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Impact of Perceptual Speed Calming Curve Countermeasures On Drivers' Anticipation & Mitigation Ability – A Driving Simulator Study

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IMPACT OF PERCEPTUAL SPEED CALMING CURVE COUNTERMEASURES ON DRIVERS' ANTICIPATION & MITIGATION ABILITY – A DRIVING SIMULATOR STUDY

A Thesis Presented

by

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ABSTRACT

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Horizontal curves are unavoidable in rural roads, are generally difficult to navigate and pose a serious crash risk to vehicle occupants. The current study investigates the impact and effectiveness of three curve-based perceptual speed calming countermeasures (advanced curve warning signs, chevron signs, and heads-up display (HUD) sign) on drivers' hazard anticipation and mitigation behavior across both left and right-winding curves, and sharp (radius 200m) and flat (radius 500m) curves. Forty-eight young drivers (18-34) were evaluated using a mixed design where the baseline condition with no countermeasures was a within factor and the three countermeasure conditions were manipulated between subjects. Eye movements were recorded for all participants and the proportion of hazards anticipated was identified across and within groups. Vehicle variables such as speed and lateral baseline were also collected from the simulator. Flat (500m radius) and sharp (200m radius) curves with indications of a safety problem were virtually developed in the driving simulator with as much representativeness as possible within the limits of the simulator's fidelity. Experimental results showed that speed selection and lateral control in the horizontal curves differed with respect to curve radii, direction, and the type of countermeasures present. These differences in behavior are likely due to curve-related disparities, the type of perceptual countermeasure, and the presence of a hazard at the apex of the curve. Head-Up Display (HUD) is found to be effective at not only reducing the drivers' speed in the curve, but also improves the latent hazard anticipation ability of the driver at the apex of the curve. The study has practical implications for reducing driver speeds and improving hazard anticipation at curves.

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CHAPTER 1

INTRODUCTION

In 2014, there were 32,675 people killed in motor vehicle crashes on U.S. roadways. An additional 2.3 million people were injured in crashes in 2014 [1]. In 2015, there were 35,092 people killed and an estimated 2,443,000 people injured in police-reported motor vehicle traffic crashes. Compared to 2014, this is a 7.2-percent increase in the number of fatalities and a 4.5 percent increase in the number of people injured [2]. Of these fatal crashes, 25 percent occurred along horizontal curves and predominantly on two-lane rural highways. Approximately 76 percent of curve-related crashes were single-vehicle crashes in which the vehicle left the roadway and 11 percent were head-on crashes. Thus, run-off-the-road (ROR) and head-on crashes accounted for 87 percent of the fatal crashes at horizontal curves [3].

1.1 Countermeasures to Improve Curve Safety

Of the nine proven safety countermeasures to reduce crashes on the road suggested by the Federal Highway Administration, one of the low-cost treatments is Enhanced Delineation and Friction for Horizontal Curves. This involves installing chevron signs, curve warning signs, sequential flashing beacons, advisory speed signs or high friction surface treatments that can have a positive effect on reducing the number of vehicles that leave the roadway on horizontal curves. The nine safety treatments vary by the severity of the curvature and the operating speeds present, but are low-cost in general. 28% of all fatal crashes occur on horizontal curves and about three times as many crashes occur on curves than in tangential sections of roadways. These countermeasures can reduce crashes from 43% to 13% [4].

Fatal crashes are also frequently a result of roadway departures. Longitudinal rumble strips and stripes on two-lane roads are also one of the low-cost countermeasures suggested to reduce curve crashes. This application provides an audible warning and physical vibration to alert drivers that they are leaving the roadway, and this application has shown good results in reducing run off the road (ROR) crashes [4].

As introduced by Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways, 2009 Edition, McGee et al., studied the nine basic countermeasures and treatments for horizontal curves. These include Centerline, Edge Line, Horizontal Alignment Signs, Advisory Speed Plaque, One-Direction Large Arrow Sign, Combination Horizontal Alignment/Advisory Speed Sign, Curve Speed Sign, Chevron Alignment Sign, and Delineators [5]. No research has documented the safety effects of installing a combination horizontal alignment/advisory speed sign. However, it was found that there was a 45-percent reduction on roadway segments and 24-percent reduction on rural highways when center lines, edge lines, and delineators were installed. Study showed that use of Horizontal Alignment Signs and Advisory Speed Plaque signs reported a 30-percent decrease in serious injury crashes at curves [6]. Chevrons assist the driver in navigating curves and was found that there was 25-percent reduction in crashes when chevrons are installed on rural highway curves [7].

1.2 Centerline and Edge Line Markings

The primary purpose of centerlines and edge lines is to provide a visual cue for drivers to follow the curve in order to mitigate opposite lane encroachments or edge line encroachments, and to prevent probable ROR incidents or crashes. When a curve does not provide adequate sight distance on two-lane roadways, a solid yellow line is necessary for one or both directions; edge lines are solid white lines along the right side of the road. NCHRP 600 states that pavement surface markings provide the strongest curvature guide [8]. A centerline is the minimum treatment for a horizontal curve. Based on the MUTCD, use of a centerline for roadways with travel widths less than 16 ft. requires engineering judgement, but roadways with lane widths of 20 ft. or more with minimum average daily traffic (ADT) of 6000 vehicles per day (vpd) require edge lines [9].

Various materials are used while marking pavements including thermoplastic marking, which lasts longer than other materials, making it cost-effective [10]. Retro-reflective pavement materials (RPMs) and retro-reflective raised pavement materials (RRPMs) are also applicable for pavement markings depending on roadway conditions, but the FHWA prohibits the use of raised pavement markings for edge lines [11]. Studies have suggested that the combination of centerlines or edge lines with rumble strips improve curve safety [12].

Conventional width for a centerline or edge line is 4–6 in., but some states use widths of 8–12 in. [13]. Edge lines with widths of 8 in. were found to be appropriate alternatives for roadways with 12 ft. wide lanes, unpaved shoulders, and ADT of 2000–5000 vpd [11]. Hallmark et al. summarized the positive benefits, drivers' feedback, and improvements, including increased visibility (especially at night for older drivers), peripheral vision stimulation, lane keeping, comfort of drivers, and aesthetics [14].

1.3 Horizontal Alignment Signs and Advisory Speed Signs

In the MUTCD, a wide variety of signs are used in advance of a curve to make drivers vigilant about the upcoming horizontal curve. Horizontal Alignment signs may be used where engineering judgement indicates a need to inform the road user of a change in the horizontal alignment of the roadway. Horizontal Alignment signs include turn, curve, reverse turn, reverse curve, winding road, large arrow, and chevron alignment signs. For a single curve, a turn sign (W1-1), a curve sign (W1-2), a hairpin curve sign (W1-11), a loop sign (W1-15) are applicable to warn drivers of an approaching horizontal curve. If the curve has a change in horizontal alignment of 135 degrees or more, the Hairpin Curve (W1-11) sign may be used instead of a Curve or Turn sign. If the curve has a change of direction of approximately 270 degrees, the 270-degree Loop (W1-15) sign may be used. Reverse turns (W1-3) and reverse curves (W1-4) are used for two sequential curves or turns. A Winding Road (W1-5) sign may be used where there are three or more changes in roadway alignment each separated by a tangent distance of less than 600 feet.

Figure 1 – Advanced curve warning signs for Horizontal Curves

Advisory Speed plaques may be used to supplement any warning sign to indicate the advisory speed for a condition. The MUTCD states that an Advisory Speed plaque shall not be installed until the advisory speed has been determined by an engineering study [9]. The horizontal alignment sign should be placed above the sign for advisory speed [8]. Advisory speed is not the legal speed limit but an advised speed for the drivers [10]. Though researchers agree about the safety benefits of using warning signs in advance of a curve, disagreement still exists concerning the use of symbols or text messages [8].

