

Impact of Perceptual Speed Calming Curve Countermeasures on Drivers' Anticipation and Mitigation Ability: A Driving Simulator Study



**SAFETY RESEARCH USING SIMULATION**

**UNIVERSITY TRANSPORTATION CENTER**

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A Report on Research Sponsored by SAFER-SIM

February 2018

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## **Abstract**

Horizontal curves are unavoidable in rural roads and are a serious crash risk to vehicle occupants. This study investigates the impact and effectiveness of three curve-based perceptual speed-calming countermeasures (advance curve warning signs, chevron signs, and a heads-up display (HUD) sign) on drivers' hazard anticipation and mitigation behavior across both left and right curves with both a sharp radius (200 m) and flat radius (500 m). Flat and sharp curves with indications of a safety problem were virtually developed in a full-scale driving simulator. Forty-eight participants were recruited with an age range of 18 to 34, and a driving experience range of 0.25 to 17.75 years. 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. Heads-up displays were found to be effective at not only reducing the drivers' speed in the curve, but also in improving the latent hazard anticipation ability of the driver at the apex of the curve. The findings from this study are significant as they indicate the behavioral differences and speed decisions of the drivers when driving in flat and sharp and left and right directional curves along with the importance of the measures to be taken to reduce crashes at sharp horizontal curves and enhance the drivers' safety on dangerous portions of roadway networks.

## 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 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 Federal Highway Administration (FHWA), 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. These treatments 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. Twenty-eight percent 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 13% to 43% [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 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 ROR crashes [4].

As introduced by the *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 a 24 percent reduction on rural highways when center lines, edge lines, and delineators were installed. The study showed that use of horizontal alignment signs and advisory speed plaque signs resulted in a 30 percent decrease in serious injury crashes at curves. Chevrons assist the driver in navigating curves, and there was a 25 percent reduction in crashes when chevrons were installed on rural highway curves.

## 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 obstruct encroachment into the opposite lane or edge line and 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. The National Cooperative Highway Research Program (NCHRP) Report 600 states that pavement surface markings provide the strongest curvature guide [6]. 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 [7].

Various materials are used while marking pavements, including thermoplastic, which lasts longer than other materials, making it cost-effective [8]. 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 [9]. Studies have suggested that the combination of centerlines or edge lines with rumble strips improve curve safety [10].

The conventional width for a centerline or edge line is 4-6 in., but some states use widths of 8-12 in. [11]. 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 [9]. 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 [12].

### 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), and 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 Turn (W1-3) and Reverse Curve (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 ft.



**Figure 1.1 – Advance 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 [7]. The horizontal alignment sign should be placed above the sign for advisory speed [6]. Advisory speed is not the legal speed limit but an advised speed for the drivers [8]. 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 [6].

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 [7]. 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 visibility at night and in 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 [8].

#### 1.4 Chevrons

Chevrons are signs used to emphasize and guide drivers through a change in horizontal alignment. The Chevron Alignment (W1-8) sign may be used to provide additional emphasis and guidance for horizontal alignment [11]. 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 [11]. Chevrons are the strongest guidance cues and offer long-range guidance (anticipatory control) as emphasized by Campbell et al. [6]. The MUTCD recommends the typical spacing of Chevron Alignment signs on horizontal curves as shown in Table 1.1 [7].

**Table 1.1 - Typical spacing of Chevron Alignment signs on horizontal curves.**

<b>Advisory Speed</b>	<b>Curve Radius</b>	<b>Sign Spacing</b>
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. Post-mounted delineators can provide drivers with a better sense of the sharpness of the curve so they can select the appropriate speed before entering the curve. They 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 [12]. Chapter 3F of the MUTCD requires the color of the delineators to match the color of the adjacent edge line [7]. McGee et al. suggest that delineators be placed 2 to 8 ft. outside the outer edge of the shoulder and spaced 200 to 530 ft. 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 [13].

