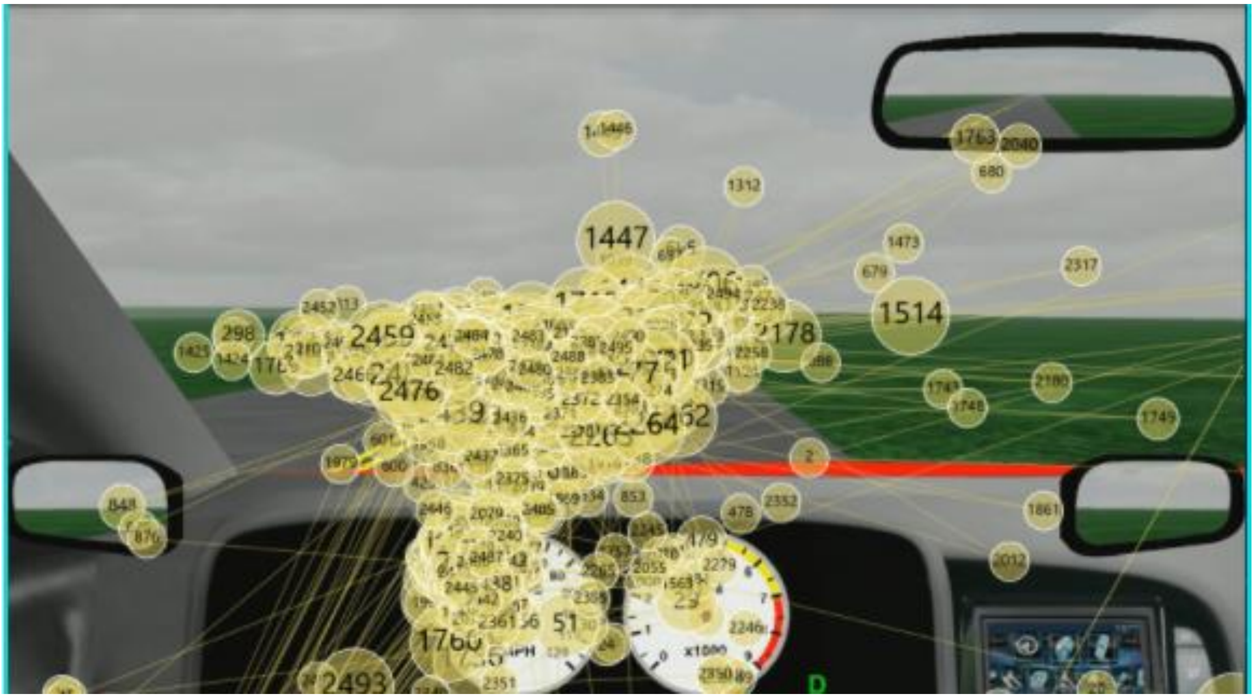


Figure 36. Screenshot. Gaze plot of an early participant for combination 1.

