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MARIA EMÍLIA SCHIO RONDORA

Driver behavioral classification on curves based on the relationship between speed, trajectories, and eye movements: a driving simulator study

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Abstract

RONDORA, MARIA. **Driver behavioral classification on curves based on the relationship between speed, trajectories, and eye movements: a driving simulator study**. 53p. Master of Science. Dissertation – Department of Transportation Engineering, São Carlos School of Engineering, University of São Paulo, São Carlos, 2022.

Horizontal curves of rural highways are prone to a considerably high number of fatalities, since an erroneous perception can lead to unsafe driving, which generally occurs when a driver fails to notice the highway geometry or changes in the driving environment, particularly curved segments. This study aimed to understand the geometric characteristics of curved segments, such as radius and approach tangents, in the driving performance towards minimizing vehicle crashes. Speed profiles and lateral position, the most common indicators of successful negotiation in curves, and eye movements were recorded during an experiment conducted in a fixed-base driving simulator equipped with an eye-tracking system with a road infrastructure (a three-lane highway) and its surroundings. Therefore, the main objective of the study was the exploration of the relationship between the behavior measures collected during the experiment and the different levels of curves geometries available. A driving simulator can faithfully reproduce any situation and enable sustainable research because it is a high-tech and cost-effective tool that enables repeatability in a laboratory. The experiment was conducted with 28 drivers, who covered approximately 500 test kilometers with 90 horizontal curves comprising nine different combinations of radii and approach tangent lengths. In addition, drivers' behaviors on each curve were classified as ideal, normal, intermediate, cutting, or correcting, according to their trajectories and speed changes for analyses of the performance parameters and their correlation by factorial ANOVA and Pearson chi-square tests. The cross-tabulation results indicated the safest behavior significantly increased when the curve radius increased, moreover, the proposed performance measures were significantly affected by the curve radii. However, the driving behavior was not impacted by the approach tangent length. A better understanding of the way drivers negotiate curves can provide valuable information for evaluating and allocating roadway-based countermeasures. The study has shown the effectiveness of the driving simulation in improving road infrastructures through the relationship between design road features and users' behavioral parameters.

Keywords: Driving Simulator. Speed. Curve Negotiation. Trajectory Classification. Eye Movements.

Resumo

RONDORA, MARIA**.** 2022. **Classificação comportamental do motorista em curvas com base na relação entre velocidade, trajetórias e movimentos oculares: um estudo em simulador de direção.** 53p. Dissertação (Mestrado em Ciências). – Departamento de Engenharia de Transportes, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2022.

As curvas horizontais em rodovias são propensas a um número consideravelmente alto de fatalidades porque uma percepção errônea pode levar a uma condução insegura. Isso geralmente ocorre quando um motorista não percebe a geometria da rodovia ou mudanças no ambiente de direção, particularmente em trechos curvilíneos. Este estudo teve como objetivo compreender as características geométricas de segmentos curvos, como raio e tangentes de aproximação, no desempenho de condução para minimizar colisões de veículos. Perfis de velocidade e posição lateral, os indicadores mais comuns de sucesso ao trafegar por curvas, e movimentos dos olhos foram registrados durante um experimento conduzido em um simulador de direção de base fixa equipado com um sistema de rastreio ocular com infraestrutura viária (uma rodovia de três pistas) e seu entorno. Um simulador de condução pode reproduzir fielmente diversas situações e permitir relevantes pesquisas por ser uma ferramenta de alta tecnologia e custo-benefício que permite a replicação do experimento em laboratório. O experimento foi realizado com 28 motoristas que percorreram aproximadamente 500 quilômetros de teste com 90 curvas horizontais compreendendo nove combinações diferentes de raios e comprimentos de tangentes de aproximação. O comportamento dos motoristas em cada curva foi classificado como ideal, normal, intermediário, cortante ou corretor, de acordo com suas trajetórias e mudanças de velocidade para análise dos parâmetros de desempenho e sua correlação, realizadas por ANOVA fatorial e testes qui-quadrado de Pearson. Os resultados da tabulação cruzada indicaram que o comportamento mais seguro aumentou significativamente quando o raio da curva aumentou, e as medidas de desempenho dos raios da curva foram bastante afetadas. No entanto, a atividade de condução do veículo não fora afetada pelo comprimento da tangente de aproximação. Trazer um melhor entendimento sobre como motoristas dirigem em curvas pode fornecer informações valiosas para avaliação e criação de contramedidas de segurança em rodovias. Além disto, o estudo demonstra a eficácia dos simuladores de direção para aperfeiçoar a infraestrutura rodoviária através da compreensão da relação entre elementos do projeto rodoviário e parâmetros comportamentais dos usuários.

