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The Impact of Perceptual Road Markings on Driving Behavior in Horizontal Curves: A Driving Simulator Study

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Abstract: Horizontal curves have been a significant safety concern on roads for years, often resulting in a high incidence of crashes. A European Road Safety Observatory report indicated that 53% of road crashes in the EU in 2020 occurred on rural roads, mainly due to misjudging when navigating these curves. This study explores innovative low-cost road designs for this issue, such as the red-white pattern edge line (RWE), the solid red edge line (RE), the alternating red-white checkered median stripe (RWM), and the red dragon's teeth (RDT) to improve driver behavior around curves. The various road markings were tested based on speed, acceleration/deceleration, and lateral position before and during horizontal curves in a driving simulator using STISIM Drive® 3. Fifty-two volunteers, aged between 20 and 75, participated in the study. The simulation road was designed according to the Flemish Road Agency (AWV) guidelines. The simulation tested twelve horizontal curves, including left and right turns, with 125 m and 350 m radii. The results were analyzed using within-subjects repeated measures ANOVA, with Greenhouse–Geisser correction for sphericity violations. It was revealed that these markings can reduce driving speeds and improve control, enhancing road safety. Specifically, the red-white median stripe resulted in better lateral positioning. At the same time, red dragon's teeth minimized deceleration before curves, although their effects were less significant for curves with larger radii.

Keywords: road design; road marking; driving simulator; horizontal curves; rural road

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1. Introduction

Horizontal curves on roadways have long been recognized as critical locations for traffic safety concerns, exhibiting significantly higher crash rates than straight road segments [1,2]. This elevated risk is intricately linked to the complexities drivers face in accurately perceiving curve geometry, judging appropriate speeds, and maintaining proper vehicle control [3,4]. Consequently, many severe and fatal crashes occur on horizontal curves, underscoring the persistent need for effective countermeasures to positively influence driver behavior and mitigate these risks [5]. Understanding the factors that shape driver perception and developing interventions that leverage these perceptual mechanisms are crucial for advancing road safety on curved alignments [6].

A diverse range of road safety interventions has been explored and implemented in response to the safety challenges presented by horizontal curves. These include geometric design modifications, improved warning signs, advisory speed limits, and pavement treatments [7,8]. Among these strategies, perceptual countermeasures, especially road markings, have gained considerable attention for their ability to directly impact driver behavior by offering prominent visual cues about the road ahead [9]. Road markings, including centerlines, edge lines, lane markings, and curve-specific treatments such as chevrons and rumble strips, are essential for delineating the roadway, indicating alignment changes, and encouraging drivers to adopt safer driving practices, like lowering speed and adjusting their lateral position [5,10].

Using driving simulators has significantly advanced the investigation of driver behavior in response to different road design elements [11–13]. These advanced tools provide a safe and controlled environment for researchers to examine how drivers engage with virtual road scenarios and react to alterations in the road environment, including changes in geometry and pavement markings [14]. Driving simulators enable precise measurement of critical driving parameters, including speed, lateral position, acceleration, and braking behavior [15]. This technology offers valuable insights into the effectiveness of various safety interventions without putting participants at risk of real-world hazards [16]. Numerous studies have used driving simulators to assess the impact of different road marking strategies on driver behavior in horizontal curves, investigating how centerline treatments, edge line enhancements, chevron designs, and speed reduction markings affect driver performance [8,10,17].

The current state of research on road markings in horizontal curves reveals a diverse range of findings. While many studies indicate that specific road marking treatments can result in positive changes in driver behavior, such as reduced speeds and improved lane keeping [18], other studies have yielded less conclusive or even contradictory results [10]. For instance, Garach et al. [19] found that applying road markings can lead to increased speeds, potentially due to drivers perceiving a safer environment. This highlights the complexity of the interaction between road markings, driver perception, and behavior, and underscores the need for further research to understand the nuanced effects of different marking types and configurations [20,21]. Research in this field includes studies analyzing the effects of wider edge lines, centerline rumble strips [22,23], chevron designs [18,24], speed reduction markings [9,25], and, more recently, self-luminous road markings [26] on driver behavior, experimentally tested using driving simulators [27]. However, a comprehensive understanding of the combined effects of specific median and edge line perceptual treatments remains limited.

This paper employs a driving simulation to investigate innovative perceptual road marking countermeasures for horizontal curves. We will examine the impact of implementing continuous red and red-white patterns on edge road markings, an alternating red-white checkered median stripe, and red dragon's teeth to enhance driver behavior around curves. This study aims to provide new insights into the effectiveness of specific perceptual road design markings for improving safety on horizontal curves. By evaluating the effects of these median and edge line treatments, this research intends to identify benefits that could lead to more effective and cost-efficient road safety interventions. The findings will guide road designers, engineers, and policymakers in developing and implementing evidence-based strategies to reduce crash risk and enhance overall safety on horizontal curves.

The remainder of the paper is organized as follows: Section 2 details the materials and methods, which include the study participants, the apparatus, the experimental road, road marking treatments, and the data collection and analysis strategies. Section 3 presents the results in three categories: speed, acceleration/deceleration, and lateral position. Section 4 discusses these findings and compares them to those of previously published papers, and Section 5 presents the conclusions.

2. Materials and Methods

This section describes the methodology applied, the sample characteristics, the driving simulator used, the simulation scenario and its development, and the primary data frame used for the analysis.

2.1. Participant

For this research, 52 volunteers with a valid type B driving license or equivalent participated. The test participants were recruited through announcements on various social media platforms, flyers, and word of mouth. The volunteers ranged from 20 to 75 years old, with a mean age of 34 years, and had driving experience from 1 to 56 years, with an average of 15 years. Each volunteer provided informed consent based on the research protocol approved by the Ethics Committee of Hasselt University. Every participant read the consent form carefully, agreed with the purpose of the research, and filled out the pretest questionnaire before starting the driving simulators. The pretest questionnaires aim to identify participants by identifying their gender, date of birth, driving license, driving experiences, and average sleep duration.

Afterward, the participants familiarized themselves with the driving simulator setup during the warm-up session. During this session, they drove a 2 km long route, and no data were collected. The warm-up route began by entering and exiting the urban area, followed by two 90° curves with a 175 m radius in both directions. The 2 km training session was determined to be sufficient based on standard practices in driving simulator studies, which typically employ short familiarization drives to allow participants to adapt to the vehicle dynamics and interface [28]. During this session, participants were also instructed to drive freely and monitored to ensure they could control the vehicle comfortably and respond appropriately to signs and curves. After the warm-up session, the participants were informed that they should drive as they used to in real life.

Five participants were excluded from the study: two due to simulation sickness and three due to extreme outlier behavior based on the established data screening criteria. Specifically, extreme outliers were identified as data points exceeding three times the interquartile range (IQR), and participants whose data contained 15% or more outliers, as suggested by Hussain et al. [17], were excluded. Consequently, data from 47 participants (15 female and 32 male drivers) were included in the final analysis. According to the participation report, 51% of the participants used an automatic transmission vehicle as their daily driver, and 67.3% drove between less than 5000 and more than 14,999 km.

2.2. Apparatus

The experiment occurred at the Institute for Mobility (IMOB) of Hasselt University. The institute itself provided the setup of the driving simulator. The driving simulator operating system consists of two primary components: a driving unit and three monitors, as shown in Figure 1 [29]. The components were connected and integrated with STISIM Drive® 3 [30]. The performance measurement system of STISIM Drive® 3 could register 67 different output parameters. The output parameters of driver behavior for this research were driving speed, lateral position, and acceleration, which were standard output parameters for this type of research [31,32].

To address the ecological validity of the driving simulator setup, it is essential to note that while simulators do not replicate all aspects of real-world driving (e.g., physical motion cues), they offer a safe and controlled environment to assess driver behavior under experimental conditions. The simulator used in this study allowed for consistent exposure to different road marking treatments while eliminating external confounding factors. Previous research has demonstrated that driver responses to visual stimuli—such as road markings, curves, and signage—are reasonably consistent between simulators and real-world environments [29]. However, we acknowledge that real-world driving involves additional complexities, such as interaction with other road users and dynamic traffic flow.