Highway curve signs are placed on the tangent section of the road before the start of the curve. This placement is related to the curve’s advisory speed and posted speed or 85th percentile speed [9]. Recommendations were provided by McGee and Hanscom for the placement of warning signs in advance of highway curves in accordance with the speed of approach of the vehicle. They emphasized that all signs be comprised of retro-reflective sheeting for increased night visibility and low-light conditions. The lower edge of the sign must be at least 5 ft. above the pavement surface, and the closest edge of the sign to the road must be at least 6 ft. from the outer edge of the shoulder [10].

1.4 Chevrons

Figure 2 - Left and Right Curve Chevron sign

Chevrons are signs used to emphasize and guide drivers through a change in horizontal alignment. *Figure 2* shows the chevron sign for Left and Right curve. The chevron alignment (W1-8) sign may be used to provide additional emphasis and guidance for horizontal alignment [13]. Lord et al. specify that Chevron Alignment signs shall be installed on the outside of a turn or curve, in line with and at approximately a right angle to approaching traffic. Chevrons are the strongest guidance cues and long-range guidance (anticipatory control) as emphasized by Campbell et al., [8]. The MUTCD recommends the typical spacing of Chevron Alignment signs on horizontal curves as shown in *Table 1* below [9].

Table 1 - Typical Spacing of Chevron Alignment Signs on Horizontal Curves

Advisory Speed	**Curve Radius**	**Sign Spacing**
15 mph or less	Less than 200 feet	40 feet
20 to 30 mph	200 to 400 feet	80 feet
35 to 45 mph	401 to 700 feet	120 feet
50 to 60 mph	701 to 1,250 feet	160 feet
More than 60 mph	More than 1,250 feet	200 feet

1.5 Delineators

Vertical delineators or post-mounted delineators (PMD) are intended to warn drivers of an approaching curve. PMDs can provide drivers with a better sense of the sharpness of the curve, so they can select the appropriate speed before entering the curve. PMDs provide continuous tracking information to drivers once they are within the curve to help position their vehicles within the travel lane while traversing the curve [14]. Chapter 3F of the MUTCD requires the color of the delineators to match the color of the adjacent edge line [9]. McGee et al. suggest that delineators be placed 2 to 8 feet outside the outer edge of the shoulder and spaced 200 to 530 feet apart on mainline tangent sections. The goal on curved alignments is to have several delineators simultaneously visible to the driver to show the direction and sharpness of the curve [15]. *Figure 3* below shows the image of post-mounted delineator along the horizontal curve.

Figure 3 - Post Mounted Delineator

Installation of Post Mounted Delineators (PMD) on horizontal curves revealed a 25% reduction in all types of crashes at horizontal curves [16]. However, for crashes on horizontal curves, the anticipated percentage reduction was not unique [13]. Neuman et al., (2003) found that enhanced delineation can reduce

ROR crashes on sharp curves and reported that PMDs could reduce ROR crashes by 15 percent on curves [11].

Efforts to reduce operating speeds on curves should concentrate on the tangent sections preceding the points of curvature because the speed at which a vehicle enters a curve is related more to the speed of the vehicle as it approaches the curve than to the sharpness of the curve [17]. Many factors contribute to run-off-the-road and head-on collisions on curves, including driver impairment, fatigue, inattention, visual deficits and excessive vehicle speed. Factors of the driver are mostly out of the direct influence of transportation engineers, but wise placement of pavement makings can influence driver speed selection upon entering horizontal curves. Retting and Farmer used a pavement marking which helped in decreasing vehicle speeds by approximately 6 percent overall and 7 percent during daytime and late-night periods [18].

1.6 Hazard Anticipation at Curves

Notable research has been done in evaluating the efficacy of various countermeasures at curves at mitigating crashes and reducing single vehicle and ROR collisions. Apart from the curve countermeasures, one important aspect which could be investigated is whether these countermeasures would also be effective in helping the drivers anticipate any latent hazards at the apex, entry, and exit of curves. If countermeasures at curves are effective, it is expected to find out which countermeasure would be effective in anticipating the hazard.

Hazard anticipation can be described as the detection and recognition of potential dangerous road and traffic situations, and the prediction of how these latent hazards can develop into acute threats [19]. Drivers must perform complex tasks like steering and braking to keep up with geometry and speed which determines their skill and competencies in driving. Age and experience also play an important role while negotiating curves. Younger drivers (17-19 years) have a higher risk of crashing in curves and are involved in twice the proportion of accidents while negotiating a curve than older drivers (30-39 years) [20].

1.7 Issues in Driving at Horizontal Curves

Horizontal curves are likely to cause safety hazards to road users because of the changes in driver expectancy and vehicle handling maneuvers [21]. Schneider et al. provided two explanations from the driver awareness perspective: the driver may be unaware of the approaching horizontal curve or the driver underestimates the radius or sharpness of the curve [22]. In another study, Schneider et al. found that horizontal curves may reduce the driver's available sight distance and reduce vehicle-handling capabilities [23].

Drivers adapt to changes in roadway characteristics. High speeds and careless driving may be induced by wider lane widths, so the benefits of wider lane widths may become null because of the negative effects associated with a driver's adaptation. Also, a narrow lane may cause a car to run off the road more easily, which may increase the risk for the driver to overturn or roll over [13].

It is generally assumed that vehicles will more easily leave their lane on a curve rather than the tangent section because of the centrifugal force that acts on the vehicle when it enters the curve. Charlton (2007) proposed three main causative factors for crashes in curves: inappropriate speed monitoring, failure to maintain proper lateral position, and inability to meet increased attentional demands [24]. Crash rates significantly increase for curves with a radius smaller than 200m.

According to FHWA (2006), over 25,000 people were killed in 2005 because the drivers left their lane and crashed with an oncoming vehicle, rolled over, or hit an object located along the roadway. Eighty percent of ROR fatalities occurred along horizontal curves on rural roadways, with about 90% of these occurring on two-lane roads [25].

Glennon et al., (1983) referred to the region three seconds before the curve as the critical region. At about 200 feet (about 60 m) before the Point of Curvature (PC), which is about three seconds of driving time, drivers should begin simultaneously adjusting both their speed and path. Such adjustments were particularly large on sharper curves [26]. The root cause of many single-vehicle crashes at curves appear to stem from inappropriate speed selection before entering the curve. In many single-vehicle crashes, drivers under steered or over steered, producing a turn that was sharper than the rural highway curve [27].

1.8 Heads-Up Display (HUD)

Several cars are using HUDs to convey information to the driver. Driver distraction is reduced by providing information only when necessary to assist the driver, and in a visually pleasing manner. Using HUD, information can be presented to the vehicle driver without their need to move their eyes from the road, and as a result, improving driver awareness [28]. By presenting information that is closer to the normal field of view, HUDs require less effort on the part of the driver than other kinds of visual displays [29].

When using HUD to present navigation information to the driver, it is essential that they are not distracted in any way and the display does not interfere with the primary task of driving. The incorporation of HUD offers the prospect for negating the negative effects associated with driving in horizontal curves and provides guidance to the driver to safely negotiate a curve. In the driving simulator, HUD image is displayed in the upper half of the center screen so that it will not cause distraction for the driver, as they need to differentiate between what is in the HUD and what is in the virtual scenario. In the actual vehicle, HUD is implemented on the windshield of cars in the direct line of sight of the driver to avoid distraction and manage the risk level [30].

Table 2 - Past research on Warning signs used in Horizontal Curves

Author	**Summary**
G Kanellaidis (1995)	Four factors influencing drivers’ choice of speed - Opposing traffic, Road cross-section, Road Alignment(curvature) and Signing(road signs)
Charlton (2004)	Curve Warning sign, Chevron Warning sign , and transverse line warning(road marking) work well at horizontal curves
Charlton (2007)	Chevron warning signs are the most effective in producing substantial reductions in drivers’ curve speeds
Rasanen (2005)	Continuous longitudinal rumble strips placed on the edge line and centerline improve lane keeping
Torbic et al., (2004)	Continuous longitudinal rumble strips placed on the edge line and centerline reduce run-off-road crashes

From *Table 2* above it can be observed that some of the researchers from the past have focused on various warning signs and pavement delineations but HUD as such has not been specifically tested in horizontal curves for its effectiveness as a warning sign to educate the driver about curve negotiation and safety.