Palavras-chave: Simulador de Direção. Velocidade. Performance de Curvas. Classificação de Trajetórias. Movimentos do Olhar.

List of publications

The following article composes this dissertation:

I. **Rondora, M.E.S.**; Pirdavani, A.; Larocca, A.P.C. Driver Behavioral Classification on Curves Based on the Relationship between Speed, Trajectories, and Eye Movements: A Driving Simulator Study. Sustainability 2022, 14, 6241. https://doi.org/10.3390/su14106241

Contents

1. Introduction

Since 2010, it is estimated that approximately 1,220 fatalities each year have resulted from road accidents on horizontal curve in Brazil. Accidents on Brazilian federal highways totaled 64,452 occurrences recorded only in 2021, which represents a higher number when comparing to 2020. In addition, it was pointed that there were, on average, 80 accidents with victims each 100 kilometers of Brazilian roadways and for every 100 of these accidents, there were, on average, 10 deaths last year (PRF, 2022). These numbers go against the grain what is expected by the World Health Organization's Decade of Action for Road Safety, which has the target of preventing at least 50% of road traffic deaths and crashes by 2030 (WHO, 2021).

Crashes are more severe in horizontal curves in comparison with tangent sections of a roadway, so that it has motivated many studies on curve negotiation. Besides, although the number of crashes in tangent sections are higher than in curves, when facing to the proportion of the crashes in relation to the length of these segments on the highway, the result is the opposite. Therefore, methods that mitigate crashes involving those factors should be studied in driving simulators, where environmental conditions can be controlled, and drivers are not at risk of injury or fatality. Moreover, such simulators have emerged as a powerful tool for the understanding of driving behavior and its interaction with the roadway (Bobermin; Silva; Ferreira, 2021).

The present study database was raised on research on Jerk (the first derivative of acceleration in time) as an indicator of run-off-road risk locations caused by a lack of geometric consistency between the approach tangents and the subsequent horizontal curves. A controlled experiment was conducted in a fixed-base driving simulator, which revealed a significant effect of the variation of the geometric characteristics on the average minimum Jerk value applied. (Torquato, 2019). The available database also enables analyses of drivers' behaviors under different geometric conditions of the road.

The development of the present study was guided by the following research topics:

i. The assumption behavioral parameters are significantly different for different road design conditions and such differences are in line with what is expected from a literature review.

ii. The choice of suitable ways for analyses and classification of curve trajectories and speed change behavior and the hypothesis curve radius and approach tangents significantly affect the behavioral classification.

iii. The assumption driver's eye movements significantly differ under different geometric conditions studied and selection of the major parameters for their evaluation.

The drivers' behaviors for different levels of approach tangents and curves radii combined were analyzed and classified regarding their speed profiles, lateral position parameters, and eye movements' data, which enabled investigations on the effect of geometric features of horizontal curves on driving performance. Statistical analyses are presented towards supporting the results and the study also demonstrates the relevance of the comprehension of drivers' behavior and the validation of their models in driving simulators to improving road safety.

1.1 Study objectives

The main objective of this research is to investigate the effects of geometric characteristics of horizontal curves - radii and approach tangents - on the driving behavior evaluated through speed profiles, lateral position (trajectories), and eye movements in a driving simulator experiment and the way such performance parameters are related to each other. A better comprehension of drivers' behavior is expected to contribute to the identification of local risky behavior, hence, its prediction and anticipation, and to corroborate previous and further studies on road safety and policies improving driving laws and regulations and in-vehicle information systems. Below are the specific objectives of the research:

a) Explore the relationship between speed and lateral position measures with the approach tangents and curve radii;
b) Classify curve trajectories and speed change behavior and investigate the effect of the different levels of approach tangents and curve radii on the behavior's classifications;
c) Investigate the way eye movements and fixations change as drivers approach and navigate through different curve conditions and analyze the differences in eye movements for the proposed classifications; and

d) Verify if the relation between the studied behavioral parameters and the road design features is in line with what is expected from a literature review.
e) This research also aims to demonstrate the effectiveness and advantages of using driving simulators for studies on driving behavior and human factors in view of their great experimental control and no risk to the volunteers' lives.