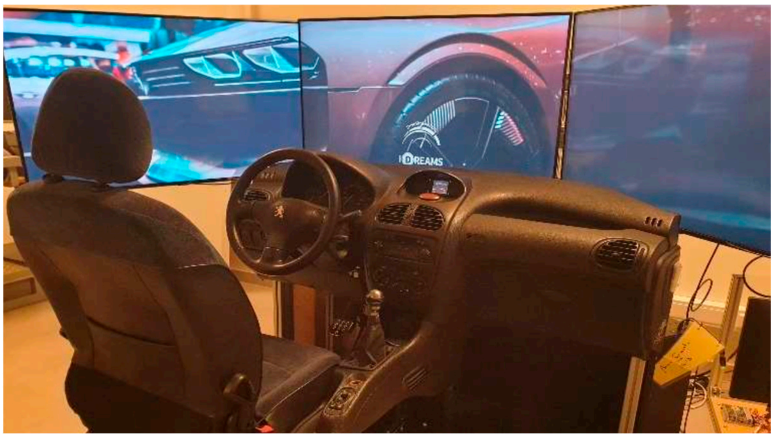


Figure 1. Fixed-based driving simulator in IMOB.

2.3. Experimental Road

Four driving routes were developed, each featuring a curve with distinct geometric characteristics. Different road marking treatments were applied for each route, along with a control condition representing the default (unmarked) scenario. Each driving experiment featured a randomized order of 20 scenarios (i.e., 2 curve radii × 2 curve directions × 5 marking conditions) with horizontal curves, including ten curves with a radius of 125 m and ten curves with a radius of 350 m. The curve with a radius of 125 m measured 183 m in length and included a transition section of 14 m, while the curve with a radius of 350 m measured 524 m in length and included a transition section of 26 m. Both transition curves in our study satisfy the requirements set by the Flemish road design guidelines, ensuring safe and comfortable navigation for drivers. Figure 2 and Table 1 show the road designs and characteristics.

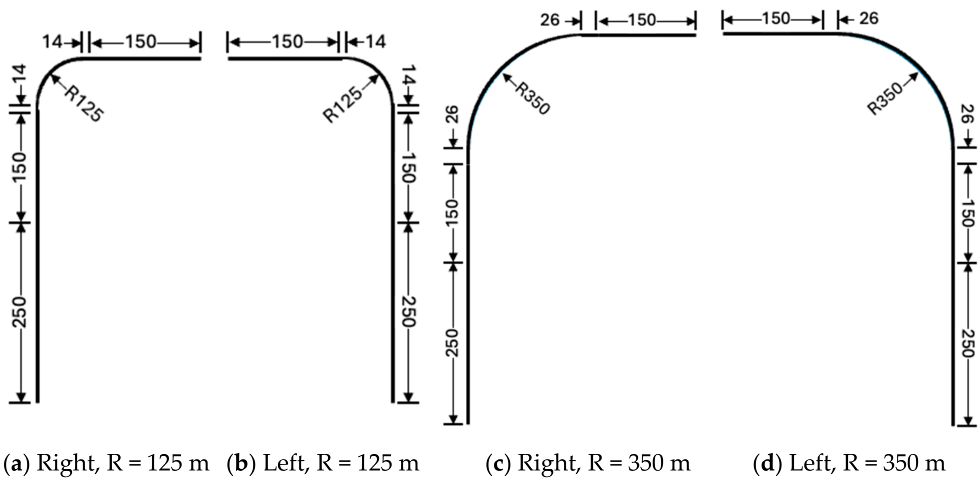


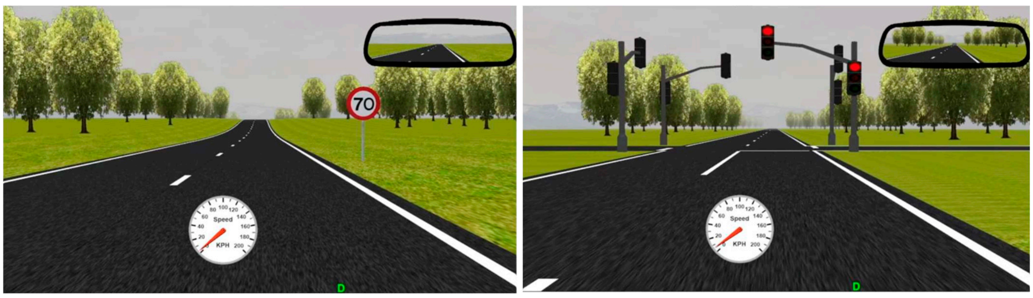
Figure 2. Road designs for both radii and curve directions. (**a**) Right, R = 125 m. (**b**) Left, R = 125 m. (**c**) Right, R = 350 m. (**d**) Left, R = 350 m.

Of the 20 scenarios, every four included different road marking treatments combined with a vertical warning sign: the control condition (solid white edge line), the red-white pattern edge line (RWE), the solid red edge line (RE), the alternating red-white checkered median stripe (RWM), and the red dragon's teeth (RDT). A vertical warning sign for dangerous curves was installed 150 m upstream of each curve, and the road marking treatments commenced 100 m before the curve, extending through to its end. The road section consisted of a two-way rural road with 3.5 m wide lanes, a 30 cm shoulder, and 15 cm white centerline and edge lines. The road markings complied with Agentschap Wegen en Verkeer (AWV) regulations [33].

Table 1. Characteristics of the routes designed for this study.

Characteristics	Route No.			
	1	2	3	4
Radius (m)	125	125	350	350
Total length (m)	183	183	524	524
Transition length (m)	14	14	26	26
Direction	Right	Left	Right	Left
Marking condition	Control, RWE, RE, RWM, RDT			
Speed limit position	The starting point of the experiment			
Curve sign position (m)	150 m before the curve			

Each route had a total length of approximately 15 km, which could correspond to a 15 min test drive in a rural area. Initially, there was a vertical speed limit sign to ensure which driving speed the participants could be ridden on the road, as shown in Figure 3a. On every route, traffic was simulated in the opposite direction toward the test driver. Besides the two-way road, the environment consisted of trees throughout the entire route, with filler sections. To ensure the sudden finishing of the route, there was a traffic light at the end of every road, as shown in Figure 3b. The participants could slow their speed to almost entirely stop, and the test route would end.