1.9 Objectives and Hypotheses

The objective of this study was to evaluate the efficacy of speed calming curve based perceptual countermeasures. An added goal was to check if the driver would be able to reduce to safe speed, maintain lateral position, and anticipate hazard at the apex while driving at horizontal curves using the cues provided.

Hypotheses were generated based on previous research on curve countermeasures related to driver performance and hazard anticipation.

Hypothesis 1: Drivers in C1 (Heads Up Warning Sign + Advanced Curve Warning Sign + Chevrons) treatment condition will anticipate greater proportion of hazards on curved sections than drivers in C2 (Heads Up Warning Sign + Advanced Curve Warning Sign), C3 (Advanced Curve Warning Sign + Chevrons), or No Countermeasure condition.

Hypothesis 2: Drivers in treatment condition C1 will have reduced speeds in curves when compared to drivers in other treatment conditions.

CHAPTER 2

METHOD

2.1. Description of Countermeasures

Three countermeasure combinations were used which consisted of various types of warning signs designed to alert drivers to the presence of curve, and hopefully produce a reduction in drivers' speeds at the approach to the horizontal curve. The description of each countermeasure is given below.

C1: Heads-Up Display (HUD) Warning Sign + Advanced Curve Warning Sign + Chevrons

C2: Heads-Up Display (HUD) Warning Sign + Advanced Curve Warning Sign

C3: Advanced Curve Warning Sign + Chevrons

NC: No Countermeasure.

It can be seen from the above combinations that Advance Curve Warning sign is common among all of the mentioned C1, C2, and C3 countermeasures. There is no Chevron sign in C2, and in C3 there is no HUD. The primary reason for having only two warning signs in C2 and C3 is to compare the effectiveness of HUD and Chevron as to which one works better in terms of giving a better visual alert to the driver. Other reason for making the specific combination in C2 and C3 is to identify if the physical chevron sign could be replaced by the in-vehicle HUD.

MUTCD states that Chevron alignment signs may be used instead of or in addition to standard delineators [9]. Results from Charlton's study indicated that advance curve warning signs by themselves were not as effective at reducing speeds as when they were used in conjunction with chevron signs [24]. Advance Curve warning sign is the standard one and Chevron sign was added to this to make the combination in countermeasure C3. In countermeasure C2, Chevron sign was removed and HUD was added to the standard advance curve warning sign. Since the effectiveness of HUD is to tested, it was added to C3 and Countermeasure C1 is outlined.

2.2. Participants

A total of 48 participants were recruited for the experiment from the University of Massachusetts Amherst and surrounding local town areas. The subject population consisted of adults aged 18 and above. The sample age ranged from 18 to 34 years. The mean age was 21.1 with a standard deviation of 3.05. Driving experience ranged from 0.25 to 17.75 years with a mean driving experience of 4.4 years and standard deviation of 3.06. The age between groups C1, C2, and C3 ranged from 18 to 31, 18 to 34, and 18 to 25 years respectively. The mean driving experience between groups C1, C2, and C3 is 5.37, 3.9, and 3.79 years respectively. All participants received monetary compensation for their involvement in the experiment.

2.3. Apparatus

The driving simulator used in this study was a Realtime Technologies Inc. (RTI) fixed-base simulator with full-body 2013 model Ford Fusion Sedan surrounded by five projection screens. Fixed base simulator at UMass Amherst is shown in *Figure 4* below. The simulator consisted of five main projectors and one rear projector. Main projectors had a resolution of 1920 x 1200 pixels and image display refresh rate of 96Hz. Rear projector had a resolution of 1400 x 1050 pixels with the same refresh rate as main projectors. Field of view is approximately 330^0. Sound system consists of a five speaker surround system plus a sub-woofer for exterior noise, and a two speaker system plus sub-woofer for interior vehicle noise. The simulator also has a customizable glass dashboard and 17-inch touchscreen center stack.

Figure 4 – Fixed base simulator at UMass Amherst

A portable ASL Mobile Eye XG eye tracker system was used to record drivers' eye movement. The eye tracker samples the position of the eye at 33 Hz with a visual range of 50° in horizontal direction and 40° in the vertical direction. The system's accuracy was 0.5° of visual angle. The information was used to determine the participant's point of gaze and was recorded for later replay.

2.4. Simulator Scenarios

All of the simulator scenarios were designed using RTI Sim Vista Version 3.2. Eight scenarios were developed on the simulator and then various combinations of countermeasures were used. All eight simulated scenarios had different Hazard Anticipation events and also differed in the countermeasure condition and road curvature as well. *Figure 5* shows the Heads-Up display sign and *Figure 6* shows the Advanced curve warning sign with advisory speed limit and Chevron sign.

Figure 5 – Scenario showing the Heads-Up Display alert

Figure 6 – Scenario showing Advance Curve warning and Chevron sign

The description of hazard anticipation scenarios used for the three countermeasures and the baseline condition is shown in *Table 3* below.

Table 3 – Hazard Anticipation scenarios' description

HA	Description	Picture	Curve type and direction
HA1	The driver approaches a crosswalk at the apex of the curve with a pedestrian crossing the crosswalk and the driver's vision is obscured by bushes and vegetation.		Right Flat
HA2	This scenario presents a work zone on the right with a stopped vehicle pulling into the traffic lane.		Left Flat
HA3	At the apex of the curve, there is a hidden driveway in front of a residential building, and the driveway is obscured by bushes		Right Sharp
HA4	A truck is parked on the right with blinkers ON. The truck is positioned 75% in the lane and 25% in the grass with an opposing vehicle at the same time.		Left Sharp

HA5	The driver drives along a curve with a line of dense bushes along the boundary of the inner curve and a slow moving vehicle on the right at the apex is present.		Right Flat
HA6	A bicycle enters the travel lane from the right in front of the driver's car at the apex of the curve.		Left Flat
HA7	A car is waiting to exit from the driveway on to the drivers' travel lane while another car is waiting to enter the driveway from the opposite lane.		Right Sharp
HA8	A truck is parked or stopped at the apex of the curve just before the crosswalk obscuring any potential pedestrians.		Left Sharp

The hazard anticipation condition is unique across all the eight scenarios. The only thing that differs is the treatment condition. Before the entry of the curve, the participant was provided with cues to make them alert about the imminent hazard posing in front of them. *Figure 7*, *Figure 8*, *Figure 9*, and *Figure 10* show the signs of cues before hazard.

Figure 7 – Slow: Work Zone Ahead sign

Figure 8 – Hidden Driveway sign

Figure 9 – Slow Moving Vehicles sign

Figure 10 – Bicycle Ahead sign

2.5. Experimental Design

Drivers were randomly placed into one of three groups which corresponded with the type of curve countermeasure present:

C1: Heads-Up Display (HUD) Warning Sign + Advanced Curve Warning Sign + Chevrons

C2: Heads-Up Display (HUD) Warning Sign + Advanced Curve Warning Sign

C3: Advanced Curve Warning Sign + Chevrons

The experimental design consisted of three groups of 16 participants each facing one of the three treatment conditions (C1, C2, and C3) and all 48 participants facing the baseline condition (no treatment (NC) condition). This is a 3x2 mixed design with countermeasure as one factor, and treatment as the other factor. The countermeasure has three levels, and is between-subjects and the treatment has two levels, and is within-subjects.

All participants drove eight scenarios (Four with countermeasures and four without countermeasures). A counterbalancing matrix was used in order to negate the effects of drive order on participants' driving behavior. The order of conditions and scenarios were pseudo randomly counterbalanced across participants using a Latin Square Design. An example of counterbalancing for a couple of participants is shown in *Table 4* below.