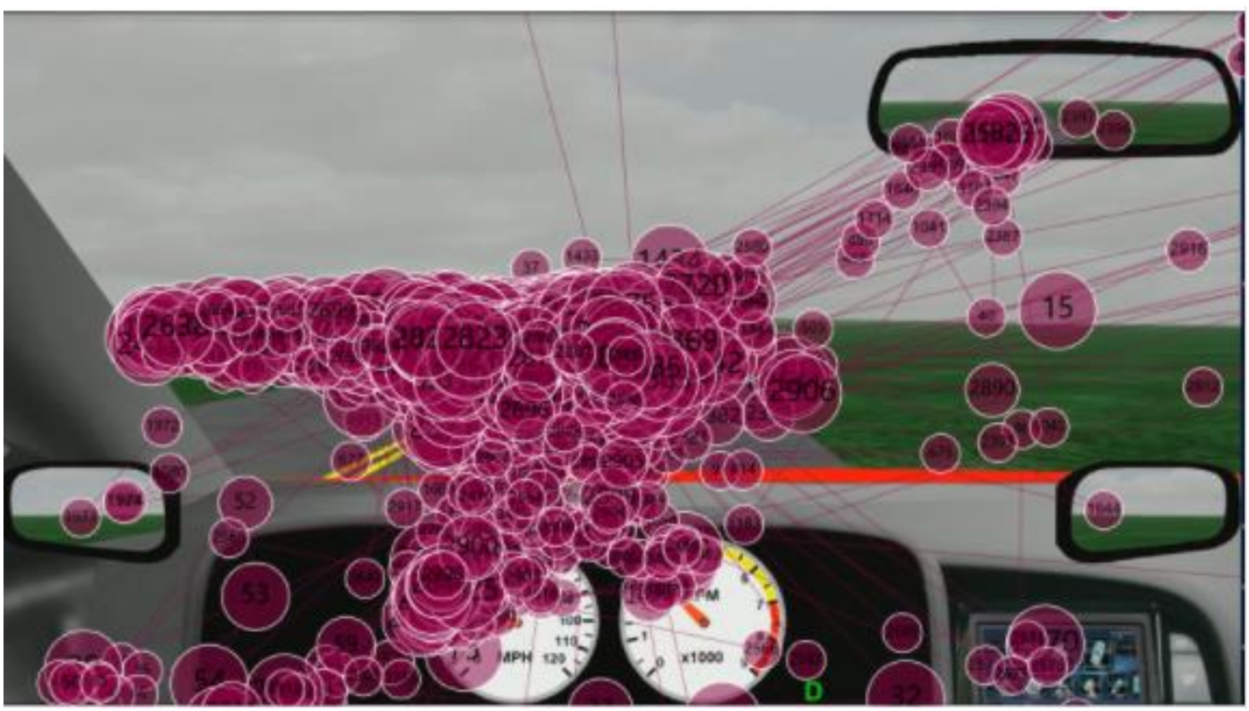


Figure 37. Screenshot. Gaze plot of an early participant for combination 2.

REGRESSIONS BETWEEN COUNTERMEASURES AND CRASH USING MACHINE LEARNING

In order to establish the relationships between the countermeasures and traffic safety, a machine learning technique was used. Machine learning can be described as the study of a sequence of computational instructions that are capable of improving by themselves with the use of data. The machine learning technique used can be referred to as *regression*. Through regression analysis, a relationship can be established between a dependent variable and various independent variables. This machine learning technique falls under one of the subclasses under machine learning that is known as *supervised learning*, where the main task is to establish a form of mapping or, in this case, relationship between inputs and an output. In regression, the inputs are referred to as the independent variables, while the output is the dependent variable. In this study, the dependent variable is the number of traffic crashes, while the independent variables are the 11 countermeasures for all 60 participants. With this analysis, a relationship where the most significant countermeasure and least significant countermeasure that leads to a traffic crash can be decided. Also, a relationship between the countermeasures, cognitive attention, and traffic crashes can be decided. The regression analysis formula can be seen as equations 4 and 5:

$$Y = \boldsymbol{WA} + c \quad (4)$$

$$\boldsymbol{A} = TC \quad (5)$$

Where,

Y refers to the dependable variable.

$\boldsymbol{W}$ is the significance parameter.

$\boldsymbol{A}$ represents the various independent variables.

c is the approximation error.

T is the identity matrix of the simulation.

Please note that both ***W*** and ***A*** are vector quantities. Due to the presence of different countermeasures in each of the runs, the ***A*** vector, which indicates the countermeasures, is equal to *T*, which is the identity matrix of the simulation multiplied by *C*, which is the column vector of the occurring countermeasures for the 11 rounds.

As a result of the present case, where there is more than one independent variable, the best way to approach this analysis is with the use of a matrix. With an independent variable of 11 countermeasures and 60 participants, a 660 by 11 matrix was to be generated for the computation of the ***A*** value. Also, from the driving simulator data, all crashes from each countermeasure for each participant were used to generate a 660 by 1 matrix, which would represent *Y* values. With these terms provided, computation for the term ***W***, which is the significance parameter, was performed by using equation 6:

$$W = (A^T A)^{-1} A^T Y \quad (6)$$

This analysis was completed for all the countermeasures and also the four combinations of weather and traffic to establish relationships between them and traffic crashes, which are shown in table 36 and table 37. The crash significance parameter (***W***) represents the effectiveness of reduction for overall crashes. There are two types of crashes. $\boldsymbol{W_1}$ represents the parameters for vehicle collisions; $\boldsymbol{W_2}$ shows the parameters for off-road collisions. A small value for ***W*** indicates that the countermeasure has high effectiveness to reduce crashes, while a large value indicates that the countermeasure has low effectiveness to reduce crashes. The effectiveness of the different countermeasures on overall crashes was obvious simply by comparing the values of

W for the countermeasures. Overall, from the information in table 36, it is possible to set run 2, which consists of the center line and edge line countermeasures, as a control ***W*** parameter (0.1 for this study) since these two countermeasures coexist in all the runs that followed. Any ***W*** parameter going below 0.1 indicates the additional countermeasure is an effective countermeasure, and vice versa. The effectiveness order showed the rank of the effectiveness of countermeasures. The smaller the effectiveness order indicated, the more effective the countermeasure was to reduce crashes. Centerline pavement marking was not ranked because it was the basic countermeasure included each time.