Installation of PMDs on horizontal curves revealed a 25% reduction in all types of crashes at horizontal curves [14]. However, for crashes on horizontal curves, the anticipated percentage reduction was not unique [11]. Neuman et al. found that enhanced delineation can reduce ROR crashes on sharp curves and reported that PMDs could reduce ROR crashes by 15 percent on curves [9].

Efforts to reduce operating speeds on curves should concentrate on the tangent sections preceding the points of curvature. Many factors contribute to ROR 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 markings can influence driver speed selection upon entering horizontal curves. Retting and Farmer used a pavement marking that helped in decreasing vehicle speeds by approximately 6 percent overall and 7 percent during daytime and late-night periods [15].

#### 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 that could be investigated is whether these countermeasures would also be effective in helping drivers anticipate latent hazards at the apex, entry, and exit of curves.

Hazard anticipation can be described as detection and recognition of potential dangerous road and traffic situations, and prediction of how these latent hazards can develop into acute threats [16]. 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) [17].

### 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 [18]. 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 [19]. In another study, Schneider et al. found that horizontal curves may reduce the driver's available sight distance and reduce vehicle-handling capabilities [20].

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 [11].

It is generally assumed that vehicles will more easily leave their lane on a curve than on a tangent section because of the centrifugal force that acts on the vehicle when it enters the curve. Charlton 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 [21]. Crash rates significantly increase for curves with a radius smaller than 200 m.

According to FHWA, over 25,000 people were killed in 2005 because drivers left their lane and crashed with an oncoming vehicle, rolled over, or hit an object located along the highway [22].

Glennon et al. referred to the region three seconds before the curve as the critical region. At about 200 ft (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 [23]. The root cause of many single-vehicle crashes at curves appears to stem from inappropriate speed selection before entering the curve. In many single-vehicle crashes, drivers understeered or oversteered, producing a turn that was sharper than the rural highway curve [24].

### 1.8 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 a safe speed, maintain lateral position, and anticipate hazards 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 the C1 treatment condition will anticipate a greater proportion of hazards on curved sections than drivers in the C2, C3, or No Countermeasure conditions.
- Hypothesis 2: Drivers in treatment condition C1 will have reduced speeds in curves when compared to drivers in other treatment conditions.

## 2 Method

### 2.1 Participants

A total of 48 participants were recruited for the experiment. 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. All participants received monetary compensation for their involvement in the experiment.

### 2.2 Apparatus

The driving simulator used in this study was a fixed-base simulator with a full-body 2013 model Ford Fusion Sedan surrounded by five projection screens. Five main projectors and one rear projector were used. Main projectors had a resolution of 1920 x 1200 pixels and an image display refresh rate of 96 Hz. The rear projector had a resolution of 1400 x 1050 pixels with the same refresh rate as the main projectors. Field of view is approximately 330°. The sound system consisted 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 had a customizable glass dashboard and 17-inch touchscreen center stack.





**Figure 2.1 – 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 the 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.

### 2.3 Simulator Scenarios

All of the simulator scenarios were designed using RTI Sim Vista Version 3.2. Eight baseline scenarios were developed on the simulator and various combinations of countermeasures were internally used. All eight simulated scenarios had different hazard anticipation events and also differed in the countermeasure condition and road curvature. Figure 2.2 shows the HUD sign, and Figure 2.3 shows the Advance Curve and Chevron signs.



**Figure 2.2 – Scenario showing the heads-up display alert.**



**Figure 2.3 – Scenario showing Advance Curve Warning and Chevron signs.**

The descriptions of the hazard anticipation scenarios used for the three countermeasures and the control condition are shown in Table 2.1.