1.2 Justification

According to the (PRF, 2022), in Brazilian roadways, a total of 14,617 fatalities, from 2010 to 2021, were resulted from runway road, overturning and rollover crashes, which are the crash types that are usually and mainly associated to horizontal curve sections of two-lane rural roadways, and represent an average of 1,220 fatalities per year.

Incidentally, the research is motivated and clearly justified by the large number of accidents that occur in curves, according to accident data of the studied stretch, made available by the federal police, which has human factor as the most cited cause. Therefore, the understanding of local drivers' behavior and the identification of drivers' profiles can significantly contribute to measures that ensure and improve road safety.

Both understanding and modelling of local driver's behavior are necessary for increasing users' trust in automated systems, since the more technology seems to have human-like capacities, the more people tend to rely on it. (Kolekar; De Winter; Abbink, 2020).

1.3 Dissertation structure

This first chapter briefly introduces the studied theme - pointing its relevance and presenting the general and specific objectives such as the justification for conducting the research and Chapter 2 shows the result of the literature review consulted during the master's degree to carry out this document. Chapter 3 and 4 present the materials and methods, and results and discussion of the research paper produced during the research and that analyzes the influence of the geometric characteristics of the road on the driving behavior, through databases obtained in a driving simulator experiment, towards better understanding the behavior of local drivers and contributing to road safety. Finally, chapter 5 closes the dissertation bringing up the main conclusions of the research and suggesting future studies.

2. Background

Evaluations of the effects of curve features on driving performance are fundamental for road safety, warranting researchers' efforts to understand drivers' behaviors on horizontal curves. The influence of the geometric characteristics of the road on the driving behavior, specially through databases obtained in a driving simulator experiment, concerning a better understanding of the drivers' behavior and contributions to road safety have a literature background, which this section presents the ones studied to base the research.

2.1. Road Safety

Security, when it comes to traffic, is evaluated mainly by the number of accidents, that's why its goal is to minimize crashes frequencies, especially of the most serious ones. The Brazilian Ministry of Infrastructure defines road safety as the set of existing methods, actions and standards that is necessary for the safe movement of people and vehicles on streets and highways, to prevent and reduce the risk of accidents.

Although it's common to treat the terms accident and crash as synonymous, it's important to mention that there is a crucial difference between them. The noun accident is defined as an unforeseen and unplanned event or circumstance, implying none's fault, while crash encompasses a wider range of potential causes for vehicular crashes, and it's already agreed that when an "accident" of traffic happens it's caused by a convergence of factors (Stewart & Lord, 2002). Moreover, it is conventional to group these risk factors into three categories associated with the physical components of the traffic system: (i) vehicles, (ii) road and environment, and (iii) humans.

- **Vehicles' shortcomings**: the risk factors associated to vehicles are usually due to lack of maintenance, coming out with critical problems such as badly worn or defective tires, uneven brakes, and faulty suspension/stabilization system (Ferraz et. al, 2012). Another critical point, regarding to the vehicle design, is the existence of blind spots and limited field of vision provided by the rear-view mirrors (Cicchino, 2018).

- **Road and environment risk factors:** the factors that increases the risk of crashes are, for example, rain, snow, strong wind, fog, and smoke (Li et al., 2015; Hamdar et al., 2016; Gao et al., 2019; Vetturi et al., 2020). The ones associated to the roadway are bearing surface defects, inadequate geometric design, such as the existence of small radius curve after long stretch in tangent and/or with smooth curves, sections with incompatible braking or overtaking sight distance with the project speed, and inadequate, insufficient, or deteriorated signaling (De Ceunynck et al., 2015; Agbelie, 2016; Larocca et al., 2018; Scalco et al., 2022).

- **Humans' mistakes risk factors:** in more than 90% of cases the cause of the car crashes is attributable to human error or a combination of it with other factors. Some factors associated to drivers' behavior and negligence are inappropriate speed, ingestion of alcohol, drugs, or medication, excessive tiredness, lack of ability and diversion of attention (Vieira and Larocca, 2017; Farahmand and Boroujerdian, 2018; Xu et al., 2018; Hooft van Huysduynen et al., 2018; Cassarino et al., 2019;).