Table 36. *W* values of the regression analysis for countermeasures and crashes.

Countermeasures	Crash Significance Parameter			Effectiveness Order
	W	W_1	W_2	
Centerline Pavement Marking	0.3167	0.1149	0.2018	-
Centerline Pavement Marking + Edge Line Pavement Marking	0.1000	0.0363	0.0637	5
Centerline Pavement Marking + Edge Line Pavement Marking + Shoulder Rumble Strips	0.1333	0.0484	0.0849	7
Centerline Pavement Marking + Edge Line Pavement Marking + Flexible delineator posts	0.0833	0.0302	0.0531	4
Centerline Pavement Marking + Edge Line Pavement Marking + Posted Speed Sign	0.0333	0.0121	0.0212	1
Centerline Pavement Marking + Edge Line Pavement Marking + Curve Warning Sign	0.1333	0.0484	0.0849	7
Centerline Pavement Marking + Edge Line Pavement Marking + Curve Speed Warning Sign	0.0667	0.0242	0.0425	3
Centerline Pavement Marking + Edge Line Pavement Marking + Increased Shoulder Width	0.2167	0.0786	0.1381	10
Centerline Pavement Marking + Edge Line Pavement Marking + Changed Horizontal Curve Curvature	0.1000	0.0363	0.0637	5
Centerline Pavement Marking + Edge Line Pavement Marking + Decreased Curve Grade on Negative Grade	0.1333	0.0484	0.0849	7
Centerline Pavement Marking + Edge Line Pavement Marking + Increased Curve Grade on Positive Grade	0.0333	0.0121	0.0212	1

Note: - indicates not applicable

Table 37. *W* values of the regression analysis for four combinations and crash.

Combinations with Weather Conditions and Traffic Flows	Crash Significance Parameter		
	W	W_1	W_2
Clear Weather and Light Traffic	0.2000	0.0686	0.1314
Foggy Weather and Light Traffic	0.3833	0.1315	0.2518
Clear Weather and Heavy Traffic	0.2667	0.0915	0.1752
Foggy Weather and Heavy Traffic	0.5167	0.1773	0.3394

The results indicated that the edge line pavement marking, flexible delineator posts, curve speed warning sign, posted speed sign, and increased curve grade on positive grade countermeasures are, in general, effective to reduce crashes. On the contrary, adding countermeasures of changed horizontal curve curvature, shoulder rumble strips, curve warning sign, decreased curve grade on negative grade, and increased shoulder width showed no effect in reducing crashes. In particular, for vehicle collisions, edge line pavement marking, flexible delineator posts, posted speed sign, curve speed warning sign, and increased curve grade on positive grade are effective countermeasures, while others did not have obvious effect. For off-road collisions, the effectiveness of countermeasures is similar to vehicle collisions. Overall, drivers had more off-road crashes than vehicle collisions in the experiment.

Then, the crash significance parameters for the four combinations of weather and traffic indicated that the combination of foggy and heavy traffic flow was the most significant factor leading to traffic crashes, while the combination of clear weather and light traffic flow was the least significant combination. The results are same for vehicle collisions and off-road collisions. The possible reason is that clear weather and light traffic flow had better visibility and required less eye workload, reducing the possibility of crashes.

REGRESSIONS BETWEEN COUNTERMEASURES, COGNITIVE ATTENTION, AND CRASH USING MACHINE LEARNING

To establish the relationships between the countermeasures, cognitive attention, and crashes, relationships must be established between the countermeasures and cognitive attention, and also between the cognitive attention and crashes, as shown in figure 38. This can also be done with regression.

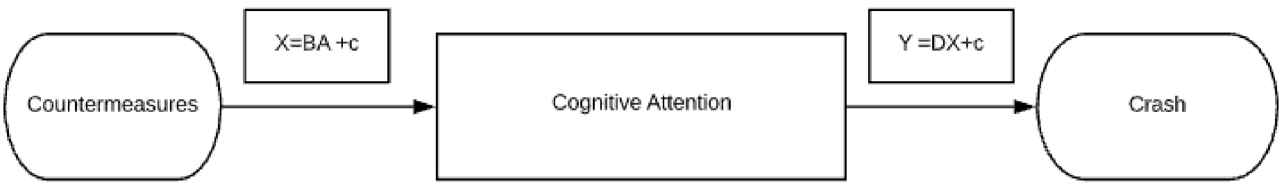


Figure 38. Diagram. Regressions for countermeasures, cognitive attention, and crash.