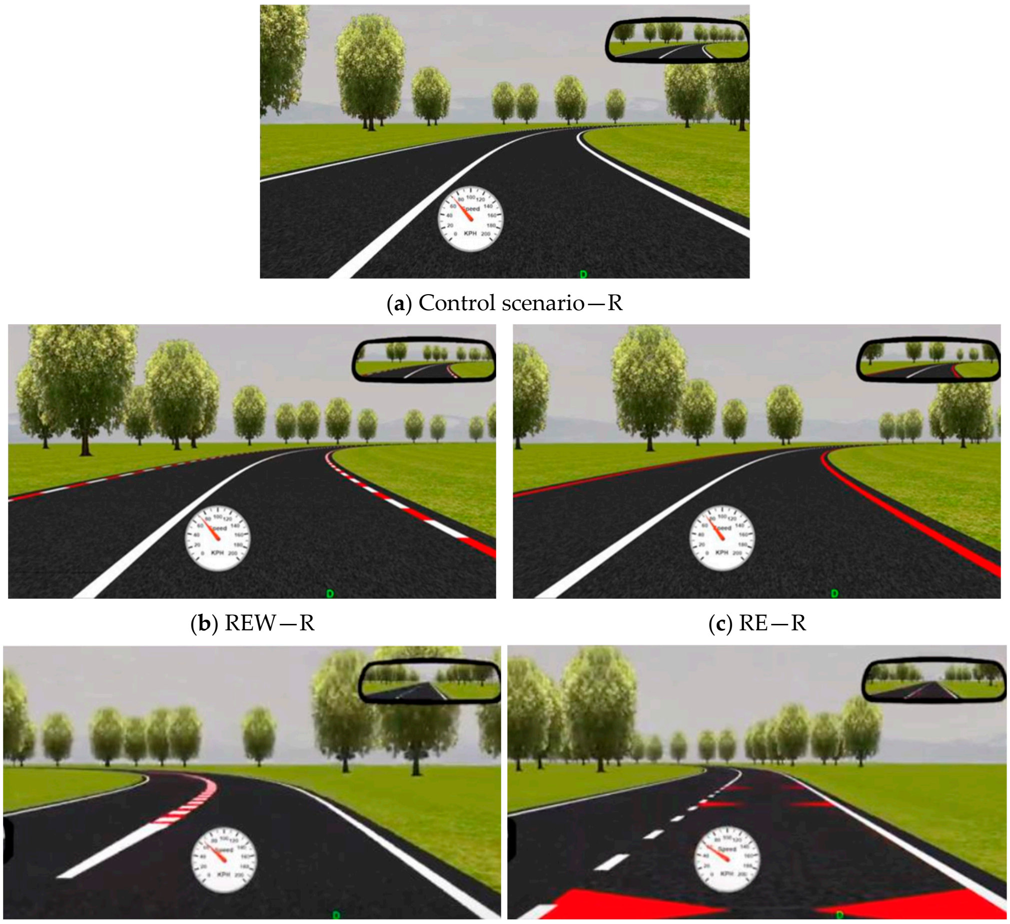
(**a**) Start (**b**) End

Figure 3. (**a**) Start and (**b**) end scenes of the simulator.

2.4. Road Marking Treatments

Based on the concept of perceptual markings, this study implemented four different low-cost road markings, including RWE, RE, RWM, and RDT, to improve driver behavior. Figure 4 demonstrates drivers' perspectives in simulation with all road marking conditions and different radii and directions of the curves. Each participant drove all scenarios with different road markings, ensuring a within-subjects design and allowing for consistent comparison across conditions.

The RWE resembled the red and white checkered line. However, the dimensions of those red and white parts differed depending on the distance to the curve. The red-white line is 10 m long for both colors and is reduced gradually to 1.5 m long. This treatment aimed to create an illusion of driving too fast by alternating red and white colors. Therefore, it is hoped that the drivers would slow down automatically before entering the curve. On the other hand, the solid RE had the same dimension as the white line in the control condition. However, during the simulation, the white edge line changed color to red at 100 m before the horizontal curve and ended at the end of the transition curve.



(**a**) Control scenario—R

(**b**) REW—R (**c**) RE—R

(**d**) RWM—L (**e**) RDT—L

Figure 4. Preview of road marking in different scenarios in the right (R) and left (L) curve, with a radius of 350 m in the driving simulator; (**a**) control scenario—R; (**b**) RWE—R; (**c**) RE—R; (**d**) RWM—L; and (**e**) RDT—L.

On the other hand, the alternating RWM began at the start of the transition curve and extended to the end of the exit transition curve. The red and white markings had a width of 40 cm and alternated every 80 cm. Additionally, the RDT markings were arranged in 8 pairs, with one tooth on each side of the road, spanning a distance of 100 m. The first pair was positioned 100 m before the beginning of the curve, with a base of 150 cm and a height of 70 cm. The subsequent 7 pairs were spaced along the next 100 m, with the last pair placed at the start of the transition curve. The distance between each pair gradually decreased, and the dimensions of the RDT markings also changed gradually. The last tooth installed was double the height of the first tooth, but the base remained consistent.

2.5. Data Collection and Analysis

Once the participants completed the driving simulations, various output parameters were collected using the STISIM Drive® 3. These parameters included longitudinal speed (km/h), lateral position (m), and acceleration/deceleration (m/s^2), which were analyzed to evaluate the participants' driving behavior before and during horizontal curves across all road marking treatments. The lateral position is the distance between the vehicle's center and the road's centerline. This factor represents one of the drivers' behavior risks, whether a frontal crash or running off the road causes the crash. The higher the lateral position, the closer the vehicle will be to the road's edge. When the car is closer to the edge of the road, the risk of run-off-road crashes will increase.

For this study, seven measurement points were taken from each curve to assess the effects of edge road marking treatments on driving behaviors. Two measurement points were positioned at 250 m (point 1) and 150 m (point 2) before the curve, while five were situated within the curve. These internal measurement points were located at the beginning of the entry transition curve (point 3), the start of the circular curve (point 4), the midpoint of the circular curve (point 5), the end of the circular curve (point 6), and the end of the exit transition curve (point 7). To clarify, Figure 5 illustrates the positioning of the seven measurement points for each curve.

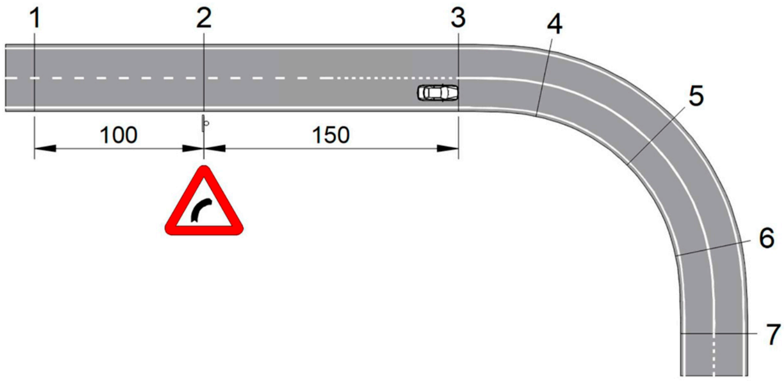


Figure 5. Seven measurement points on a horizontal curve.

A within-subjects repeated measures ANOVA was conducted to analyze and compare driving behaviors in response to different road marking treatments, utilizing the Greenhouse–Geisser correction for sphericity violations on various output parameters. This technique enabled the evaluation of the significance of mean differences for each independent variable, such as measuring points, across multiple scenarios involving dependent variables like vehicle speed or lateral positioning. This approach identified the significance of differences across all possible pairings of independent variables for every dependent variable. It is important to understand the order of significance among the dependent variables, meaning which is the most important and has the least effect. The dependent variables in this research included longitudinal speed, acceleration/deceleration, and lateral position. The independent variables comprised parameters used to create horizontal curves for testing, such as the radius of the curve, curve directions, road marking conditions, and measuring points. A General Linear Model (GLM) with repeated measures was used to perform pairwise comparisons, accounting for within-subject variability. Bonferroni correction was applied to control for Type I error. This analysis focused on differences related to marking conditions in terms of driving speed, acceleration/deceleration, and lateral position.

3. Results and Discussions

This section uses within-subjects repeated measures ANOVA to explain the results regarding driving speed, acceleration/deceleration, and lateral position.

3.1. Driving Speed

To determine statistically significant speed differences between the factors at a 95% confidence level, the p-values should be below 0.05. Table 2 displays the within-subjects repeated measures ANOVA results, using the Greenhouse–Geisser correction for sphericity violations. The results show statistically significant differences for the curve radius ($F(1.00, 46.00) = 130.23$, $p < 0.001$, $\eta^2_p = 0.74$), condition ($F(2.90, 133.52) = 6.219$, $p < 0.001$, $\eta^2_p = 0.12$), and measuring point ($F(2.14, 98.59) = 51.67$, $p < 0.001$, $\eta^2_p = 0.53$). This implies that the driving speed was significantly influenced, regardless of any other factors, for various curve radii and road marking conditions in different measuring points. Additionally, the two-way interaction effects of curve radius × measuring point ($F(2.06, 94.63) = 64.12$, $p < 0.001$, $\eta^2{}_p = 0.58$) and condition × measuring point ($F(8.56, 393.65) = 4.825$, $p < 0.001$, $\eta^2{}_p = 0.10$) were also significant. The significant interaction between the curve radius and measuring points indicates that the effect of the curve radius on speed varies across measurement locations. Similarly, the significant interaction between the condition and measuring points suggests that the impact of the conditions depends on the measuring point. These results highlight the location-specific influence of geometric and design factors on driving speed. In addition, the three-way interaction effect of curve direction × condition × measuring point ($F(8.32, 382.71) = 3.09$, $p = 0.002$, $\eta^2{}_p = 0.06$) being significant indicates that the combined effects of curve direction, condition, and measuring points influence speed. Also, the significant three-way interaction of curve radius × condition × measuring point ($F(7.66, 352.14) = 2.85$, $p = 0.005$, $\eta^2{}_p = 0.06$) means that the effects of measuring points on speed vary depending on the curve radius and the road marking condition.