As seen, multiple studies have investigated these factors, but as long as the number of road accidents keeps concerning and the emergence of new technologies allows new contributions to road safety, studying the road infrastructure and its interaction with human factors will remain an essential field of research to ensure geometric design consistency.

2.2. Horizontal Curves

Drivers intend to operate vehicles at a safe speed based on the roadway's geometric features characterized by gradient, horizontal curvature, curves' length, tangent sections, and superelevation. Curves are the geometric elements of the road alignment characterized by the highest driver's exposure to a crash risk (Nama et al., 2016). The incidence of crashes on horizontal curves in Brazilian highways in 2021 was 22.3%, which seems a small rate at first glance, but that shows its relevance since the extension of the stretches in curves is significantly smaller than the extension of straight segments (CNT, 2022).

The probability of road crashes on horizontal curves is high due to the increase in the strain of both driver and vehicle, which leads to an erroneous judgment of speed and trajectory. Therefore, such crashes require greater efforts for the understanding of drivers' behavior

(Barendswaard et al., 2019; Calvi, 2015; Charly and Mathew, 2020; Choudhari and Maji, 2019; Hallmark et al., 2014; Mauriello et al., 2018; Sil et al., 2019; Suh et al., 2006; Wang and Wang, 2018). When negotiating a curve, a driver must anticipate it and react to it by adjusting speed and lane position towards accommodating its severity and spending more attentional resources than driving on a straight section of a road.

The steps of driving on curved stretches can be grouped into four distinct areas, namely, (i) approach, in which drivers locate a curve and make initial speed adjustments, (ii) discovery, in which they determine the curvature, make additional speed adjustments, and adjust the path for curve entry, (iii) entry and negotiation, in which they adjust speed based on curvature and lateral acceleration and maintain proper trajectory and safe lane position, and (iv) exit, in which they accelerate toward an appropriate speed and adjust lane position to properly follow their path on the straight segment (Campbell et al., 2012).

The curve's radius is one of the most cited geometric parameters as significant for crashes' frequency, which increases as the radius value decreases (Ma and Li, 2010; Schneider, Savolainen and Moore, 2010; Garnaik, 2014). Additionally, the recent studies concerning horizontal curves, especially those of radii with less than 200 meters, showed an increased road accident risk mainly due to inappropriate speed and failure to maintain proper lateral position (Babić & Brijs, 2021). As mentioned before, the road crash types usually associated to horizontal curves are runway road, overturning and rollover crashes, the second e third most common types in 2021 in Brazil, respectively (CNT, 2022).

2.3. Performance parameters

Studies on the association between road design and human factors use performance parameters to measure successfulness in curve negotiation, including speed (Choudhari and Maji, 2019; Montella et al., 2014, 2015; Sil et al., 2019; Wang et al., 2015), lateral position (Charlton, 2007; Montella et al., 2014; Spacek, 2005), lateral acceleration, and drivers' eye movement (Brimley, 2014; Suh et al., 2006). Additionally, research on the relationship among those parameters, mainly speed and lateral position in horizontal curves, has been developed (Fitzsimmons et al., 2013; Hallmark et al., 2014).

2.3.1. Speed

Speed, a primary factor in crash occurrences, is a traditional measure for driving performance along curve negotiation, mainly in terms of operating speed (or operating speed reduction). Several studies have investigated the effect of horizontal curves on vehicle speed reduction, in addition to road safety (Montella et al., 2014; Wang and Wang, 2018; Choudhari and Maji, 2019b; Sil et al., 2019).

Another parameter used for safety evaluation is operating speed differential along successive highway sections, when the maximum and minimum speeds reached by drivers on each curve are extracted from data and its location. Wang and Wang (2018) calculated speed differences and grouped them establishing three speed change behavior classifications, namely substantial speed decrease (SSD), when the speed difference is smaller than -10km/h, steady speed (SS), when the absolute value of speed difference is lower than or equal to 10km/h, and substantial speed increase (SSI), when the speed difference is greater than 10km/h. The authors analyzed the impact of different curve configurations on speed change behavior using multinomial logit models and average marginal effects tests, thus confirming the proposed groups are significantly different.