The regression formula seen in equations 4 and 5 can be rewritten as in equations 7 and 8:

$$Y = (BD)\boldsymbol{A} + c \quad (7)$$

$$\boldsymbol{W} = BD \quad (8)$$

where ***W***, the significant parameter for the relationship between countermeasures and crash is equal to the product of the significant parameter *B*—obtained from the regression analysis between the countermeasure and drivers' cognitive attention—and the significance parameter *D* between drivers' cognitive attention and traffic crash. Due to the varying range of data obtained from the eye tracker that represents cognitive attention, these values needed to undergo a process known as *nominalization*. This is the act of converting each obtained value into a standardized form that carries similar weight power; this is done by dividing each value by its mean value, i.e., each value of the cognitive attention indicator under each countermeasure would be divided by the mean value of that indicator.

Table 38 and table 39 show the regression results, guided by figure 37. The significance parameters (*B*) for eye movements were different for each countermeasure (see table 38). Similarly, a large *B* value meant a high value of the indicator of the eye movements under each countermeasure.

The parameters of *D* for each indicator of eye movements are listed in table 39. The parameters of *D* were notably different for the various eye movements indicators. A large parameter *D* indicated a big crash rate. The smaller the parameter *D*, the fewer the crashes. It can be concluded that those cognitive properties of average pupil diameter, saccade duration, number of fixations, and fixation duration are major factors influencing traffic crashes, while the other cognitive properties are not so influential to the crashes.

Table 38. *B* values of regression analysis between countermeasures and eye movements.

Counter measure	Significance Parameter (*B*)							
	Change of Pupil Diameter	Average Pupil Diameter	Saccade Duration	Number of Saccade	Saccade Distance	Saccade Speed	Number of Fixations	Fixation Duration
1	1.0569	1.0020	1.0387	1.0259	1.0908	1.0615	1.0494	0.9996
2	1.3459	1.0121	1.0157	0.9491	1.0368	1.0469	0.9766	1.0291
3	0.8478	0.9859	1.0143	0.9928	0.9742	0.9656	1.0077	1.0262
4	0.9684	0.9960	1.0064	0.9756	1.0029	0.9939	0.9555	0.9927
5	1.0713	1.0021	0.9890	1.1034	0.9774	0.9656	1.0188	0.9483
6	1.0781	1.0114	0.9808	0.9501	0.9795	0.9991	0.9709	0.9965
7	0.8160	0.9959	0.9667	0.9787	0.9339	0.9446	0.9892	0.9962
8	1.1439	1.0011	0.9938	0.9060	1.0403	1.0519	0.9247	1.0108
9	1.0265	1.0104	1.0091	1.0205	1.0556	1.0697	1.0551	1.0140
10	0.8025	0.9901	0.9974	1.0536	0.9296	0.9227	1.0376	1.0186
11	0.8427	0.9930	0.9881	1.0442	0.9791	0.9786	1.0144	0.9680

Table 39. ***D*** **values of regression analysis between eye movements and crash.**

Eye Movements Indicator	Significance Parameter (*D*) to Traffic Crash
Change of Pupil Diameter	−0.0020
Average Pupil Diameter	0.2852
Saccade Duration	−0.1117
Number of Saccade	−0.0697
Saccade Distance	0.0482
Saccade Speed	−0.0490
Number of Fixation	0.1277
Fixation Duration	−0.1048

Table 40 summarizes the relationships between the countermeasures and the cognition properties of drivers. The title of each column is the meaning of eye movement indicators shown in table 7. Saccade durations and number of saccades were not included because, based on the ANOVA results, the countermeasures did not show a significant impact on the two indicators. For cognitive workload, the parameters were the averages for both changes of pupil diameter and average pupil diameter, which measure the cognitive workload of drivers. Then, the average parameters of saccade distance and speed were used to represent the attention shifts. Finally, the parameters of number of fixations and fixation durations showed the level of interest and difficulty of information extraction and understanding, respectively.

Table 40. Significance parameters (*B*) between countermeasure and cognition.