Table 2. Analysis of speed: within-subjects repeated measures ANOVA with Greenhouse–Geisser correction.

Effect	*df*	*F*	*p*	$\eta^2{}_p$
Curve direction	(1.00, 46.00)	0.119	0.658	0.004
Curve radius	(1.00, 46.00)	130.234	**<0.001** *	0.739
Condition	(2.90, 133.52)	6.219	**<0.001**	0.119
Measuring points	(2.14, 98.59)	51.668	**<0.001**	0.529
Curve direction × Curve radius	(1.00, 46.00)	0.035	0.852	0.001
Curve direction × Condition	(3.55, 163.33)	0.654	0.607	0.014
Curve radius × Condition	(3.64, 167.59)	1.132	0.342	0.024
Curve direction × Curve radius × Condition	(3.46, 159.22)	1.134	0.340	0.024
Curve direction × Measuring points	(2.28, 104.65)	1.585	0.207	0.033
Curve radius × Measuring points	(2.06, 94.63)	64.121	**<0.001**	0.582
Curve direction × Curve radius × Measuring points	(2.51, 115.60)	0.665	0.549	0.014
Condition × Measuring points	(8.56, 393.65)	4.825	**<0.001**	0.095
Curve direction × Condition × Measuring points	(8.32, 382.71)	3.088	**0.002**	0.063
Curve radius × Condition × Measuring points	(7.66, 352.14)	2.845	**0.005**	0.058

* Bolded values are statistically significant at the $p < 0.05$ level.

The descriptive statistics of means and pairwise comparisons for speed, adjusted using the Bonferroni correction, can be found in Table 3. Speed in all four REW, RE, RWM, and RDT conditions showed a significant difference compared to the control condition, and drivers maintained their highest speeds without special road markings. RE and RDT produced the lowest speeds and demonstrated a difference in driving speed compared to the RWE condition, suggesting that drivers slowed down more in RE and RDT than in RWE, although not statistically significant.

The average speed in measuring points based on curve directions and curve radii is shown in Figure 6 to study the speed variations. The mean speed for curve directions at each measuring point is demonstrated in Figure 6a. The overall speed patterns for both directions were remarkably similar, indicating insignificant differences. The proximity of the speed diagrams for left and right curve directions supports the statistical findings reported in Table 2, highlighting the minimal effect of curve direction on driver speed behavior.

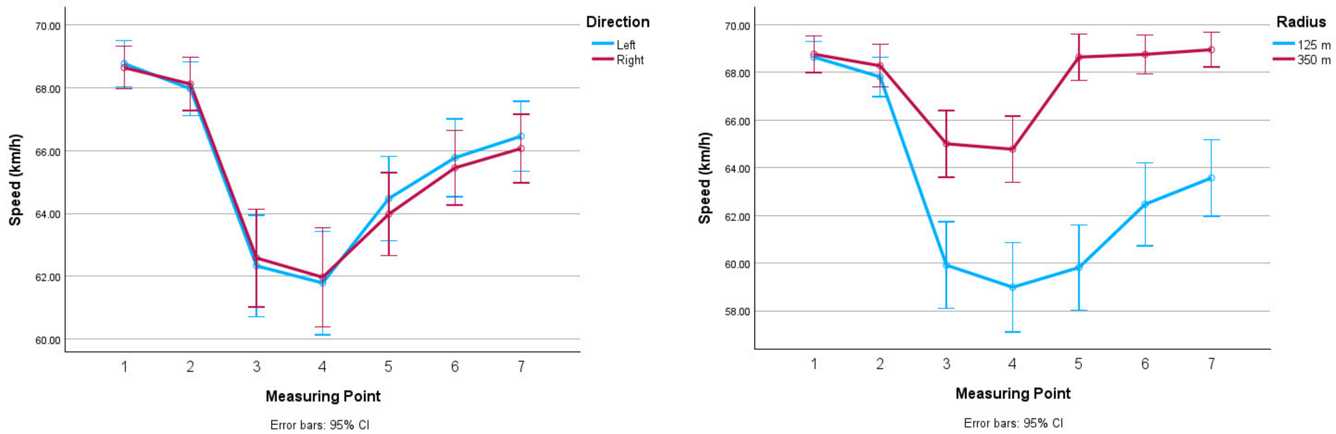
More particularly, the speeds from 250 m before the curve (point 1) to the end of the beginning of the circular curve (point 4) decreased at almost the same rate for both directions. In addition, Figure 6b demonstrates the mean driving speed for different curve radii. It indicates that the driver's average speed at the beginning of the entry transition curve (point 3) with a radius of 125 m is 5 km/h lower than at a curve with a radius of

350 m. This difference in speed was consistent throughout the entire segment until exiting the transition curve (point 7).

Table 3. Descriptive statistics: mean and pairwise comparison of speed with Bonferroni correction.

Condition	Control	RWE	RE	RWM	RDT
Mean speed (km/h)	66.33	65.29	64.91	65.11	64.92
Pairwise comparison (p-values)					
Control	1	**<0.001** *	**<0.001**	**<0.001**	**<0.001**
RWE		1	0.082	1	0.283
RE			1	1	1
RWM				1	1
RDT					1

* Bolded values are statistically significant at the $p < 0.05$ level.



(**a**) Average speed by curve directions (**b**) Average speed by curve radii

Figure 6. Average speed on measuring points based on (**a**) curve directions and (**b**) curve radii.

Figure 7 displays the driving speed for the control scenario and the four marking treatments at each of the seven measuring points before, during, and after the curve. The results indicate that the treatments generally led to lower mean speeds than the control condition at the beginning of the entry transition curve (point 3) and at the beginning of the circular curve (point 4). Specifically, at point 4, the speed for all conditions reached its lowest point. RDT experienced the lowest speed at 60.5 km/h, while RWE and RWM reached the minimum of 62 km/h, and RE demonstrated the least reduction in speed, reaching 62.5 km/h at its lowest. From point 4 onward, the speed for all conditions gradually increased until the end of the curve.

Speed varies significantly at different points along the curve ($p < 0.001$), showing that drivers adjust their speed as they approach, navigate, and exit the curve, which is supported by Altamira et al. [34]. The RDT condition exhibits the lowest speed and the highest deceleration due to the early noticeability and the visual perception created by the treatment 100 m before the curve. This treatment creates an illusion for drivers, making them perceive they are driving faster than they actually are by presenting the treatment at increasingly smaller intervals. Additionally, by increasing the height of the markings, the road also appears narrower. The speed-reducing effect of the RDT treatment diminishes as drivers progress further through the curve. In addition, road markings affect speed differently at various points, suggesting some markings may encourage early slowing while others maintain lower speeds within the curve [35].