Table 4 – Example of scenario order counterbalancing

SCENARIO							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
HA1_C1	HA2_NC	HA8_NC	HA3_C1	HA7_C1	HA4_NC	HA6_NC	HA5_C1
HA2_NC	HA3_C2	HA1_C2	HA4_NC	HA8_NC	HA5_C2	HA7_C2	HA6_NC

2.6. Independent and Dependent Variables

Independent variables are the treatment conditions and participants' demographics.

Dependent variables are the eye measures (proportion of LHA, proportion of clues detected, and glance towards countermeasure), and vehicle measures (Steering angle, Acceleration, Lane Offset, and Velocity). The participants' glances are binary coded as 1, if the participant correctly glances at the target zone while in the launch zone, while they are scored 0 otherwise. A target zone is defined as where participants should glance to appropriately anticipate latent threats while a launch zone is described as that part of the roadway when the participant should begin scanning the threat zone for any threats. The coding of the eye movement data was conducted after obtaining the data from all participants.

2.7. Procedure

All participants were given the opportunity to read and sign the informed consent form when they entered the research lab. They were then made to sit in the fixed base simulator and were fitted with the head-mounted eye tracking equipment to record the eye glance data. In order to make the participants familiar with the simulator, they were given the opportunity to drive one virtual scenario and were instructed to let the researcher know if they felt dizzy or motion sick. Participants also filled out pre-study questionnaires related to their basic demographics and driving history. After being fitted with an eye tracker, and the calibration of the eye tracker, participants were assigned to one of the three experimental conditions and navigated eight scenarios each. After finishing their respective eight drives, participants filled post-study questionnaires, signed a stipend voucher and were excused from the study.

CHAPTER 3

RESULTS AND DISCUSSION

The current driving simulator study evaluated the effectiveness of perceptual speed calming horizontal curve countermeasures and also examined drivers' behavior when they were posed with a hazard at the apex of the curve. Three countermeasures, advanced curve warning signs, heads-up display signs, and chevron signs were used for this study. The primary objective of these countermeasures was to make the driver reduce their speed at the entry of the curve and increase overall hazard anticipation. No secondary tasks were given to the driver while driving, other than the primary task of driving, which implies that there was no additional cognitive workload on the driver.

A mixed subjects experimental design was employed in which each participant drove four baseline drives and four experimental drives. The order of the drives was counter-balanced, so half of the participants started with the baseline drive first and half with the experimental drive first. The controlled laboratory settings allowed for the control of ambient traffic, manipulation of critical variables as well as the direct measurement of dependent variables. As this is a mixed-subject design, Mixed Model ANOVA has been used to analyze the vehicle data. Since the glance data is binary, logistic regression analysis has been carried out. Both of the methods were carried out using the statistical tool IBM SPSS. All error bars represent 95% confidence intervals.

3.1. Vehicle Data

3.1.1. Velocity and Lane Offset Behavior

Driver behavior can be analyzed using the information provided by the vehicle. Data that can be collected from the vehicle include velocity and lateral position. Information about driver can be used to detect variations in driver behavior in different environments [31]. Velocity and Lane Offset behavior was captured from the vehicle using data markers in the virtual scenarios. Two data markers were placed in each scenario at the same coordinates to maintain consistency.

The mean and standard deviation of velocity and lane offset across treatment conditions in CURVE and TANGENT segments is shown in *Table 5* and *Table 6* below respectively.

Table 5 – Mean and Std. Deviation of Velocity and Lane Offset at Curve

Treatment Condition	**Velocity (mph)**		**Lane Offset (m)**	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
C1	42.37	5.96	0.28	0.11
C2	43.35	6.73	0.26	0.11
C3	45.38	9.12	0.32	0.13
NC (C1)	42.20	7.38	0.29	0.10
NC (C2)	42.32	7.45	0.32	0.12
NC (C3)	44.26	9.11	0.34	0.13

Table 6 – Mean and Std. Deviation of Velocity and Lane Offset at preceding Tangent

Treatment Condition	**Velocity (mph)**		**Lane Offset (m)**	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
C1	51.91	5.47	0.20	0.08
C2	53.50	5.85	0.22	0.11
C3	52.56	4.88	0.23	0.12
NC (C1)	51.80	5.02	0.20	0.08
NC (C2)	53.37	6.31	0.22	0.12
NC (C3)	52.59	4.58	0.21	0.10

Figure 11 below illustrates the differences in velocities between the curve and the preceding tangent segment for the three treatment conditions. It was found from the study that the velocities in the tangent

section across the various treatment conditions are almost the same, but velocities at the apex of the curve varied by the type of the countermeasure used.

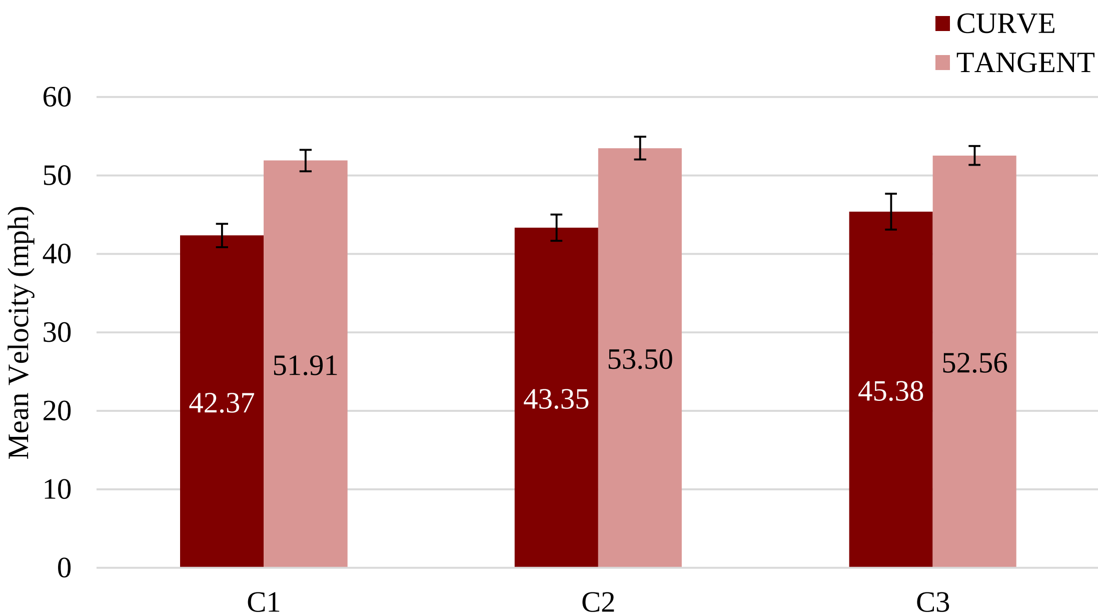

Figure 11 – Velocity differences between Curve and Tangent sections

Results from 2-Sample t-tests concluded that mean velocities at curve segments between C1 and C3 were statistically significant with p-value<0.05. p-values from t-tests are shown in *Table 7* below.

Table 7 – 2-sample t-tests for velocity at curve between countermeasure groups

Treatment								
C1 vs C2			C2 vs C3			C3 vs C1		
df	T	P-Value	df	T	P-Value	df	T	P-Value
126	-0.88	0.383	126	-1.43	0.154	126	2.21	0.029*

* indicates statistical significance at 95% confidence.

Figure 12 below illustrates the differences in Lane Offset between the curve and the preceding tangent segment for the three treatment conditions. It was found from the study that the lane offset in tangent section across the various treatment conditions is almost the same, but varied at curve and also varied by the type of the countermeasure used.