Countermeasures	Significance Parameter (*B*)			
	Cognitive Workload	Attention Shifts	Level of Interest	Difficulty of Information Extraction and Understanding
Centerline Pavement Marking	1.0295	1.0762	1.0494	0.9996
Edge Line Pavement Marking	1.1790	1.0419	0.9766	1.0291
Shoulder Rumble Strips	0.9169	0.9699	1.0077	1.0262
Flexible delineator posts	0.9822	0.9984	0.9555	0.9927
Posted Speed Sign	1.0367	0.9715	1.0188	0.9483
Curve Warning Sign	1.0448	0.9893	0.9709	0.9965
Curve Speed Warning Sign	0.9060	0.9393	0.9892	0.9962
Increased Shoulder Width	1.0725	1.0461	0.9247	1.0108
Changed Horizontal Curve Curvature	1.0185	1.0627	1.0551	1.0140
Decreased Curve Grade on Negative Grade	0.8963	0.9262	1.0376	1.0186
Increased Curve Grade on Positive Grade	0.9179	0.9789	1.0144	0.9680

Again, the result for centerline pavement marking could not be compared with the others. Adding countermeasures of edge line pavement marking, increased shoulder width, curve warning sign, and posted speed sign reduced the cognitive workload. As discussed previously, a proper level of cognitive workload can usually lead to better driving performance. Then, adding other countermeasures to the section of the curve with the centerline can reduce the attention shifts. A proper level of attention shifts can also improve driving performance. Next, most countermeasures reduced the level of interest after they were added to the basic countermeasure 1. The countermeasure of changed horizontal curve curvature led to the highest level of interest. For the difficulty of information extraction and understanding, countermeasures of flexible delineator posts, posted speed sign, curve warning sign, curve speed warning sign, and increased curve grade on positive grade reduced the difficulty levels and improved the driving performance.

Finally, to examine the relationships between countermeasures, drivers' cognitive attention, and traffic crashes, the combined significance parameters $B \times D$ in equation 7 are shown in table 41. The smaller $B \times D$ is, the more effective the countermeasures are. The effectiveness order showed the rank of countermeasures in reducing crashes. The way to judge the effectiveness of countermeasures is performed as follows:

1. The top four effective countermeasures on combined significance parameters in each column in table 41 were selected. For the cognitive workload, shoulder rumble strips, decreased curve grade on negative grade, increased curve grade on positive grade, and flexible delineator posts were selected. For the attention shifts column, curve warning sign, changed horizontal curve curvature, increased shoulder width, and edge line pavement marking were selected. For the level of interest, shoulder width, flexible delineator posts, curve warning sign, and edge line pavement marking were selected. For the difficulty of information extraction and understanding, edge line pavement marking, shoulder rumble strips, decreased curve grade on negative grade, and changed horizontal curve curvature were selected. A total of 16 countermeasures were selected.
2. The duplicates in the 16 countermeasures were removed, resulting in eight countermeasures. Besides, changed horizontal curve curvature, decreased curve grade on negative grade, and increased curve grade on positive grade were removed since those were not able to be accurately felt by drivers during simulation. As a result, edge line pavement marking, shoulder rumble strips, flexible delineator posts, curve warning sign, and increased shoulder width were the effective countermeasures.

Table 41. Combined significance parameters ($B \times D$) between crash, countermeasure, and cognition.

Countermeasures	Combined Significance Parameters ($B \times D$)							
	Cognitive Workload		Attention Shifts		Level of Interest		Difficulty of Information Extraction and Understanding	
	$B \times D$	Effectiveness Order	$B \times D$	Effectiveness Order	$B \times D$	Effectiveness Order	$B \times D$	Effectiveness Order
Centerline Pavement Marking	0.1418	-	0.0003	-	0.1340	-	−0.1048	-
Edge Line Pavement Marking	0.1430	8	−0.0007	3	0.1247	4	−0.1078	1
Shoulder Rumble Strips	0.1397	1	−0.0002	7	0.1287	6	−0.1075	2
Flexible Delineator Posts	0.1411	4	−0.0002	7	0.1220	2	−0.1040	8
Posted Speed Sign	0.1418	6	−0.0001	10	0.1301	8	−0.0994	10
Curve Warning Sign	0.1431	9	−0.0009	1	0.1240	3	−0.1044	6
Curve Speed Warning Sign	0.1412	5	−0.0006	5	0.1263	5	−0.1044	6
Increased Shoulder Width	0.1416	7	−0.0007	3	0.1181	1	−0.1059	5
Changed Horizontal Curve Curvature	0.1431	9	−0.0008	2	0.1347	10	−0.1063	4
Decreased Curve Grade on Negative Grade	0.1404	2	−0.0002	7	0.1325	9	−0.1067	3
Increased Curve Grade on Positive Grade	0.1408	3	−0.0004	6	0.1295	7	−0.1014	9