**Table 2.1 – Descriptions of hazard anticipation scenarios for all the treatment conditions.**

HA	Description	Curve type and direction
HA 1	Crosswalk at apex of the curve, with either one or two pedestrians following each other with a time gap of 1 to 2 secs and driver's vision obscured by bushes	Right Flat
HA 2	Work zone on right with vehicle pulling into the traffic lane	Left Flat
HA 3	At the apex of the curve, have a hidden driveway residential building or gas station and driveway obscured by bushes	Right Sharp
HA 4	Truck parked on the right with blinkers ON and 75% in the lane and 25% in the grass and with opposing vehicle at the same time	Left Sharp
HA 5	Tree wall or bushes along the boundary of the inner curve with slow moving vehicle at the apex	Right Flat
HA 6	Bicycle entering the travel lane from the right at the apex of the curve	Left Flat
HA 7	Truck parked or stopped at the apex just before the crosswalk, obscuring the pedestrian	Right Sharp
HA 8	Car exiting driveway into travel lane and other car waiting to enter driveway from opposite lane	Left Sharp

The hazard anticipation condition was the same across all the eight scenarios. The only thing that differed was the treatment condition. Before the entry of the curve, the participant was provided with cues to alert them to the imminent hazard posing in front of them. Figure 2.4, Figure 2.5, Figure 2.6, and Figure 2.7 show the signs of cues before hazard.



**Figure 2.4 – SLOW: WORK ZONE AHEAD sign.**



**Figure 2.5 – HIDDEN DRIVEWAY sign.**



**Figure 2.6 – SLOW MOVING VEHICLES sign.**





**Figure 2.7 – Bicycle Ahead sign.**

#### 2.4 Experimental Design

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

C1: Heads-Up Warning Sign + Advance Curve Warning Sign + Chevrons

C2: Heads-Up Warning Sign + Advance Curve Warning Sign

C3: Advance Curve Warning Sign + Chevrons

The experimental design consisted of a mixed-subject design with three groups of 16 participants, each facing one of the three treatment conditions; all 48 participants faced the no treatment condition.

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 was pseudo randomly counterbalanced across participants using a Latin square design.

## 2.5 Independent and Dependent Variables

Independent variables are the participant's age, gender, driving behavior, and driving experience, time of day in the virtual drive, and duration of each simulated drive.

Dependent variables are the eye measures (proportion of latent hazard anticipation (LHA), proportion of clues detected, and glance towards countermeasure), and vehicle measures (steering angle, acceleration, lane offset, and velocity).

## 2.6 Procedure

All participants were given the opportunity to read and sign the informed consent form when they entered the research lab. They were then asked to sit in the fixed-base simulator and were fitted with 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 a couple of scenarios and were instructed to let the researcher know if they felt dizzy or motion sick.

### 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 encountered a hazard at the apex of the curve. Three countermeasures—Advance Curve Warning signs, HUD signs, and Chevron signs—were used for this study. The primary objective of these countermeasures was to make the driver reduce speed at the entry of the curve and to 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 control drives and four experimental drives. The order of the drives was counter-balanced, so half the participants started with the control drive first and half with the experimental drive first. The controlled laboratory settings allowed for the control of ambient traffic and manipulation of critical variables, as well as the direct measurement of dependent variables. All statistical tests were conducted using two-sample t-tests with the help of the statistical tool Minitab. 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 includes velocity and lateral position. Information about drivers can be used to detect variations in driver behavior in different environments [25]. Velocity and lane offset behavior was captured at fixed points throughout the drives using data markers in the virtual scenarios. Two data markers were placed in each scenario at the same coordinates to maintain consistency. Speeding, the degree of road curvature, and poor judgment are the major contributing factors for crashes on horizontal curves [26]. This calls for the analysis of the vehicle

data for the drivers. Table 3.1 below shows which of the described countermeasures were present in the three treatment conditions: C1, C2, and C3.

**Table 3.1 – Description of Countermeasures C1, C2, and C3.**

<b>C1:</b> HUD + Advance Curve Sign + Chevron	<b>C2:</b> Advance Curve Sign + HUD	<b>C3:</b> Advance Curve Sign + Chevrons
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The mean and standard deviation of velocity and lane offset across treatment conditions in the curve and tangent segments are shown in Table 3.2 and Table 3.3, respectively.