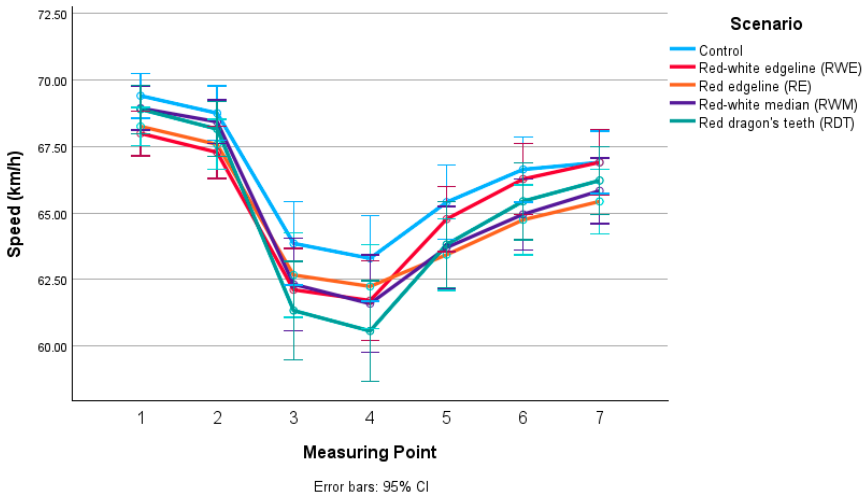


Figure 7. Average speed across conditions and measuring points.

3.2. Acceleration/Deceleration

The results of the within-subjects repeated measures ANOVA, with Greenhouse–Geisser correction for acceleration/deceleration (acc/dcc), are presented in Table 4. It indicates that both curve radius (F(1.00, 46.00) = 6.73, p = 0.013, $\eta^2{}_p$ = 0.02) and measuring point (F(2.69, 123.57) = 71.27, p < 0.001, $\eta^2{}_p$ = 0.61) significantly impacted acceleration and deceleration. This showed that the measuring points and the curve radii significantly affected the differences in acceleration. However, the curve direction and condition factors were insignificant, suggesting that the differences in ACC and DCC were not noticeably different across different conditions and curve directions.

Table 4. Analysis of acc/dcc: within-subjects repeated measures ANOVA with Greenhouse–Geisser correction.

Effect	*df*	*F*	*p*	$\eta^2{}_p$
Curve direction	(1.00, 46.00)	0.975	0.328	0.021
Curve radius	(1.00, 46.00)	6.730	**0.013** *	0.128
Condition	(3.72, 170.88)	2.254	0.070	0.047
Measuring points	(2.69, 123.57)	71.267	**<0.001**	0.608
Curve direction × Curve radius	(1.00, 46.00)	1.004	0.322	0.021
Curve direction × Condition	(3.86, 177.37)	3.290	**0.014**	0.067
Curve radius × Condition	(3.55, 163.46)	0.361	0.814	0.008
Curve direction × Curve radius × Condition	(3.33, 153.30)	1.044	0.379	0.022
Curve direction × Measuring points	(3.39, 155.99)	1.350	0.258	0.029
Curve radius × Measuring points	(2.58, 118.61)	75.275	**<0.001**	0.621
Curve direction × Curve radius × Measuring points	(3.30, 151.77)	1.167	0.326	0.025
Condition × Measuring points	(9.36, 430.50)	3.035	**0.001**	0.062
Curve direction × Condition × Measuring points	(10.49, 482.60)	1.828	**0.050**	0.038
Curve radius × Condition × Measuring points	(9.51, 437.23)	0.836	0.589	0.018

* Bolded values are statistically significant at the p < 0.05 level.

Moreover, the two-way interaction effects of curve direction × condition (F(3.86, 177.37) = 3.29, p = 0.014, $\eta^2{}_p$ = 0.07) are significant. This means that the effect of curve direction on acceleration/deceleration depends on the road condition. Depending on the visual road treatments, drivers may respond differently to the left vs. right curves. In addition, the two-way interaction effect of curve radius × measuring point (F(2.58, 118.61) = 75.28, p < 0.001, $\eta^2{}_p$ = 0.62) is highly significant. This means that the impact of the curve's radius on acceleration/deceleration varies significantly depending on the location within the curve.

Drivers adjust their speed differently based on how sharp the curve is. Another significant two-way interaction is condition × measuring point (F(9.36, 430.50) = 3.04, p = 0.001, $\eta^2{}_p$ = 0.06), meaning that road marking conditions affect acceleration/deceleration patterns differently at various measuring points. Some markings may encourage earlier or later deceleration in the curve.

The three-way interaction effect for the factor curve direction × curve radius × measuring point (F(10.49, 482.60) = 1.83, p = 0.050, $\eta^2{}_p$ = 0.04) was also marginally significant, suggesting that the combined effect of curve direction and road markings might vary across measuring points, but the evidence is weak.

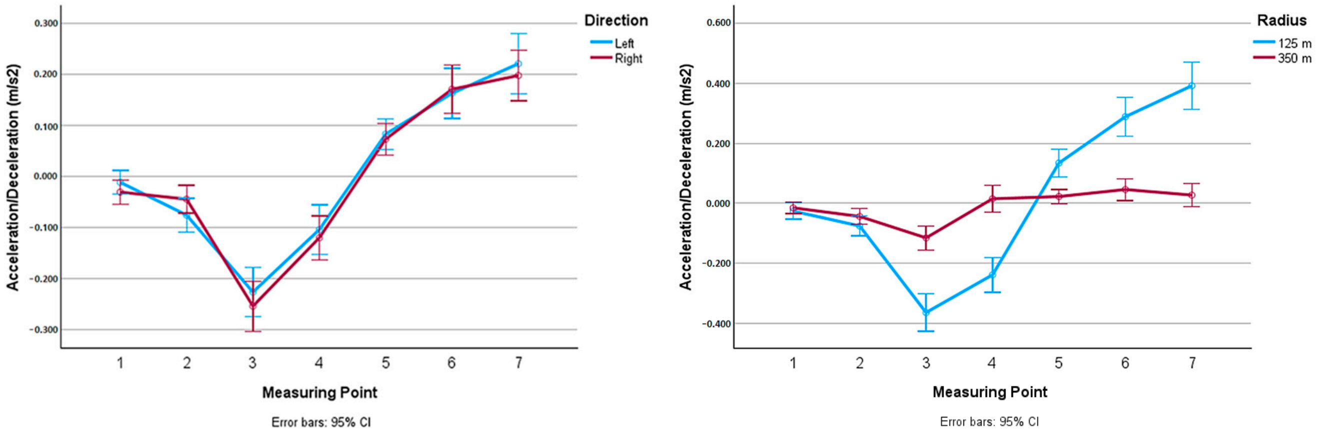
The descriptive statistics and pairwise comparisons of acc/dcc for the road marking conditions, adjusted using the Bonferroni correction, are presented in Table 5. The acceleration in the RWE condition was the highest compared to the other conditions. Mean acceleration, being lower in the control condition, might be due to the fact that drivers tended to brake less compared to other conditions, and they maintained their high speeds throughout the path. According to the pairwise comparisons, RWE and RE conditions demonstrate a difference compared to the control condition, while RDT and RWE were also different but not statistically significant.

Table 5. Descriptive statistics: mean and pairwise comparison of acc/dcc with Bonferroni correction.

Condition	Control	RWE	RE	RWM	RDT
Mean acceleration (m/s^2)	−0.01364	0.01722	0.00908	0.00823	−0.00639
Pairwise comparison (p-values)					
Control		0.064	0.445	0.761	1
RWE		1	1	1	0.318
RE			1	1	1
RWM				1	1
RDT					1

The average acceleration/deceleration at measuring points based on curve directions and radii is illustrated in Figure 8. The average acceleration between the curve directions at each measuring point is demonstrated in Figure 8a. The horizontal axis represents the different measuring points, while the vertical axis indicates the vehicle's average acceleration on the road. From 250 m prior to the curve (point 1) to the beginning of the entry transition curve (point 3), drivers decelerated at nearly the same rate in both directions. From that point until the end of the exit transition curve (point 7), there is a consistent acceleration at a comparable rate. Furthermore, the overall speed patterns for both directions are strikingly similar, suggesting negligible differences.

In addition, Figure 8b illustrates the average acceleration and deceleration between the curve radii and the measuring points. Drivers begin active deceleration 150 m prior to the curve (point 2), and they decelerate more abruptly at the beginning of the entry transition curve, especially for the sharper curve (radius 125 m). At point 3, they experienced their most significant deceleration for both radii (deceleration of −0.33 m/s^2 for radius 125 m and −0.11 m/s^2 for radius 350 m). However, as they reach the midpoint of the circular curve (point 5), drivers experience a significant increase in acceleration in curves with a radius of 125 m, reaching their peak at 0.36 m/s^2 as they exit the curve. In contrast, the average acceleration for drivers in curves with a radius of 350 m plateaued at about zero, indicating no change in speed from the initial slowdown before entering the curve until exiting the curve.