First, adding the countermeasure of edge line pavement marking maintained the proper level of attention shifts, attracted drivers' visual attention on fewer points, but had more time on each point to extract and understand information. Thus, drivers had the focused attention under this countermeasure, and it was an effective countermeasure to reduce crashes in this case. Another study also identified edge line pavement marking as an effective countermeasure that can reduce 23–28 percent of crashes (Jalayer and Zhou 2016). Second, the countermeasure of shoulder rumble strip effectiveness was identified in reducing speed (Charlton 2007), reducing 47–61.6 percent of all-severity traffic crashes (Jalayer and Zhou 2016), and was shown to be an effective countermeasure to reduce crashes in this case. Third, the countermeasure of flexible delineator posts was identified to effectively improve safety by reducing off-road collisions. The effectiveness of this countermeasure was also supported by previous work (Siddharthan et al. 2003). Fourth, the countermeasure of curve warning sign maintained the proper level of attention shifts of drivers to reduce crashes, which can be supported by previous work (Jalayer and Zhou 2016). Finally, the countermeasure of increased shoulder width attracted drivers' attention and provided proper visual information to improve traffic safety, as emphasized in other work (Gross and Jovanis 2007).

It can be concluded that after considering drivers' cognitive attention, the results are close to realistically showing the effectiveness of countermeasures. Thus, the proposed methodology considering both drivers' cognition and performance is reliable to evaluate countermeasures.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This study simulated a selected curve section of rural road on Cypress Lake Road, Statesboro, GA, with both horizontal and vertical curves, and both left and right turns. A total of 11 countermeasures of pavement marking, signage, roadway improvement, and 4 combinations of 2 weather conditions (foggy and clear) and 2 traffic flows (light and heavy traffic volume) were simulated to create different scenarios. A driving simulator, eye tracker, and questionnaires were used to collect data on eye movements, driving performance, and short-term memory. Sixty participants of diverse genders, ages, ethnicities, etc. participated in the experiment for collecting data. ANOVA was used for the analysis of the data to determine if the eye movements and driving performance were affected by the countermeasure, combination of weather and traffic, and sequence of driving. Regression analyses were performed to discover the effectiveness of the countermeasures to reduce crashes.

The main conclusions from the study were made as follows:

1. There were significant differences in most of the eye movements and driving performance indicators for different countermeasures based on the ANOVA tests.
2. The combinations of different weather conditions and traffic flows also had a significant impact on the indicators of driving performance, eye movements, and short-term memory. Different driving scenarios were key factors influencing drivers' performance and attention during the experiment.
3. The proposed methodology using both the driving simulator and eye tracker was more effective in measuring the effectiveness of countermeasures to improve traffic safety in

comparison with the method that only considered driving performance and countermeasures.

4. The regressions between the countermeasures and the crash that considered cognitive properties indicated that the countermeasures of edge line pavement marking, shoulder rumble strips, flexible delineator posts, curve warning sign, and increased shoulder width are effective countermeasures that can attract drivers' attention and maintain the proper level of cognitive workload and visual information to reduce traffic crashes and improve the traffic safety. These findings considering cognitive properties were close to what is expected in a real situation.
5. The regressions between the countermeasures and the crash that did not consider cognitive properties indicated that the countermeasures of posted speed sign, curve speed warning sign, and increased curve grade on positive grade were also effective to improve traffic safety based on the relationships between crashes and countermeasures without cognition. They can reduce the number of crashes in the selected two-lane rural road curve section. These findings without considering cognitive properties were different from what is expected in a real situation.
6. For the combinations of weather conditions and traffic flow, foggy weather with heavy traffic flow was the most dangerous scenario that caused the most crashes including vehicle collisions and off-road collisions, while clear weather and light traffic flow was a safer combination that led to the lowest number of crashes.

RECOMMENDATIONS

These conclusions have important practical and theoretical contributions. Practically, the effects of countermeasures and the combinations of weather conditions and traffic flow on driving performance, eye movements, and short-term memory were identified to improve roadway safety. The experiment design based on a driving simulator and eye tracker can also be used for future projects in Georgia to evaluate the effectiveness of countermeasures or to simulate diverse driving scenarios.