**Table 3.2 – Mean and standard deviation of velocity and lane offset at curve.**

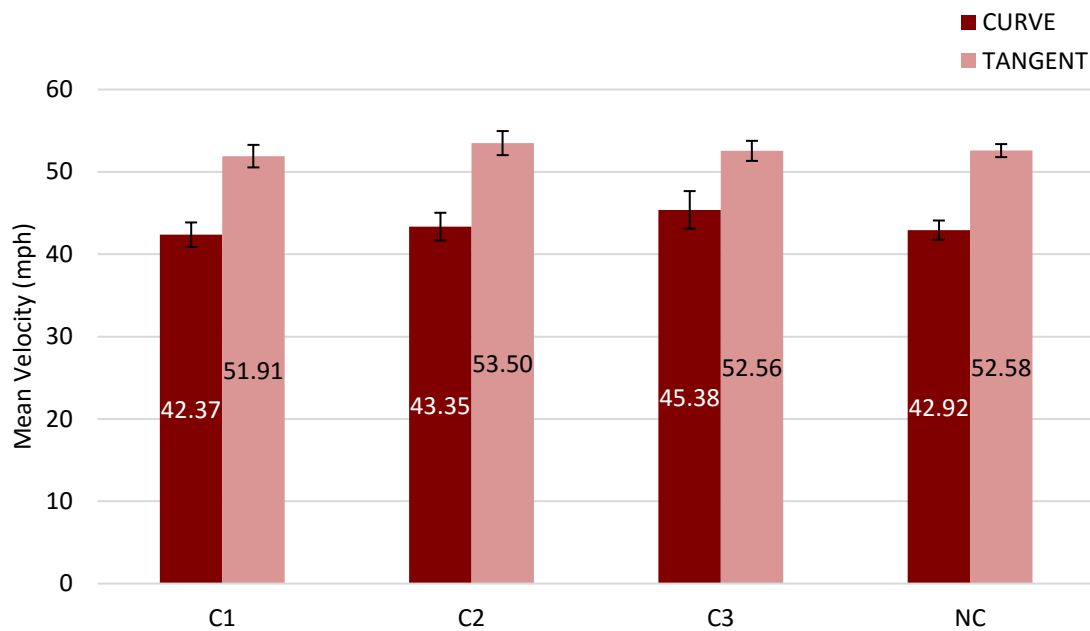
Treatment Condition	Velocity (mph)		Lane Offset (m)	
	Mean	St. Dev.	Mean	St. Dev.
C1	42.37	5.96	0.28	0.11
C2	43.35	6.73	0.26	0.11
C3	45.38	9.12	0.32	0.13
NC	42.92	8.07	0.32	0.12

**Table 3.3 – Mean and standard 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	52.58	5.42	0.21	0.10

Figure 3.1 below illustrates the differences in velocities between the curve and the preceding tangent segment for the four treatment conditions. It was found in the study that the velocities in tangent section across the various treatment conditions are almost the same, but velocities at the curve varied by the type of treatment condition used.





**Figure 3.1 – Velocity differences between curve and tangent sections.**

Results from t-tests concluded that the difference in mean velocities at curve segments between C1 and C3 were statistically significant at 95% confidence ( $p < 0.05$ ). P-values from t-tests are shown in Table 3.4.

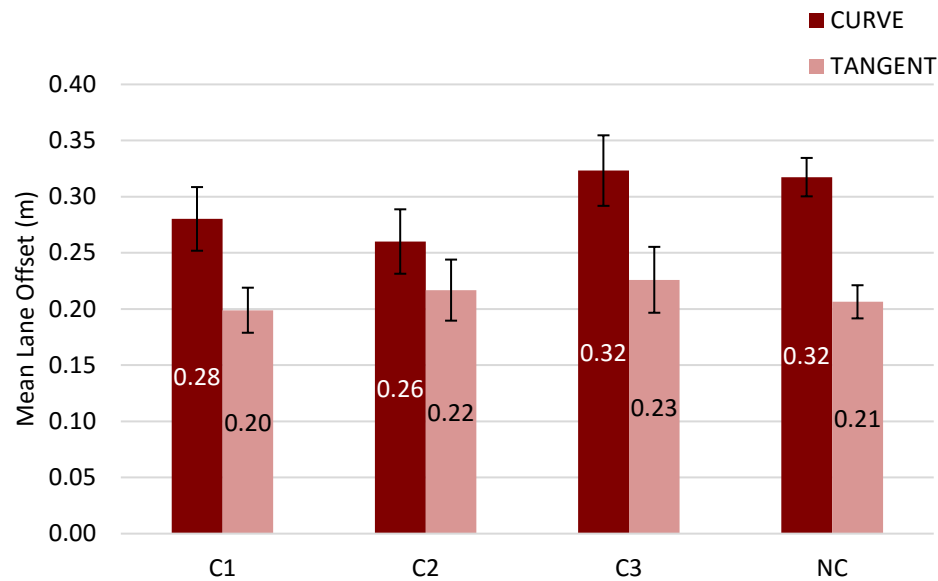
**Table 3.4 – Two sample t-tests for velocity at curve between countermeasure groups.**