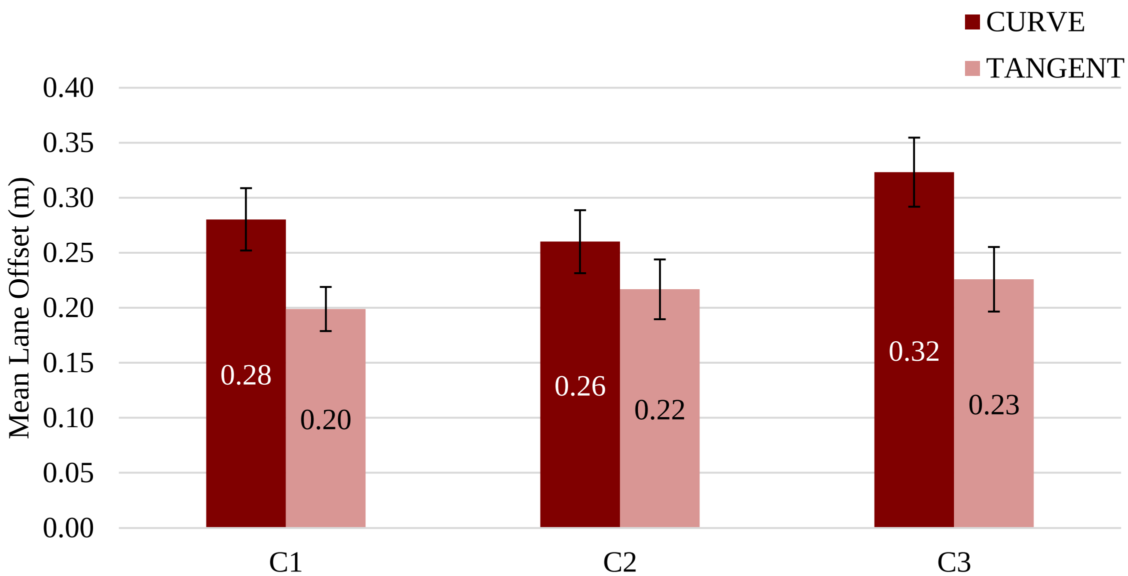

Figure 12 – Differences in Lane Offset between Curve and Tangent sections

From the t-test results for Lane Offset shown in the *Table 8* below it is evident that lane offset was significantly different between curve sections of C2 & C3, and C3 & C1 in which HUD warning sign is available to the driver in C1 and C2 countermeasures. It highlights the fact that HUD is effective in reducing the lane offset as well as driver speed at curves.

Table 8 – 2-sample t-tests for Lane Offset at curve between countermeasure groups

Treatment

C1 Vs C2			C2 Vs C3			C3 Vs C1		
df	T	P-Value	df	T	P-Value	df	T	P-Value
126	1.0	0.32	126	-2.97	0.004*	126	2.03	0.044*

* indicates statistical significance at 95% confidence.

It has been observed from the experiment that the velocities were reduced in sharp horizontal curves as opposed to flat. The results between flat and sharp curves were found to be statistically significant with p-value<0.05. However, the lane offset between sharp and flat curves was found to be not statistically significant with p-value>0.05.

Figure 13 below shows the differences in velocities between flat and sharp curves based on the countermeasures. C1 has HUD and C3 has no HUD, and it is obvious that C1 group drove with lower velocities when compared to group C3, with differences in mean velocities being statistically significant between groups C1 and C3 when they drove in a sharp curve.

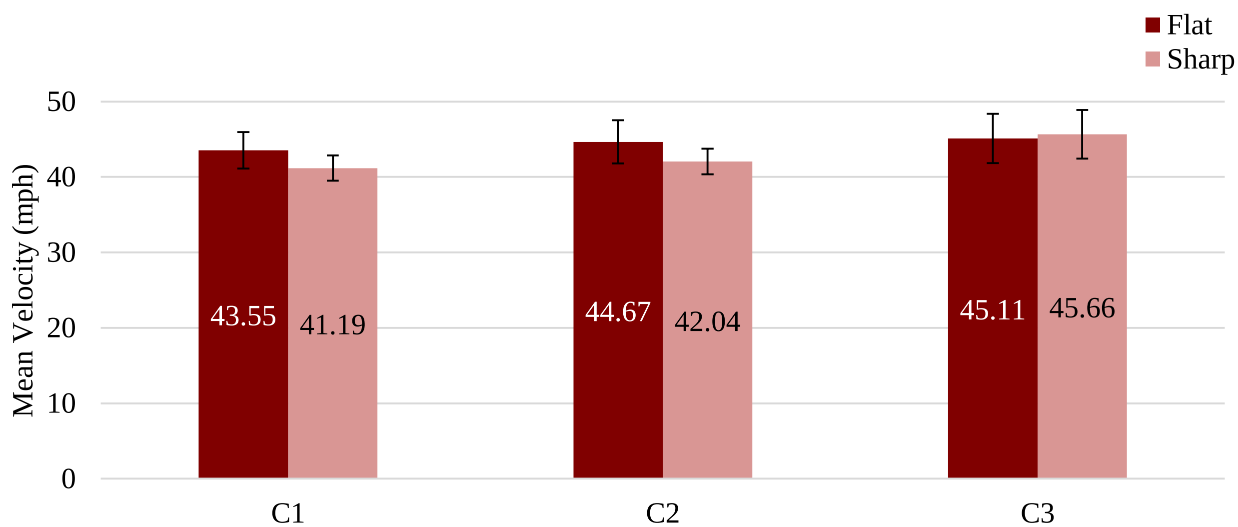

Figure 13 – Differences in Velocities between Flat and Sharp curve based on Countermeasure

T-tests have been conducted between those groups who drove flat and sharp curves based on countermeasure. *Table 9* below shows the results from the t-tests conducted across the groups.

Table 9 – T-tests for velocities across groups in a Sharp curve

Treatment

C1 Vs C2			C2 Vs C3			C3 Vs C1		
df	T	P-Value	df	T	P-Value	df	T	P-Value
62	-0.72	0.475	62	-1.98	0.053	62	2.46	0.017*

* indicates statistical significance at 95% confidence.

Figure 14 below shows that the lane offset in sharp curves was more for C3 group which had no HUD warning sign as compared to C1 and C2 groups which had HUD.

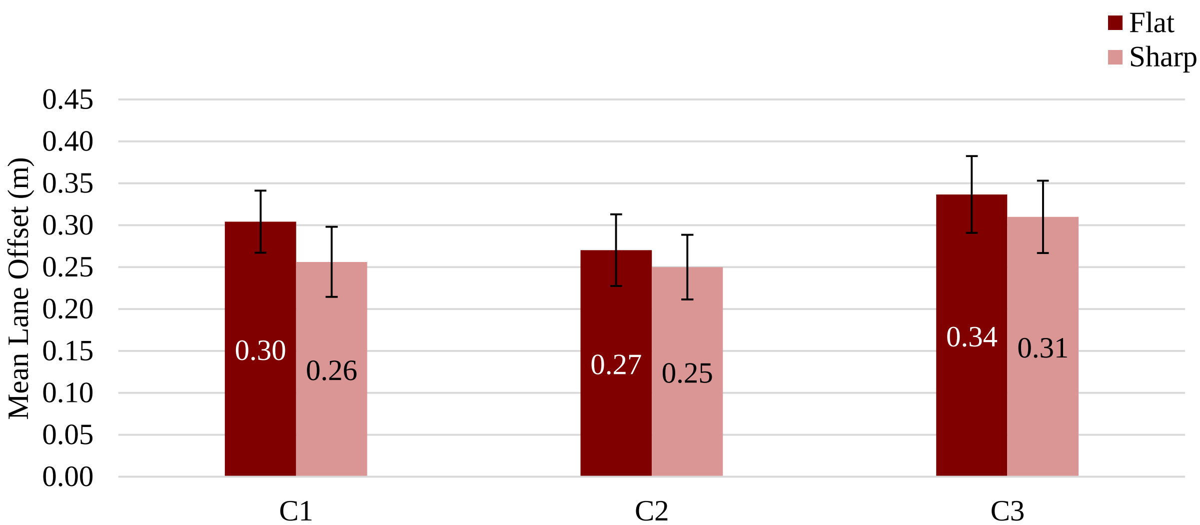

Figure 14 – Differences in Mean Lane Offset between Flat and Sharp curve by Countermeasure

Table 10 below shows the results from t-tests conducted between countermeasures in a sharp curve. It was found that lane offset was statistically significant between C2 and C3 groups, in which C3 had no heads-up display sign.