(**a**) Average acc/dcc by curve directions (**b**) Average acc/dcc by curve radii

Figure 8. Average acc/dcc on measuring points based on (**a**) curve directions and (**b**) curve radii.

Figure 9 illustrates the average acceleration across three conditions at each measuring point. The results show that drivers nearly decelerated at a similar rate across all conditions, from 150 m prior to the curve (point 2) to the beginning of the entry transition curve (point 3). The RDT condition recorded the lowest value of $-0.3\ \mathrm{m/s^2}$, representing the greatest deceleration, followed closely by the RWM condition. Beyond this point, drivers decrease their deceleration, maintaining the same order among the conditions until they reach the circular curve's midpoint (point 5). At this point, the control condition ceases to increase at the same rate as the other conditions and attains its highest value of $0.10\ \mathrm{m/s^2}$. However, other conditions reach their peak values, reflecting the greatest acceleration while exiting the curve.

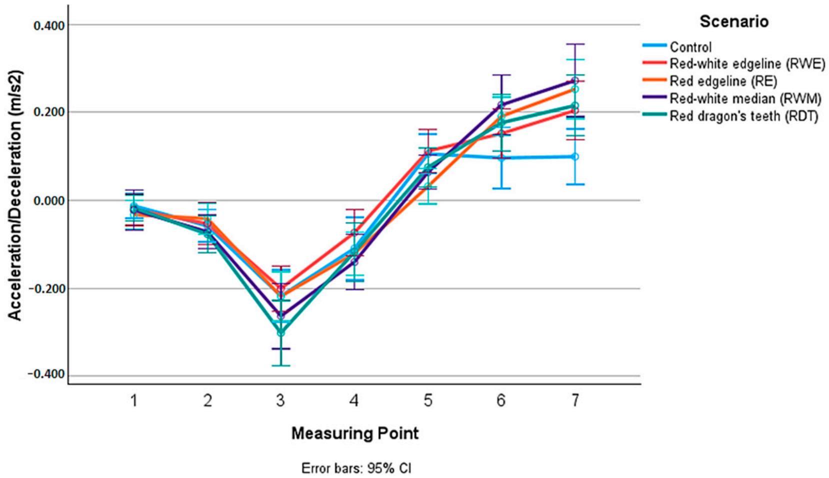


Figure 9. Average acc/dcc across conditions and measuring points.

3.3. Lateral Position

Table 6 presents the results of the within-subjects repeated measures ANOVA, with Greenhouse–Geisser correction. It demonstrates that all factors, including curve direction (F(1.00, 46.00) = 15.89, $p < 0.001$, $\eta^2{}_p = 0.26$), curve radius (F(1.00, 46.00) = 9.28, $p = 0.004$, $\eta^2{}_p = 0.17$), condition (F(2.99, 137.96) = 16.80, $p < 0.001$, $\eta^2{}_p = 0.27$), and measuring point (F(2.85, 130.92) = 5.35, $p = 0.002$, $\eta^2{}_p = 0.10$), significantly influenced the lateral position. This indicates that the overall variations in lateral positioning are affected considerably, regardless of other factors.

Table 6. Analysis of lateral position: within-subjects repeated measures ANOVA with Greenhouse–Geisser correction.

Effect	*df*	*F*	*p*	η^2_p
Curve direction	(1.00, 46.00)	15.885	**<0.001** *	0.257
Curve radius	(1.00, 46.00)	9.280	**0.004**	0.168
Condition	(2.99, 137.96)	16.800	**<0.001**	0.268
Measuring points	(2.85, 130.92)	5.345	**0.002**	0.104
Curve direction × Curve radius	(1.00, 46.00)	57.411	**<0.001**	0.555
Curve direction × Condition	(3.41, 156.95)	1.120	0.346	0.024
Curve radius × Condition	(3.56, 163.55)	3.936	**0.006**	0.079
Curve direction × Curve radius × Condition	(3.41, 156.77)	2.800	**0.035**	0.057
Curve direction × Measuring points	(2.59, 118.93)	62.929	**<0.001**	0.578
Curve radius × Measuring points	(3.63, 166.75)	6.407	**<0.001**	0.122
Curve direction × Curve radius × Measuring points	(2.39, 110.01)	27.452	**<0.001**	0.374
Condition × Measuring points	(10.52, 483.83)	13.111	**<0.001**	0.222
Curve direction × Condition × Measuring points	(12.21, 561.47)	5.678	**<0.001**	0.110
Curve radius × Condition × Measuring points	(11.35, 521.98)	1.173	0.302	0.025

* Bolded values are statistically significant at the $p < 0.05$ level.

Furthermore, the two-way interaction effects of curve direction × curve radius ($F(1.00, 46.00) = 57.41$, $p < 0.001$, $\eta^2_p = 0.56$), curve radius × condition ($F(3.56, 163.55) = 3.94$, $p = 0.006$, $\eta^2_p = 0.08$), curve direction × measuring point ($F(2.59, 118.93) = 62.93$, $p < 0.001$, $\eta^2_p = 0.58$), curve radius × measuring point ($F(3.63, 166.75) = 6.41$, $p < 0.001$, $\eta^2_p = 0.12$), and condition × measuring point ($F(10.52, 483.83) = 13.11$, $p < 0.001$, $\eta^2_p = 0.22$) were also significant. These findings revealed that lateral positioning varied significantly between the two curve radii, five road marking conditions, and seven measuring points. The three-way interaction effect for the factors curve direction × curve radius × condition ($F(3.41, 156.77) = 2.80$, $p = 0.035$, $\eta^2_p = 0.06$), curve direction × curve radius × measuring point ($F(2.39, 110.01) = 27.45$, $p < 0.001$, $\eta^2_p = 0.37$), and curve direction × condition × measuring point ($F(12.21, 561.47) = 5.68$, $p < 0.001$, $\eta^2_p = 0.11$), are also significant.

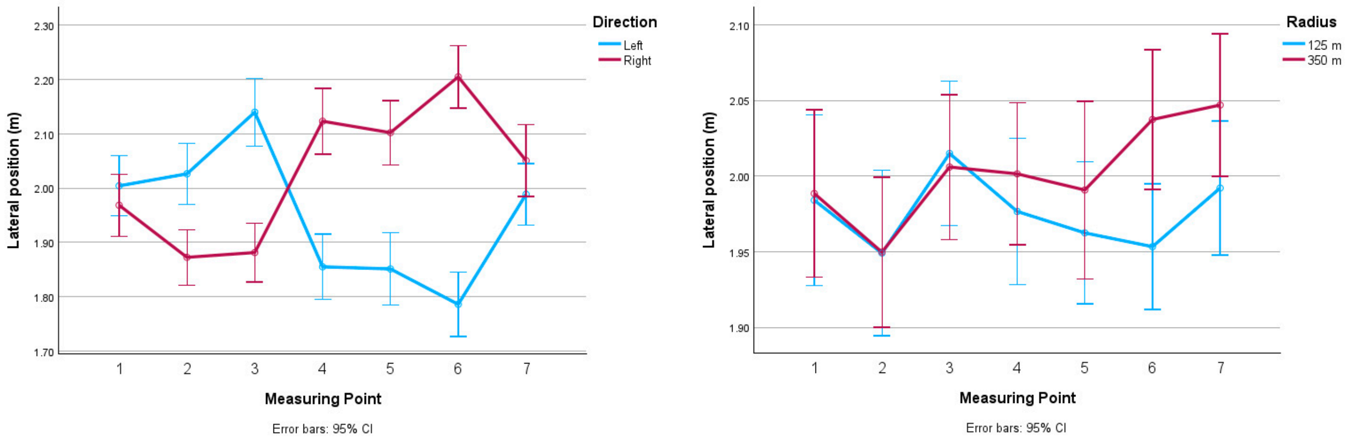
The descriptive statistics and pairwise comparisons of lateral positioning, adjusted using the Bonferroni correction, are shown in Table 7. The RWM condition exhibits a considerable difference in mean lateral positioning compared to the other conditions. Furthermore, the vehicle's position under the RE condition was, on average, closest to the centerline. Additionally, only RWE and RDT did not show a significant difference compared to the control condition, while other conditions demonstrated a significant difference.