Treatment								
C1 vs C2			C2 vs C3			C3 vs C1		
df	T	P-Value	df	T	P-Value	df	T	P-Value
124	-0.88	0.383	115	-1.43	0.154	108	-2.21	0.029*

\* indicates statistical significance at 95% confidence.

Figure 3.2 illustrates the differences in lane offset between the curve and the preceding tangent segment for the four treatment conditions. It was found in the study

that the lane offset in the tangent section across the various treatment conditions was almost the same, but it varied at the curve and also varied by the type of treatment condition used.



**Figure 3.2 – Differences in lane offset between curve and tangent sections.**

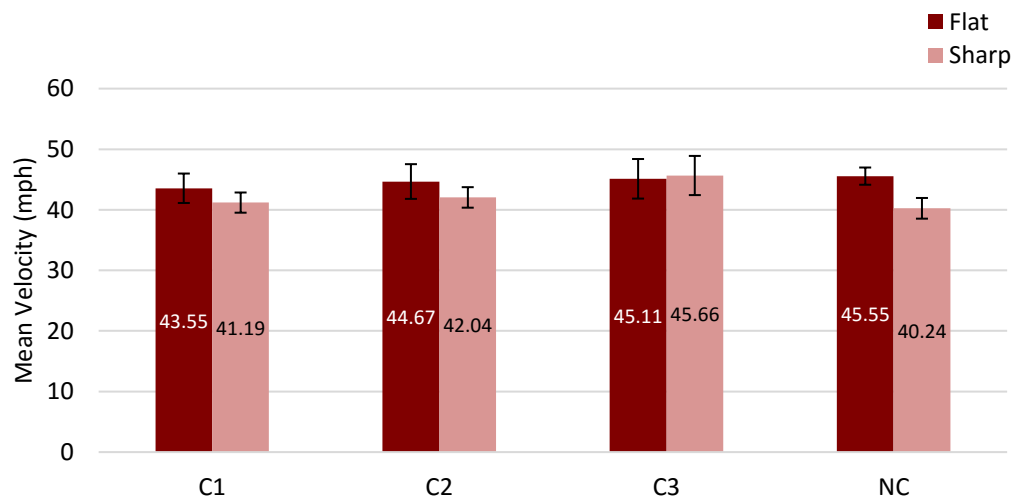
From the t-test results for lane offset shown in Table 3.5, it is evident that lane offset was significant between curve sections of C2 & C3 and C3 & C1, in which a HUD warning sign was available to the driver. It highlights the fact that HUD is effective in reducing the lane offset as well as speed at curves.

**Table 3.5 – Two 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
125	1.0	0.32	124	-2.97	0.004*	124	2.03	0.044*

\* indicates statistical significance at 95% confidence.

It has been observed from the experiment that velocities were reduced in sharp horizontal curves as opposed to flat ones. The results between flat and sharp curves were found to be statistically significant with p-value < 0.05. Figure 3.3 shows the differences in velocities between flat and sharp curves based on the countermeasures.