Table 10 – T-tests for lane offset across groups in a Sharp curve

Treatment

C1 Vs C2			C2 Vs C3			C3 Vs C1		
df	T	P-Value	df	T	P-Value	df	T	P-Value
62	0.22	0.825	62	-2.08	0.042*	62	1.79	0.079

* indicates statistical significance at 95% confidence.

Figure 15 below shows the drivers' speed per each drive. It is apparent that drivers' speed was slow in the initial drive and as the drives progressed their speed was stabilized.

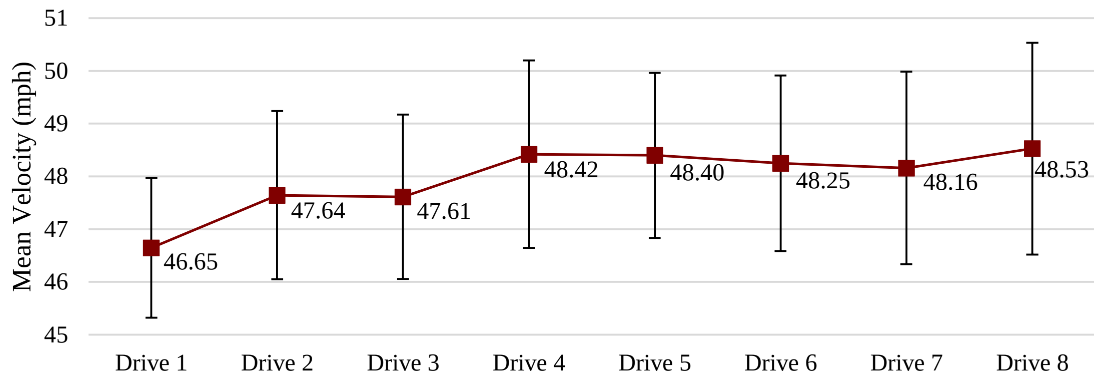

Figure 15 – Mean velocity per drive for all participants

From the graphs and t-tests obtained by analyzing the vehicle data, it can be concluded that Heads-Up Display (HUD) warning sign has been the most effective among HUD, Advanced Curve sign, and Chevron sign in making the drivers reduce their speed while driving in sharp curves and staying in the lane. It was also found that drivers' speed was less when encountered with drives which had HUD as opposed to advanced curve and chevron signs. The same could be said of the lane offset as well implying that drivers' had more lateral control with HUD rather than Advanced Curve and Chevron signs.

3.1.2. Mixed Methods ANOVA

Analysis of Variance (ANOVA) method allows the researcher to test whether participants perform differently in different experimental conditions. While a 'repeated-measures ANOVA' contains only within participants' variables and an 'independent ANOVA' uses only between participants' variables, Mixed ANOVA contains both variable types.

In this research experiment, there are two independent variables:

1. Countermeasure which has three levels: C1, C2, and C3.
2. Treatment which has two levels: Experimental (with countermeasure) and Baseline (without countermeasure).

Countermeasure is a between-subject and Treatment is a within-subject. This is a 3x2 factorial mixed-subject design.

Main effect is the effect of the independent variable on the dependent variable. While main effects are caused autonomously by each independent variable, an interaction effect occurs if there is an interaction between the independent variables that affects the dependent variable. The main effects plot for velocity is shown in *Figure 16* below.

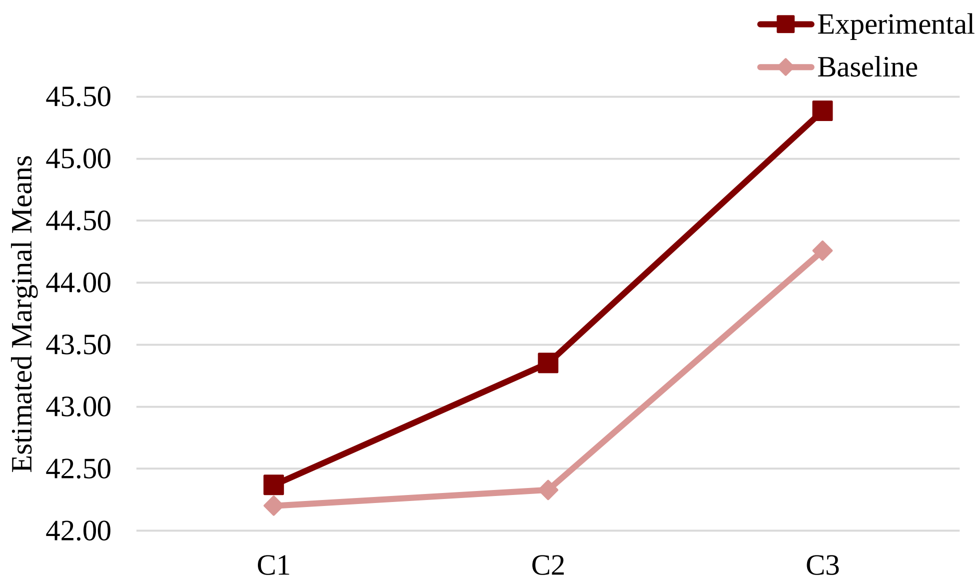

Figure 16 – Main Effects plot for Velocity

Table 11 – SPSS output from analysis of effect of Treatment and CM on Velocity

Dependent Variable: VELOCITY								
Source	df	Type III Sum of Squares	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[b]
Corrected Model	5	532.572[a]	106.514	1.791	.114	.023	8.953	.614
Intercept	1	720368.034	720368.034	12110.567	.000	.970	12110.567	1.000
TREATMENT	1	58.278	58.278	.980	.323	.003	.980	.167
CM	2	456.493	228.246	3.837	.022	.020	7.674	.695
TREATMENT * CM	2	17.801	8.901	.150	.861	.001	.299	.073
Error	378	22484.424	59.483					
Total	384	743385.030						
Corrected Total	383	23016.996						

a. R Squared = .023 (Adjusted R Squared = .010)

b. Computed using alpha = .05

In *Table 11* shown above, we are interested in three rows: two main effects (Treatment and CM) and one interaction effect (TREATMENT * CM). This table shows the main effect of Treatment and Countermeasure (CM) on Velocity. Looking under the "Sig." column, we see that the main effect of Treatment on Velocity was not significant (F (1,378) = 0.980, p = 0.323) but the main effect of Countermeasure (CM) on Velocity was significant (F (2,378) = 3.837, p = 0.022). The R^2 value indicates how much of the total variation in the dependent variable (i.e., Velocity) can be explained by the independent variables. In this case, 2.3% can be explained. Taken as a set, the predictors Treatment, and Countermeasure (CM) account for 2.3% of variance in the Velocity. As you can see, adding the interaction to the main effect increased the R^2 from 0.010 to 0.023. In *Table 11* the "Corrected Model" and "Intercept" tests can be ignored. The "Corrected Model" is a test of the hypothesis that all effects (main effects and interactions) are zero. The "Intercept" is a test of the hypothesis that the overall mean for the dependent variable (Velocity) is zero. Usually, neither of these tests is of any interest to us. The main effects plot for lane offset is shown in *Figure 17* below.