2.3.2. Lateral position

Successfulness in curve negotiation is also measured as a function of lane-keeping, commonly assessed by lateral position (Spacek, 2005; Charlton, 2007; Mauriello et al., 2018). Some studies focused on understanding the relationship between speed and lateral position on horizontal curves (Fitzsimmons et al., 2013; Hallmark, Hawkins and Smadi, 2014). Furthermore, Barendswaard et al. (2019) found a directly and significantly proportional relation between drivers' maximum prepositioning, a swing left behavior while approaching right curves, and speed, but inversely proportional to curve radii.

Mauriello et al. (2018) analyzed and classified drivers' behavior on horizontal curves of two-lane rural highways regarding trajectories. They used parameters such as mean value of laeral position, standard deviation, among others, and concluded driving trajectories are a good surrogate measure of safety. They also performed a categorical analysis of variance (CATANOVA) to test the hypothesis the proportions of each category in all groups are equal and a non-parametric Bhapkar's test to evaluate the homogeneity for all categories simultaneously.

2.3.3. Lateral acceleration

Lateral acceleration is another performance parameter used in evaluations of curves (Eboli, Mazzulla and Pungillo, 2016; Choudhari and Maji, 2019a; Choudhari and Maji, 2021). Charly and Mathew (2020) demonstrated the combination of driving performance, such as speed measures and mean lateral acceleration with geometric parameters resulted in reliable crashes estimations. Choudhari and Maji (2019a, 2021) resorted to hierarchical clustering to categorize their data into risk levels and the decision tree algorithm to clarify the relation between lateral acceleration and geometric parameters.

2.3.4. Eyes' movements

Analyzing the correlation between the previous parameters and drivers' eye movement, Suh et al. (2006) conducted field experiments to demonstrate the relations among driver behaviors and different geometric and illumination conditions and made suggestions towards increasing highway safety. Regarding eye movements, the authors proposed the "eye-fixation distribution index (EDI)" to indicate the distribution of a subject's eye fixation and the "horizontal width of eye-fixation distribution (HWED)" to represent subjects' visual attention while driving. They also used the "deviation of lateral placement (DLP)" to represent a driver's steering behavior along a given section of highway, and further calculated the maximum speed reduction for each subject.

Torquato (2019) classified drivers' behaviors into levels of aggressiveness through Jerk's minimum values and tested the hypothesis the eye distribution of more aggressive drivers was different than that of less aggressive ones. The author adopted the relation between the standard deviations of the eye tracking in X and Y axles to assess the difference in eye screening. Nevertheless, analysis of variance (ANOVA) did not validate differences in the gaze tracking of the groups.

2.4. Driving simulators

Driving simulators provide researchers with a fully controlled environment and the possibility of monitoring various parameters with no physical risk associated with driving on real roads in road safety and sustainable studies. Moreover, they are efficient tools for the inclusion of human factors. They are particularly relevant and promising for research on traffic; they enable studies of driving behavior in different situations, and their use for analyses of accident aspects in developing countries is a sustainable achievement, since naturalistic studies are not always conducted due to their high costs.

According to Wynne, Beanland and Salmon (2019), the validity of results from driving simulators is strongly associated with their fidelity. However, such a relationship is not direct, since low-fidelity simulators have already shown acceptable validity, whereas some high-fidelity ones have proved invalid. The authors highlighted the existence of several forms of validation, of which absolute and relative validities are highly used. In the former, the results are validated through direct comparisons with real-world data through statistical tests (e.g. in Bella (2008) and Calvi (2018)). Although desirable, this form is not always used, and, in some contexts, a relative validity is acceptable. It is achieved when the results show the same pattern as that of a real environment, according to empirical tests (Bella, 2008; Llopis-Castelló et al., 2016; Hussain et al., 2019).

Another categorization of validation reported in the literature refers to objective and subjective validations, of which the former is achieved by comparing simulated and field data and the latter resorts to drivers' perception. The second type was reported by Hussain et al. (2019), Hooft Van Huysduynen, Terken and Eggen (2018), Larocca et al. (2018), from questionnaires on the experience of driving in a simulator compared with driving in a real environment.

Despite the aforementioned advantages, the use of driving simulators also has some limitations, e.g. psychological ones related to the lack of a reason for the trip, which affects the driver’s behavior, and lower perception of risk, as well as those regarding fidelity of sound, visual, and movement stimuli. (Andersen, 2011; Greenberg and blommer, 2011; Ranney, 2011). Moreover, some drivers experience nausea - usually referred to as simulation sickness - during the experiment, as reported by Hussain et el. (2019), Hooft Van Huysduynen, Terken and Eggen (2018), Ariën et al. (2017), and Llopis-Castelló et al. (2016).