**Figure 3.3 – Differences in velocities between flat and sharp curves based on countermeasure.**

T-tests were conducted between those groups who drove flat and sharp curves based on countermeasure. C1 has HUD, and C3 has no HUD, and it is obvious that the

C1 group drove with lower velocities than group C3, with differences in mean velocities being statistically significant between groups C1 and C3 when they drove in a sharp curve. Table 3.6 shows the results from the t-tests conducted across the groups.

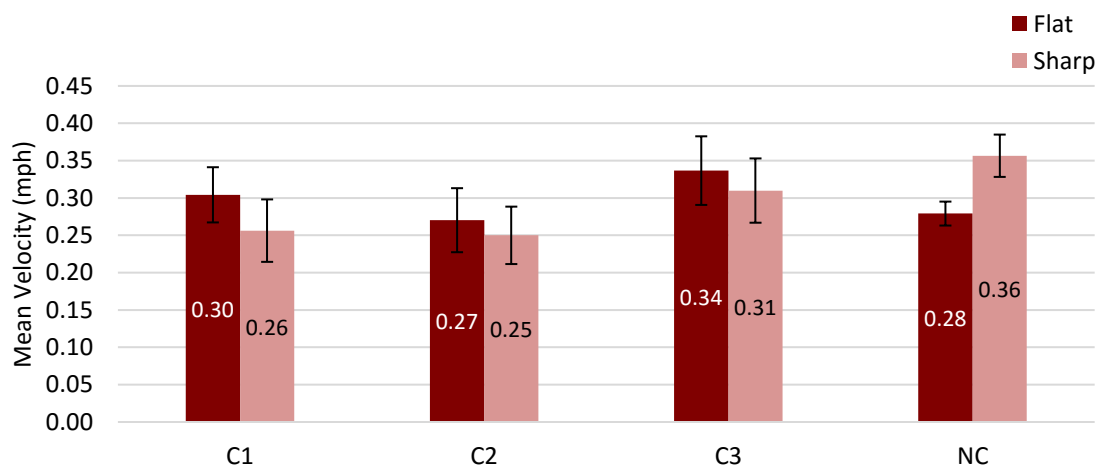
**Table 3.6 – T-tests for velocities across groups in a sharp curve.**

Treatment

C1 Vs C2			C2 Vs C3			C3 Vs C1		
df	T	P-Value	df	T	P-Value	df	T	P-Value
61	-0.72	0.475	46	-1.98	0.053	46	2.46	0.018*

\* indicates statistical significance at 95% confidence.

The lane offset between sharp and flat curves was found not to be statistically significant with p-value > 0.05, as shown in Figure 3.4.



**Figure 3.4 – Differences in mean lane offset between flat and sharp curve by countermeasure.**

However, by examining sharp curves only, a statistical difference was identified between the countermeasure groups. Table 3.7 shows the results from t-tests conducted between countermeasures in a sharp curve. It was found that lane offset was statistically significant between the C2 and C3 groups, in which C3 had no HUD sign.

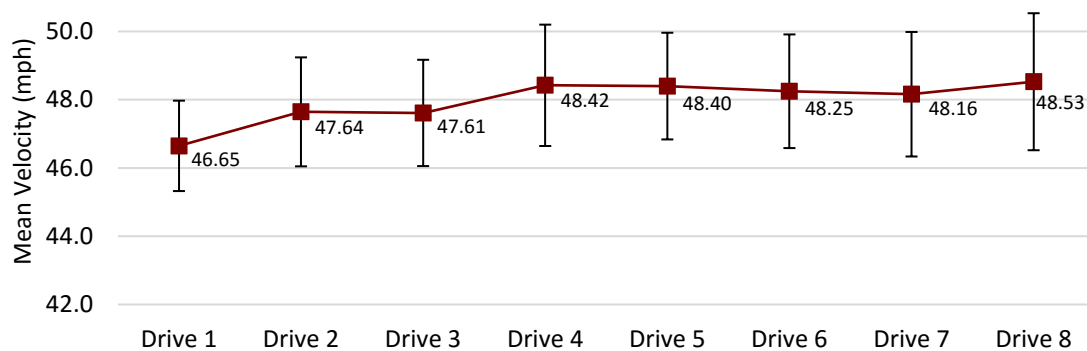
**Table 3.7 – T-tests for lane offset across groups in a sharp curve.**

Treatment

C1 Vs C2			C2 Vs C3			C3 Vs C1		
df	T	P-Value	df	T	P-Value	df	T	P-Value
61	0.22	0.825	61	-2.08	0.042*	61	1.79	0.079

\* indicates statistical significance at 95% confidence.