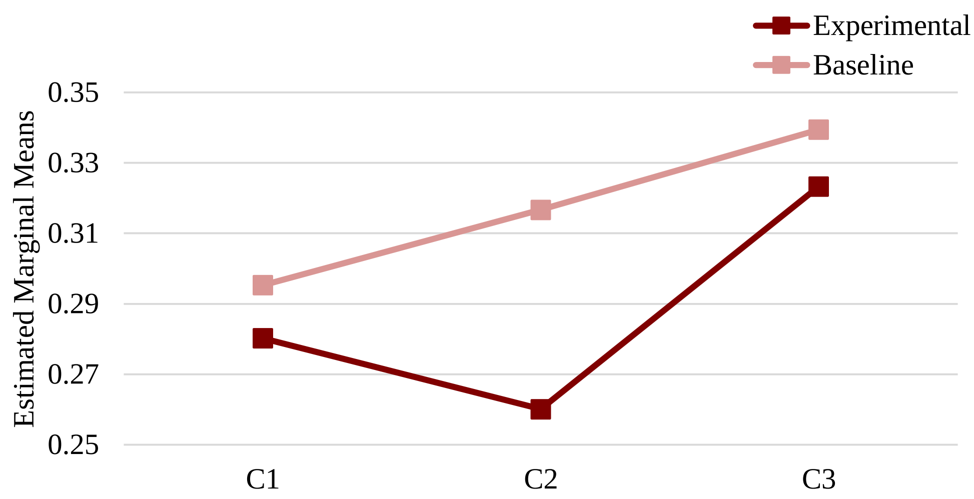

Figure 17 – Main Effects plot for Lane Offset

Table 12 – SPSS output from analysis of effect of Treatment and CM on Lane Offset

Dependent Variable: LANE OFFSET								
Source	df	Type III Sum of Squares	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[b]
Corrected Model	5	.278[a]	.056	4.047	.001	.051	20.234	.952
Intercept	1	35.156	35.156	2557.386	.000	.871	2557.386	1.000
TREATMENT	1	.083	.083	6.047	.014	.016	6.047	.689
CM	2	.159	.079	5.782	.003	.030	11.564	.868
TREATMENT * CM	2	.036	.018	1.312	.271	.007	2.623	.283
Error	378	5.196	.014					
Total	384	40.630						
Corrected Total	383	5.474						

a. R Squared = .051 (Adjusted R Squared = .038)

b. Computed using alpha = .05

Table 12 above shows the main effect of Treatment and Countermeasure (CM) on Lane Offset. Looking under the "Sig." column, we see that the main effect of both Treatment (F (1,378) = 6.047, p = 0.014) and Countermeasure (F (2,378) = 5.782, p = 0.003) was significant. The R^2 value indicates how much of the total variation in the dependent variable (i.e., Lane Offset) can be explained by the independent variables. In this case, 5.1% can be explained. Taken as a set, the predictors Treatment, and Countermeasure (CM) account for 5.1% of variance in the lane offset. As you can see, adding the interaction to the main effect increased the R^2 from 0.038 to 0.051. In *Table 12* the "Corrected Model" and "Intercept" tests can be ignored. The "Corrected Model" is a test of the hypothesis that all effects (main effects and interactions) are zero. The "Intercept" is a test of the hypothesis that the overall mean for the dependent variable is zero. Usually, neither of these tests is of any interest to us.

3.2. Eye Glance Data

3.2.1. Eye Glance and Hazard Anticipation

To analyze whether drivers successfully anticipated latent hazards, it should be determined if a participant glanced towards the pre-determined target zone while in the launch zone. A *target zone* was defined as the area where a potential hazard might be present, and the *launch zone* was defined as the area where the driver should glance at the hazard.

Countermeasures C1 and C2 had HUD and *Figure 18* below shows the fact that drivers anticipated hazard better in C1 and C2 conditions than in the C3 condition which is consistent with Hypothesis 1. As for the No Countermeasure (NC) or baseline scenarios is considered, drivers' latent hazard anticipation (LHA) percentage was higher when compared to the experimental group. Differences in sample size between experimental and baseline group could be one of the reason for high LHA percentage. Low visual task load on drivers in baseline group might be one of the reason for higher proportions of hazard anticipation at the apex of the curve. However, in *Figure 19* below it can be seen that drivers' glance percentage at HUD warning sign was higher among the three perceptual curve countermeasures presented.

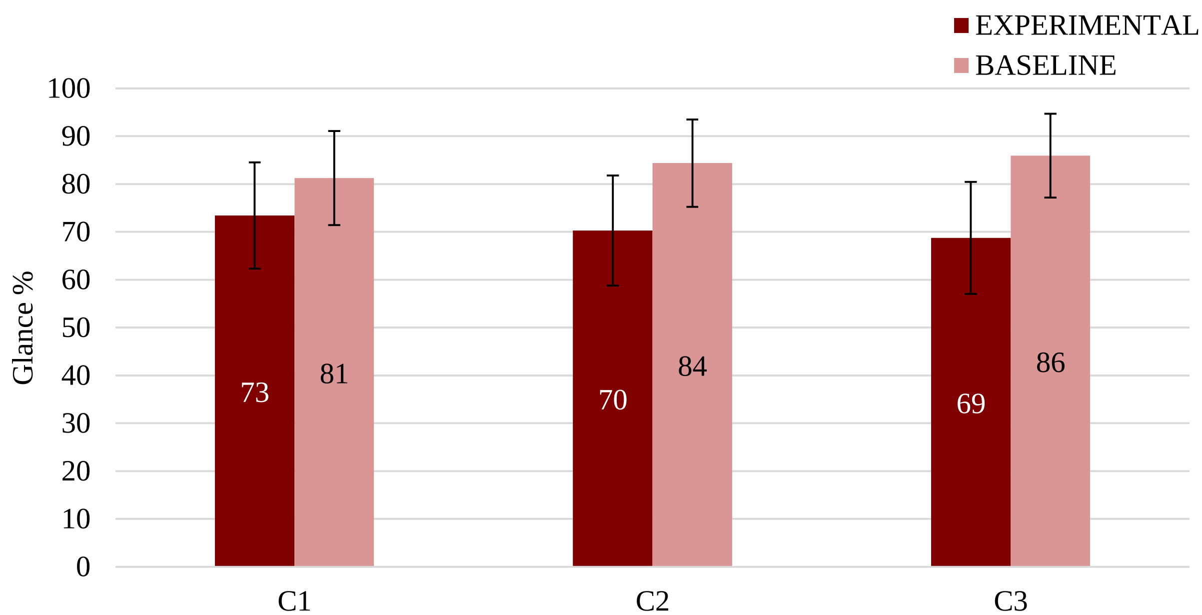

Figure 18 – Hazard anticipation by countermeasure groups

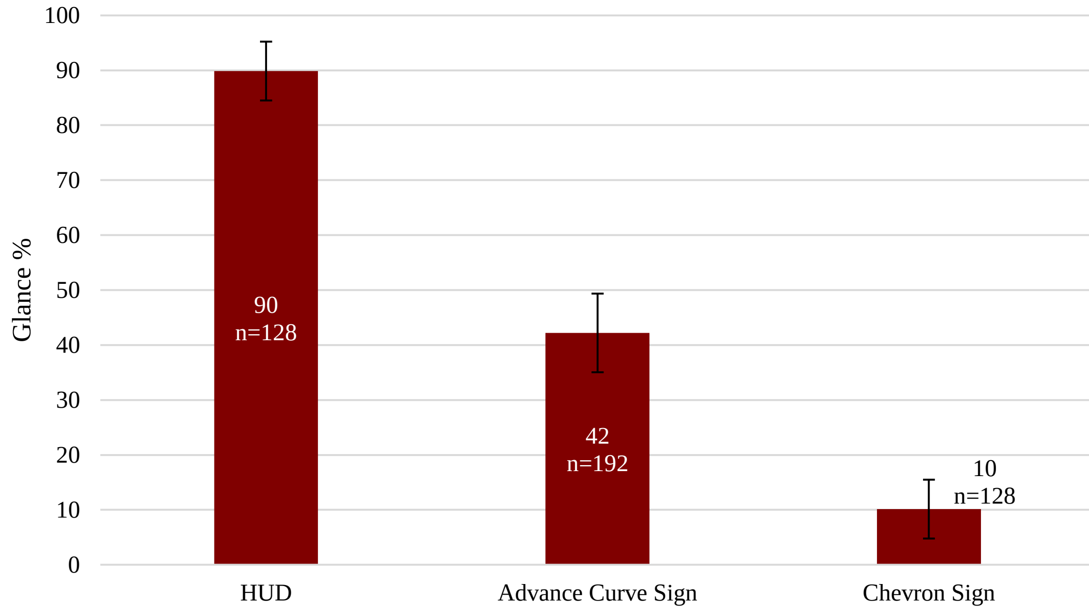

Figure 19 – Percentage of Glance at the warning sign itself

3.2.2. Logistic Regression of Eye Glance and Hazard Anticipation Data

Logistic regression models a relationship between predictor variables and a response variable. The goal of an analysis using this method is to find the best fitting and, yet reasonable model to describe the relationship between an outcome (dependent or response) variable and a set of independent (predictor or explanatory) variables. In logistic regression the outcome variable is *binary* or *dichotomous*. Binary Logistic Regression model is used when the response is binary (i.e., it has two possible outcomes).