Table 7. Descriptive statistics: mean and pairwise comparison of lateral position with Bonferroni correction.

Condition	Control	RWE	RE	RWM	RDT
Mean lateral position (m)	1.99	1.98	1.95	2.05	1.98
Pairwise comparison (*p*-values)					
Control	1	1	**<0.001** *	**<0.001**	1
RWE		1	**<0.001**	**<0.001**	1
RE			1	**<0.001**	**<0.001**
RWM				1	**<0.001**
RDT					1

* Bolded values are statistically significant at the $p < 0.05$ level.

The average lateral position in measuring points based on curve directions and radii is shown in Figure 10. The horizontal axis displays the different measuring points before and during the horizontal curve. The vertical axis indicates the distance between the vehicle's center and the road's centerline on the right lane side. A greater lateral position implies that the car is farther from the centerline and closer to the road's edge. As shown in Figure 10a, on the left curve, the lateral position initially moves towards the right side of the lane at the beginning of the entry transition curve (point 3), then leans towards the midpoint of the circular curve (point 5). Conversely, on a right curve, the lateral position is the opposite of the left curve, being closer to the centerline at the start of the curve and leaning toward the edge road marking at the exit of the curve.



(**a**) Average lateral position by curve directions (**b**) Average lateral position by curve radii

Figure 10. Average lateral position on measuring points based on (**a**) curve directions and (**b**) curve radii.

Furthermore, Figure 10b illustrates the average lateral position for various curve radii at each measuring point. It shows that the lateral position for both radii fluctuates between 1.95 m and 2.05 m. Specifically, the lateral position on the smaller curve tends to be closer to the road's centerline. Particularly at the end of the circular curve (point 6), there is almost a 0.09 m difference between the lateral positions, where the lateral position for the larger curve radius was 2.04 m and for the smaller curve radius was 1.95 m.

Figure 11 demonstrates the average lateral position at each measuring point under various conditions. It indicates that 150 m prior to the curve (point 1), the drivers change their lateral position gradually, and at the beginning of the entry transition curve (point 3), RWM and RDT conditions induce a movement further away from the median in comparison with the other conditions, with lateral positions of 2.06 m and 1.95 m, respectively. In addition, the lateral position for all conditions fluctuated between 2.12 m and 1.90 m. In the control condition, the lateral position ranged from 2.01 m to 1.96 m, while in the RWE condition, it ranged from 2.06 m to 1.92 m; in the RE condition, it ranged from 1.98 m to 1.90 m. In RWM, it ranged from 1.95 m to 2.12 m, and in RDT, it ranged from 1.93 m to 2.04 m.

Notably, the lateral position in the control condition tended to stay towards the centerline compared to the rest, and the highest variation was observed for RWM. In addition, the RDT condition prompts the driver to move closer to the median compared to the control condition throughout the path at all measuring points.

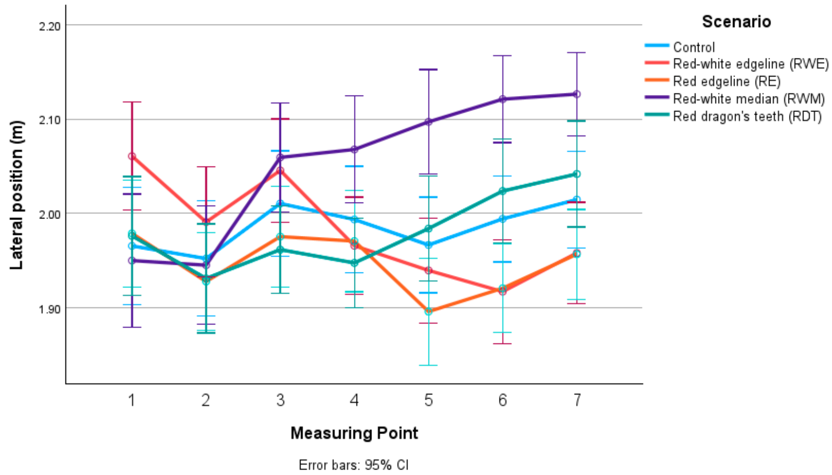


Figure 11. Average lateral position across conditions and measuring points.

4. Discussion

The statistical analysis indicates that the road marking treatments positively influenced driving behavior before and during horizontal curves. This section explored the results in greater depth, emphasizing their effects and comparing them to previous studies. Across all scenarios, RE and RDT markings consistently reduced speeds most effectively (e.g., 64.91 km/h and 64.92 km/h vs. 66.32 km/h control, Table 3), with RDT showing the greatest deceleration (-0.3 m/s^2, Figure 9). RWM improved lateral positioning farthest from the centerline (2.05 m mean, Table 7), while RE kept vehicles closest (1.95 m). Effects were more pronounced in sharper 125 m curves than in 350 m curves.

4.1. Impact on Driving Speed and Acceleration/Deceleration

The findings revealed that road markings such as RWE, RE, RWM, and RDT reduced driving speed before and during the curve, indicating that these perceptual countermeasures successfully influence driver behavior. However, there were no significant variations in driving speed between left and right turns. This suggested that the conditions decrease speed independently of the curve directions, as confirmed by Babić et al. [9]; however, earlier research contradicted this [36,37].

This study also found that the average speed on curves with a small radius of 125 m is 5 km/h lower than on curves with a radius of 350 m due to the sharper geometry of the horizontal curve. It is observed that drivers tend to slow down more in sharper curves due to increased perceived risk or steering demands. In agreement with the literature [38–40], speed adjustments differ between sharp and gentle curves. For instance, drivers may decelerate more abruptly in sharper curves (see Figure 8b).

Before the curve, the participants drove close to the maximum allowed speed of 70 km/h in all conditions. The posted speed limit of 70 km/h closely matches the design speed of the curve, meaning that the geometric design supports safe travel at a regulated speed. This alignment is important for interpreting driver behavior observed in the simulator study. The results indicated that they slowed down slightly upon seeing the vertical warning sign located 150 m before the curve, which is consistent with the findings of Yotsutsuji et al. [41]. The drivers continued to decrease their speed after passing the vertical sign while approaching the horizontal curve [42]. Among all conditions, in terms of reducing driving speed, RWM and RE exhibited similar effects; RWE was the least effective intervention, while RDT proved to be the most effective in lowering speed at the beginning of the curve. Similar effectiveness of the two different interventions may be due to the low attention paid to road markings and vertical changes, which aligns with the findings of

Babić et al. [43] and Costa et al. [44]. The results of earlier research revealed that drivers tend to fixate their eyes and attention on the place they are heading towards. For example, when drivers drove on a straight section, they focused more on the distant horizon and less on the sides of the road [45]. However, when drivers navigated a curve, they tended to focus more on the sides of the road, particularly the edge road marking [46].

In conclusion, all road markings lower speeds compared to the control condition, with RE and RDT being the most effective, reducing speeds by about 1.4 km/h on average. This aligns with the study's aim to enhance safety through perceptual cues. Although the overall speed reduction observed with non-conventional markings might seem negligible, even small speed reductions can significantly impact road safety, particularly in high-risk areas such as horizontal curves. Additionally, the influence of the maximum speed limit (70 km/h) on driver behavior may have contributed to the observed effects, which should be considered when interpreting the results.

The significant interactions show that speed reduction depends on curve sharpness, direction, and location along the curve. For example, sharper curves may see greater speed drops, and certain markings may work better at specific points (e.g., before vs. within the curve). Therefore, RE and RDT show potential as supportive measures in high-risk areas like sharp curves, where even slight reductions in speed may contribute to improved safety.