Figure 3.5 shows the drivers' speed per drive. While not statistically significant, a trend was observed where the drivers' speed was slower in the initial drive and, as the drives progressed, their speeds increased and then stabilized.



**Figure 3.5 – Mean velocity per drive for all participants.**

From the vehicle data, it can be concluded that HUD warning signs were most effective at making drivers reduce their speeds and stay in their lane while driving in

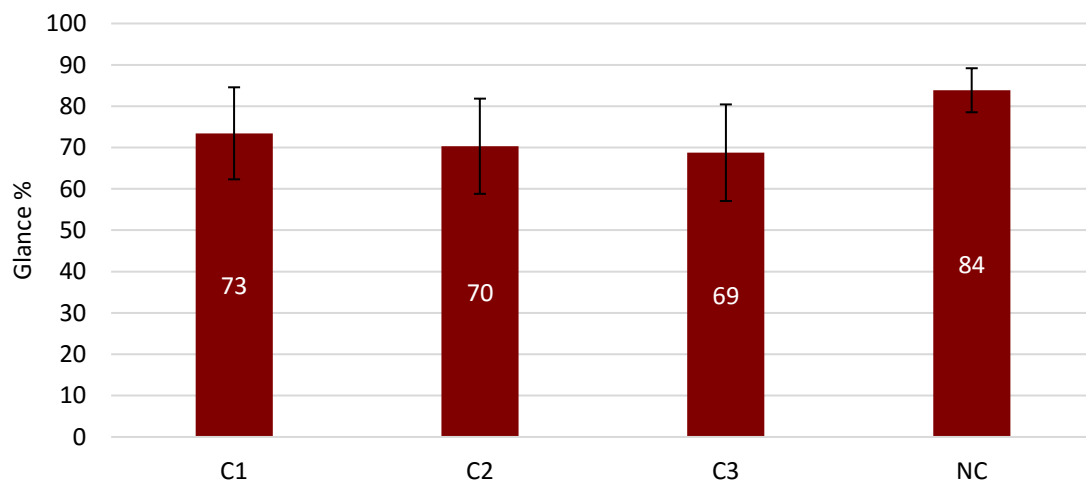
sharp horizontal curves. It was found that driver speeds were lower when HUD were present as opposed to Advance Curve and Chevron signs. The same could be said of the lane offset as well, implying that drivers had more lateral control with HUD than Advance Curve and Chevron signs.

### 3.2 Eye Glance Data

Eye glance data was collected using the aforementioned eye tracker. Glance data was recorded and analyzed after the experimental drives.

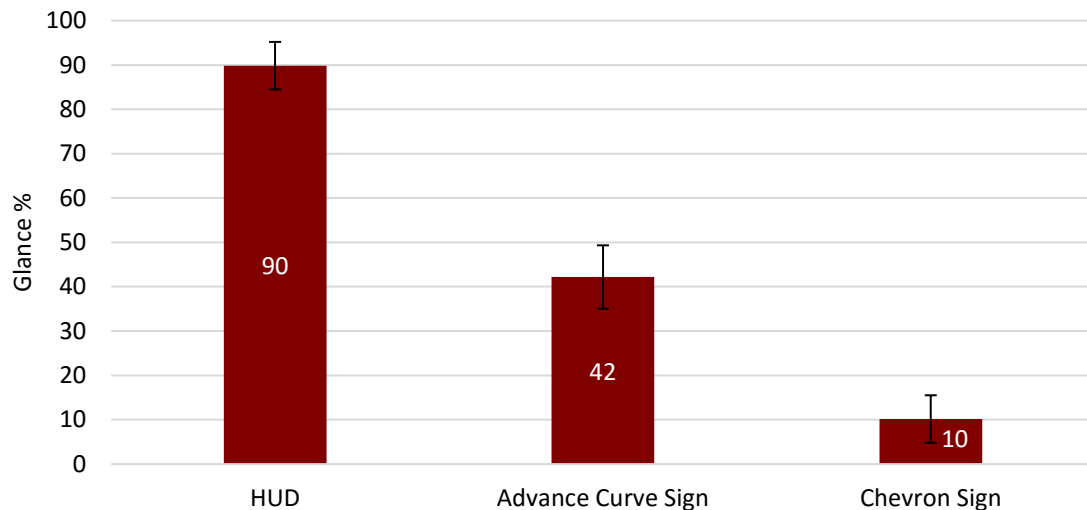
#### 3.2.1 *Eye glance and hazard anticipation*