In order to understand how much variation in the dependent variable can be explained by the model, *Table 13* which contains the "**Model Summary**" can be checked. Under 'Model Summary' we see that the -2 Log Likelihood statistic is 374.448. This statistic measures how poorly the model predicts the decisions. The smaller the statistic the better the model. This table contains the **Cox & Snell R Square** and **Nagelkerke R Square** values, which are both methods of calculating the explained variation. These values are sometimes referred to as *pseudo* R^2 values. The explained variation in the dependent variable based on our model ranges from 9.1% to 13.8%, depending on whether you reference the Cox & Snell R^2 or Nagelkerke R^2 methods, respectively. The Cox & Snell R^2 can be interpreted like R^2 in a multiple regression, but cannot reach a maximum value of 1. The Nagelkerke R^2 can reach a maximum of 1, is a modification of Cox & Snell R^2, and it is preferable to report the Nagelkerke R^2 value.

Table 13 – Summary of variance explained by the Model

Model Summary			
Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	374.448[a]	.091	.138

a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.

The **Variables in the Equation** output shows us that the regression equation is

$$\ln(ODDS) = 4.514 + 0.812TREATMENT + 0.014CM - 0.083SPEED\_CURVE$$

Table 14 below shows the contribution of each independent variable to the model and its statistical significance. The Wald test (**"Wald"** column) is used to determine statistical significance for each of the independent variables. The statistical significance of the test is found in the **"Sig."** column. From these results you can see that SPEED_CURVE ($p = 0.000 < 0.05$) added significantly to the model/prediction, but TREATMENT ($p = 0.098$), and CM ($p = 0.946$) did not add significantly to the model.

Table 14 – Contribution of each independent variable to the model

Variables in the Equation									
		B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I.for EXP(B)	
								Lower	Upper
Step 1[a]	TREATMENT	.812	.490	2.744	1	.098	2.252	.862	5.884
	CM[b]	.014	.204	.005	1	.946	1.014	.679	1.514

	SPEED_CURVE[c]	-.083	.017	23.625	1	.000	.921	.891	.952
	Constant	4.514	.834	29.281	1	.000	91.321		

a. Variable(s) entered on step 1: TREATMENT, CM, SPEED_CURVE.

b. CM means countermeasure.

c. SPEED_CURVE means speed in the curve section of the road.

Binary logistic regression estimates the probability of an event (in this instance, anticipating the hazard) occurring. If the estimated probability of an event occurring is greater than or equal to 0.5 (better than even chance), SPSS statistics classifies the event as occurring (anticipate the hazard). If the probability is less than 0.5, SPSS Statistics classifies the event as not occurring (did not anticipate the hazard). The observed and predicted classifications are presented in *Table 15* as shown below. The table has a subscript which states, "The cut value is .500". This means that if the probability of anticipating hazard being classified into the "yes" category is greater than .500, then that particular hazard anticipation is classified into the "yes" category. Otherwise, it is classified in the "no" category. The classification results, with almost 80% correct in classifying the outcome, the model is not too bad.

Table 15 – Classification table for observed and predicted values

Classification Table[a]					
Observed			Predicted		
			Anticipate_Hazard		Percentage Correct
			No	Yes	
Step 1	Anticipate_Hazard	No	12	75	13.8
		Yes	8	289	97.3
	Overall Percentage				78.4

a. The cut value is .500

Table 16 – Values from Hosmer-Lemeshow Test

Hosmer and Lemeshow Test			
Step	Chi-square	df	Sig.
1	6.955	8	.541

In summary, a logistic regression was performed to ascertain the effects of TREATMENT, CM, and SPEED_CURVE on the likelihood that participants have anticipated hazard. The Hosmer & Lemeshow test of the goodness of fit suggests the model is a good fit to the data as p = 0.541 > 0.05, as shown in *Table 16* above. The model explained 13.8% (Nagelkerke R^2) of the variance in hazard anticipation and correctly classified 78.4% of anticipations.

3.3. Limitations and future work

In this study, participants aged only between 18 and 35 were recruited. This same study could be extended using older experienced drivers and teenage drivers between age 16 and 19 with less than one year of driving experience. This study could be conducted with different environmental conditions (e.g., fog or rain). Horizontal curve negotiation would be more critical when adverse environmental conditions are added to the driving task. Only a single curve was used in all of the virtual drives which could be increased to more than one curve per virtual drive so that the effectiveness of a countermeasure could be examined over multiple curves to investigate whether there are diminishing returns to the countermeasure benefits.

Future work could be conducted with sharper curves in virtual scenarios with radius less than 200m so that the pattern of horizontal curve negotiation could be detected and examined. The duration of the virtual drives can be increased with inclusion of multiple left & right, and flat & sharp curves and examine how it affects the drivers' safety when subjected to prolonged driving. Future study could also focus on introducing a secondary or distraction tasks while driving at curves so that definitive conclusions could be drawn about how those specific task types influence curve negotiation.

CHAPTER 4

CONCLUSIONS

The three types of curve countermeasures that were used for the experiment were Heads-Up Display (HUD), Advanced Curve Warning sign with advisory speed limit, and Chevron signs. Speeds at curves were reduced when compared to the tangent sections, which highlighted the fact that drivers had better speed control and were adhering to the recommended speed limit of 45 mph at curve segments. There was no significant difference in speeds on the tangent section across the three countermeasures. However, it was found that the presence of a heads-up display significantly reduced speeds on curves as compared to just chevrons and advanced curve warning signs.

The driver's glance rate was higher with Heads-Up Display (HUD) warnings as opposed to the traditional advanced curve warning sign and Chevron sign. Participants in the virtual drives who had HUD (C1 and C2) as part of the countermeasure were able to anticipate hazards better than drivers who did not, which justifies the *Hypothesis 1* of the experiment. Also, from *Figure 18* it is noted that, when compared to experimental condition, hazard anticipation in baseline condition is higher across all the three countermeasure groups.

Results from the experimental study showed that drivers were able to slow down on horizontal curves when provided with C1 countermeasure before they entered the curve, in the entry tangent section which aligns with *Hypothesis 2* of the experiment. Additionally, it was also observed that speeds were reduced in countermeasure C2 as well, which had Heads-Up display alert. It was also noted that speeds were reduced more for sharp curves when compared to flat curves.

In consideration of lateral control, drivers in countermeasures which had HUD had lesser lane offset which means that their lane control was better when compared to drivers in other countermeasures. It was also found out from the study that lane offset in sharp curves was less in C1 and C2 which highlights the fact that drivers were in better lateral control when provided with heads-up display as countermeasure for reducing speed.

Overall, the research study indicated that one of the countermeasure configurations was found to be more effective compared to the other two countermeasure types. There are several implications for practitioners, car manufacturers and policy makers. HUDs improve the driver's ability to safely negotiate a horizontal curve by accessing the display information while viewing the forward roadway. This study also gives us a suggestion that HUD is advantageous, but an optimal location for displaying HUD sign to the driver while driving in a horizontal curve is yet to be found out. It was beneficial to place HUD image at a distance close to the driver's focal distance, though placing of HUD in the normal line of vision of the driver was not considered. Vehicle manufacturers may require the communication of additional information and warnings for the driver driving in rural horizontal curves. Consequently, how information is presented in head-up displays is the key to not visually overload the driver and the design concept needs to be more driver-focused.

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