In addition, drivers decelerated and accelerated more abruptly on a smaller horizontal curve (radius of 125 m) than on a larger curve (radius of 350 m). This result is consistent with established findings, confirming that road geometric features, such as curve radius, influence acceleration and deceleration behavior within the simulated environment. The results also suggest that curve radius and measuring points are the most influential factors in acceleration/deceleration in curves. Road markings (condition) also play a role, particularly when combined with measuring points. However, more complex interactions between the factors do not have a significant impact.

4.2. Impact on Lateral Position

Curve direction, radius, road markings (condition), and measuring points significantly influence lateral position, and the direction of the curve affects the lateral position, which is in agreement with findings from Luo et al. [47]. Drivers position their vehicles differently in left versus right curves, possibly due to differences in visibility, steering demands, or driver behavior. In addition, the sharpness of the curve significantly impacts the lateral position. Sharper curves may require more precise steering, leading to distinct positioning compared to gentler curves. On the other hand, the type of road marking significantly influences lateral position, which is in line with the available literature [48]. Different markings likely guide drivers' perception and lane-keeping behavior in unique ways. The lateral position varies considerably depending on where it is measured along the curve (e.g., before, start, middle, or end). This suggests drivers adjust their position as they progress through the curve.

Considering the two-way interactions, the effect of curve direction on lateral position depends on the curve radius. For example, the difference between left and right curves might be more considerable in sharper versus gentler, possibly due to increased steering difficulty. However, the effect of road markings on lateral position is consistent across left and right curves, meaning markings work similarly regardless of curve direction. In addition, specific markings may be more effective in sharper or gentler curves, suggesting that marking design should consider curve sharpness. The results also demonstrate that lateral position changes at different points along the curve depending on direction and radius. This suggests complex adjustments in driver behavior based on curve characteristics.

The lateral movement results showed that 150 m before the curve, participants deviated toward the centerline of the road, regardless of the conditions. This behavior was attributed to participants perceiving vertical warning signs as obstacles near the road, prompting the drivers to move toward the centerline before returning to their initial position at the start of the curve. During the horizontal curve, drivers maintained a consistent lateral position, about 2 m from the centerline in the control condition. However, the RWE treatment led vehicles to move closer to the centerline throughout the entire curve, reaching a maximum lateral position of 1.92 m at the end of the circular curve. In addition, the RE treatments did not significantly alter the initial lateral position, indicating a consistent proximity to the centerline, ranging between 1.90 m and 1.98 m.

The RWM treatment, on the other hand, caused lateral movement throughout the entire curve closer to the edge of the road while reaching its furthest position of 2.12 m from the centerline at the end of the circular curve. Although movement closer to the edge of the road increases the risks of more run-off-road crashes, the RWM treatment simultaneously caused a speed reduction compared to the control condition throughout the entire curve. Moreover, moving closer to the edge reduces the risk of head-on collisions with vehicles coming from the opposite direction. Therefore, the lateral position to the edge caused by the RWM treatment can be evaluated as a safe consequence. Compared with a similar study [8], Babić highlighted that vehicles tended to move closer to the edge of the road marking due to the implemented red median, which aligned with the results of our study.

The results of this study and the literature [5,48] show that some marking treatments, when placed in the median, led to drivers positioning themselves farther from the centerline. In contrast, edge markings caused drivers to move closer to the centerline. This behavior suggests that drivers avoid markings, whether positioned at the median or edge [49]. The tendency to distance oneself from these treatments may reflect an instinctive effort to maintain a comfortable and safe position on the road, potentially avoiding perceived risks such as oncoming traffic or road edge hazards. From a road safety perspective, this behavior could have mixed implications. While the treatments aim to guide drivers and promote safer lane positioning, the tendency to steer away from the markings could indicate that drivers perceive these boundaries as risks, especially if they feel too close to them, which is in accordance with findings in the literature [35]. This phenomenon suggests that while the treatments may encourage attention to lane boundaries, they may also unintentionally provoke overcorrection. To enhance safety, future road marking designs could focus on reducing the perceived risk of proximity to the markings, such as using more gradual transitions or dynamic markings that adjust to traffic conditions. Additionally, a better understanding of how different driver populations respond to these cues could improve the overall effectiveness of visual guidance strategies.

In conclusion, the tendency to distance from marking treatments highlights the complex relationship between road markings, driver behavior, and safety [50]. Further investigation into how these treatments influence driver positioning and risk perception could lead to more effective design strategies for improving road safety.

5. Conclusions

The study investigated the impact of four low-cost road marking interventions on driver behavior in horizontal curves with sharp (125 m) and wide (350 m) radii. The road marking interventions were continuous red and red-white patterns on edge road markings, an alternating red-white checkered median stripe, and red dragon's teeth, all accompanied by a vertical warning sign 150 m before the curve. These interventions prompted drivers to reduce their speed before entering the circular curve. Drivers decreased their speed at a rate similar to the control condition before the curve began. They continued to slow down until the vehicle gradually passed the transition curve. The dragon tooth condition had the highest reduction in speed in the transition curve, but the effect faded away when vehicles reached the middle of the curve. This was because this particular intervention was implemented before the curve.

In the RWE condition, the lateral position of the vehicles tended to shift toward the center of the road. Additionally, in the RE condition, the lateral movement remained similar, closer to the road's centerline, and leaned towards the centerline at the end of a sharp curve. These treatments could serve as a beneficial countermeasure for horizontal curves where run-off-road crashes are a concern. Conversely, the RWM treatment significantly impacted the lateral position before and during the curve, moving the vehicle closer to the edge of the road. Moreover, the RDT treatment influenced the lateral position to a lesser extent, with the car moving closer to the centerline at the beginning of the transition curve before drifting further away upon reaching the midpoint.

Overall, the study reinforces the potential of cost-effective road design interventions in improving driver behavior in hazardous horizontal curves. However, these countermeasures and road markings are not universally effective, and their impact varies with curve radius, direction, and position along the curve. By optimizing lateral position, these markings could reduce lane departure crashes, especially if tailored to specific curve types. Implementing such perceptual markings can be an alternative or complementary measure to traditional road safety strategies, particularly in rural road settings where infrastructure modifications may be impractical or costly. This study demonstrates that perceptual road markings (RE, RWE, RWM, RDT) reduce speeds and adjust lateral positioning in horizontal curves, enhancing safety. RE and RDT are most effective for speed reduction, while RWM optimizes lane position.

The study was conducted in a controlled simulator, so it does not account for real-world variables like traffic density, driver distractions, or road surface variations, all of which could influence driver behavior. In addition, while highly effective for controlled experiments, driving simulators have inherent differences from real-world road environments. Factors such as driver perception, vehicle dynamics, road surface conditions, and environmental influences (e.g., lighting, weather, and traffic interactions) may vary between simulation and real-world scenarios.

Based on the research findings, it is recommended to install perceptual road markings, such as RE and RDT, on horizontal curves with high crash rates, especially those with sharper turns. These markings have been shown to reduce driving speeds, lowering the risk of crashes in dangerous areas. Focusing on high-risk spots makes the best use of limited resources. In addition, running pilot programs and field trials in different areas and traffic conditions can demonstrate how well these markings work outside of simulations. Real-world tests ensure the markings perform well under various conditions, like bad weather or heavy traffic, and help confirm their value. In future research, the authors plan to extend simulations by incorporating varying weather conditions and time-of-day factors to validate the proposed designs more comprehensively. In addition, potential real-world testing strategies that account for these variables will also be discussed. Moreover, the gender distribution of participants was not fully balanced in this study, and this limitation will be addressed in future research.

Further study is also required to explore the long-term behavioral adaptation to these markings and their real-world effectiveness in different traffic conditions. In addition, other potentially important aspects of driving behavior, such as visual attention, reaction time, or drivers' subjective perception of risk, must be explored to add more insight into driving safety.

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