Countermeasures C1 and C2 had HUD, and Figure 3.6 below shows that drivers anticipated hazards better in the C1 and C2 conditions than the drivers in the C3 condition. This finding is consistent with Hypothesis 1. As for the no countermeasure (NC) scenario, drivers' LHA percentage was higher when compared to the experimental group. Differences in sample sizes between the experimental and control groups could be one reason for higher LHA percentage. A low visual task load on drivers in the control group might be one reason for higher glance percentage at the hazard at the apex of the curve.



**Figure 3.6 – Hazard anticipation by countermeasure type.**

Figure 3.7 shows that HUD had the highest glance percentage among the three perceptual curve countermeasures. The high visibility of the HUD sign could explain the reduced speeds and improved lateral positioning in the HUD countermeasure scenarios.



**Figure 3.7 – Percentage of glance at the countermeasure itself.**

### 3.3 Limitations and Future Work

In this study, only participants between the ages of 18 and 35 were recruited. This same study could be extended using older experienced drivers and teenage drivers with less than one year of driving experience. In addition, this study could be conducted with environmental conditions in place. Horizontal curve negotiation would be more critical if adverse environmental conditions were added to the driving task. Only a single curve was used in all of the virtual drives, and that 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 radii less than 200 m 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 and right and flat and sharp curves to examine how that affects driver performance when subjected to prolonged driving. A future study could focus on introducing secondary distraction tasks while driving at curves so that definitive conclusions could be drawn about how those specific task types influence curve negotiation.

#### **4 Conclusions**

Three types of curve countermeasures were used for the experiment: HUD, Advance Curve Warning signs with an advisory speed limit, and Chevron signs. Overall, speeds at curves were reduced when compared to the tangent section. This highlighted the fact that drivers had better speed control and were adhering to the recommended speed limit of 45 mph at the horizontal curves. There was no significant difference in speeds on the tangent section across the three countermeasures. However, it was found that the presence of a HUD significantly reduced speeds on curves as compared to just Chevron and advance Curve Warning signs.

Driver glance rates were higher with HUD warnings than with the traditional Advance Curve Warning sign and Chevron signs. Participants in the virtual drives who had HUD (C1 and C2) as part of the countermeasure anticipated hazards better than drivers who did not, which supports our first hypothesis. However, it was noted that drivers in the NC condition glanced at the hazard more often overall.

Results from the experimental study showed that drivers slowed down on horizontal curves when provided with the C1 countermeasure on the tangent section before entering the curve; this aligns with Hypothesis 2. Additionally, it was observed that speeds were reduced in Countermeasure C2 as well, which had HUD alert. It was also noted that speeds were reduced more for sharp curves than for flat curves.



With respect to lateral positioning, drivers in countermeasures that had HUD had smaller lane offsets, which means that their lane control was better than drivers with other countermeasures. It was also found that lane offset in sharp curves was less in C1 and C2. This highlights the fact that drivers were in better control when provided with HUD as compared to other countermeasures.

Overall, this research met the stated objectives and found that HUD were the most effective at reducing driver speeds at curves and were the most visible to drivers, resulting in increased hazard anticipation. Further research should be conducted to investigate how HUD can be integrated into vehicles to most effectively improve traffic safety.

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