Theoretically, through the involvement of cognitive attention, the study provided comprehensive evidence of and insights into the effectiveness of countermeasures, weather conditions, and traffic flow on drivers' behavior and cognitive attention. In addition, the project identified the effectiveness of creating groups with different sequences for participants in the experiment, which can be applied in future studies.

In addition, based on the findings, the following recommendations are provided for GDOT to improve traffic safety in rural road curve sections in Georgia:

1. The project identified the relationships between drivers' cognitive attention, driving performance, and countermeasures to examine the effectiveness of the countermeasures on reducing crashes. GDOT can use drivers' cognitive attention to explain and understand the driving performance to improve the design and setting of countermeasures and further improve traffic safety.
2. The combination of a driving simulator and eye tracker was verified to be an effective method to evaluate the effectiveness of countermeasures on traffic safety in a two-lane rural road curve section. The methodology proposed by the project can also be applied to

investigate other countermeasures, as well as to simulate different scenarios (e.g., other types of roads, weather conditions, traffic flows, etc.).

3. The countermeasures of edge line pavement marking, shoulder rumble strips, flexible delineator posts, curve warning sign, and increased shoulder width were proven to be effective countermeasures that can attract drivers’ cognition and further reduce traffic crashes. They should be properly implemented in order to improve safety in two-lane rural curve areas in Georgia.
4. Finally, weather conditions and traffic flow were also critical factors impacting drivers’ cognition and performance. GDOT can consider the common traffic flows and weather conditions in the road areas when designing and setting up the countermeasures to better improve traffic safety.

TABLE OF TERMS

Symbol and term	**Definition**
Terms used for statistical analysis	
μ_i	Group mean value for countermeasure *i*
c	A constant value
p	P-value of the ANOVA test
Y	The dependable variable
W	The significance parameter
$\boldsymbol{W_1}$	The significance parameter for vehicle collisions
$\boldsymbol{W_2}$	The significance parameter for off-road collisions
A	The various independent variables
c	The approximation error
T	The identity matrix of the simulation
B	The significant parameter between the countermeasure and drivers' cognitive attention
D	The significance parameter between drivers' cognitive attention and traffic crash
Terms used for simulation plan	
MUTCD	Manual on Uniform Traffic Control Devices
Combination	Four combinations of two weather conditions (clear and foggy) and two traffic flows (light and heavy traffic flows)
Sequence	the different sequences of combinations that appeared in the driving simulation task
Order	the different starting time points for each combination
Terms used for cognition	
Pupillometry	Diameter of pupil
Saccade	Fast eye movements between different fixation points
Fixation	Eye movements located within a spatially limited region for a minimum period

APPENDIX A: PRE-SURVEY

Your ID (provided by the research team):

Part 1: Basic Information

Do you have a valid Georgia driver's license?

What county do you live in?

What city do you live in?

What is your gender?
- Male
- Female
- Prefer not to say

What is your ethnicity?
- White
- Hispanic or Latino
- Black or African American
- Native American or American Indian
- Asian/Pacific Islander
- Other (please specify)
- Prefer not to say

What is your age?

What is your highest level of education?
- Some High School
- High school
- Some college
- Associate
- Bachelor
- Master
- Doctorate
- Other (please specify)

What is your current occupation?

Part 2: Household Status and Habits

What is your marital status?

- Single, never married
- Married or domestic partnership
- Widowed
- Divorced
- Separated
- Prefer not to say

What is your visual ability (select all the items that you meet)?
- Myopia
- Hypermetropia
- Normal
- Color blindness
- Other (please specify)

Do you wear glasses when driving?
- Yes
- No

What is your smoking habit?
- Not at all
- Sometimes
- Everyday

What is your alcohol consumption habit?
- Not at all
- Sometimes
- Everyday

Part 3: Driving experience

Please specify the year you got your U.S. driving license:

How many years of driving experience do you have?

How many hours do you drive on average per week?

How many miles do you drive annually?

Did you receive any tickets/traffic violation?
- No
- Yes (please specify)

Did you have any crashes during your driving experience?
- No
- Yes (please specify)

Did you have any near-miss crashes during your driving experience?

- No
- Yes (please specify)

APPENDIX B: SHORT-TERM MEMORY QUESTIONNAIRE

Your ID (provided by the research team): _______________

Combination 1

1. Please choose ALL the items that you saw during the simulation.

A

B

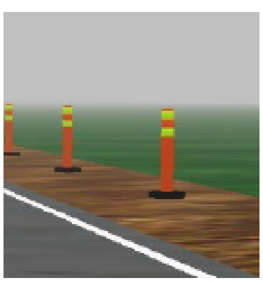
C

D

2. Please choose ALL the items that you saw during the simulation.

A

B



C

D

E

3. Please choose ALL the items that you saw during the simulation.


A


B


C


D


E

4. How confident are you in your ability to identify road signs quickly and accurately?

1	2	3	4	5
Not at all confident	Slightly confident	Moderately confident	Very confident	Extremely confident

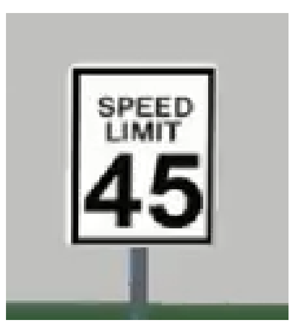
Combination 2

1. Please choose ALL the items that you saw during the simulation.


A


B

C



D

2. Please choose ALL the items that you saw during the simulation.

A

B

C

D

E

3. Please choose ALL the items that you saw during the simulation.

A

B

C

D

E

4. How confident are you in your ability to identify road signs quickly and accurately?

1	2	3	4	5
Not at all confident	Slightly confident	Moderately confident	Very confident	Extremely confident

Combination 3

1. Please choose ALL the items that you saw during the simulation.

A

B

C

D

E

2. Please choose ALL the items that you saw during the simulation.

A

B

C

D

3. Please choose ALL the items that you saw during the simulation.


A


B


C


D


E

4. How confident are you in your ability to identify road signs quickly and accurately?

1	2	3	4	5
Not at all confident	Slightly confident	Moderately confident	Very confident	Extremely confident

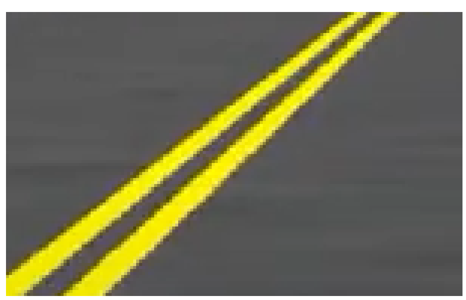
Combination 4

1. Please choose ALL the items that you saw during the simulation. If you choose the item, please specify your **understanding of this countermeasure** (e.g., turn right, stop, etc.).


A
Understanding: ___________________


B
Understanding: ___________________

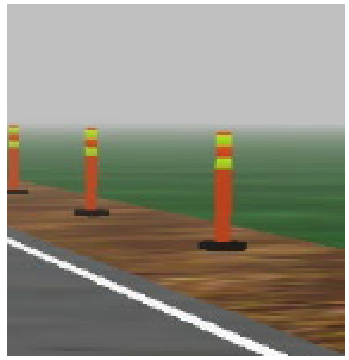

C
Understanding: ___________________


D
Understanding: ___________________

2. Please choose ALL the images that you saw during the simulation. If you choose the item, please specify your **understanding of this countermeasure** (e.g., turn right, stop, etc.).

A

Understanding: ___________________



B

Understanding: ___________________

C

Understanding: ______________

D

Understanding: ___________

E

Understanding: ___________

3. Please RANK the following images as the sequence you saw them during the simulation:

____

A

B

C

4. How confident are you in your ability to identify road signs quickly and accurately?

1	2	3	4	5
Not at all confident	Slightly confident	Moderately confident	Very confident	Extremely confident

APPENDIX C: POST-SURVEY

Your ID (provided by the research team): _______________

1. Did you experience dizziness during the simulation experiment? Check the answers that match your results. If you had any other symptoms, please specify in the box.
   - Yes
   - No
   - Other Symptoms (please specify below)

2. Was it your first time attending an experiment with the use of an eye tracker? Check the answers that match best your experience.
   - Yes
   - No
   - Other (please specify below)

3. How helpful was the incentive to encourage your participation in this experiment?

1	2	3	4	5
Not at all helpful	Slightly helpful	Moderately helpful	Very helpful	Extremely helpful

4. Please rank the helpfulness of the research team on a scale of 1 to 5?

1	2	3	4	5
Not at all helpful	Slightly helpful	Moderately helpful	Very helpful	Extremely helpful

5. Please check the one that matches your experience best and sign at the end.

I took break sessions during the testing and did not experience dizziness/injury	
I took break sessions during the testing and experienced dizziness/injury	
I did not take any break and did not experience dizziness/injury	
I did not take any break and experienced dizziness/injury	

____ ______________________

Participant Signature Date

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