As addressed elsewhere, this study is a continuation of a previous one conducted by Torquato (2019). The database analyzed was generated in a controlled experiment performed in a driving simulator equipped with an eye-tracking system that enables the analysis of drivers' behavior under different geometric conditions of the road. The validation of the simulation experiment was subjective, by applying immersion to the simulation questionnaires where the drivers assigned high scores regarding the sensation of great immersion in the virtual environment (Torquato, 2019).

Following the assumption behavioral parameters are significantly distinct in different road stretches, the main objective of the research is to investigate drivers' performance and the effects of geometric characteristics of horizontal curves (i.e., radii and approach tangents) on their behavior evaluating speed profiles, lateral position, and eye movements. No participant reported sickness during the experiment.

3. 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 adopted for the analysis.

3.1 Participants

Data were extracted from files of the simulation of Vires Virtual Test Drive® (VIRES Simulationstechnologie GmbH, 2018) and Smart-Eye Recorder® ("Smart Eye Recorder," 2020) devices conducted with 28 volunteers (19 men and 9 women) of 26.61 years average age (SD = 4.07 years) that ranged from 20 to 38 years. The average driving experience was 7.52 years (SD = 3.97 years).

3.2 Apparatus

An instrumented driving simulator equipped with an eye-movement tracking system (Pro 5.10® Smart Eye) was used in the experiment (Figure 1). It comprises three front cameras that perform the driver's eye-tracking and an additional rear camera that records the scenes seen by the drivers. This was done by recording eye movements through the direction of the gaze, head position, eyelid opening, blinks, attachment points, pupil size, and other monitoring and measurement. Data on the eyes' movements of 23 subjects were recorded during the experiment. The simulated environment was projected on a 1.40 x 0.80 m flat panel of 1080p resolution and 60 Hz projection rate, which also projects rear and lateral mirrors and the speedometer. Speakers reproduce sounds similar to vehicle engines and traffic environments to enhance participants' immersion with visual and auditory stimuli.

Figure 1. Driving simulator used in the experiments

3.3 Experimental road

The scenario is based on a Brazilian highway covering 10 kilometers with 20 horizontal curves. Transition curves were designed for creating a smooth change between tangents and circular curves. The road has three lanes with a total separation of flows and an 80 km/h speed limit. The lower and upper extreme values of the actual curve radius and approach tangent lengths and their average were taken from the 20 curves in an existing stretch, leading to three different levels for each factor and nine conditions or treatments, as shown in Table 1. The abbreviations for the treatments, provided in the first column of the table, refer to combinations of radius (R) and tangent (T) lengths at different levels, namely small (s), medium (m), and large (l) (Torquato, 2019).

The experiment considered free-flow conditions, and the direction of the curves, which was randomized, was assumed not to influence drivers' behavior, since there was no opposite flow. A 56º deflection angle (i.e., an intermediate value of the actual stretch), a flat grade, and three 3.6 m wide lanes and 1.0 m shoulder on both sides were adopted.

Table 1. Geometric data of the curves

Treatments	Length (m)	Deflection angle (degrees)	Radius (m)	Approach tangent (m)	Number of observations
Rs-Ts	182.17	56	125	50	56
Rs-Tm	421.63	56	125	310	56
Rs-Tl	661.09	56	125	570	56
Rm-Ts	182.17	56	370	50	56
Rm-Tm	421.63	56	370	310	56
Rm-Tl	661.09	56	370	570	56
Rl-Ts	182.17	56	615	50	56
Rl-Tm	421.63	56	615	310	56
Rl-Tl	661.09	56	615	570	56
Total					504

The treatments were randomly ordered until there was no overlap in creating the scenario, which contained different sequences of curves (i.e., sequences of the nine treatments shown in Table 1). Each volunteer drove through two of the nine possible sequences, covering 18 kilometers and encountering 18 curves. The sequences were carefully randomized towards avoiding drivers' familiarity with the scenario and simulation experience, which might influence their performance.

3.4 Database

Driving simulator data were collected from each driver at a 60 Hz sampling frequency and treated with Python 3.0 programming language. The initial treatment consisted in the reading of each driver's file and identification of variables of interest, i.e., those helpful for the study (e.g., simulation time, inertial vehicle coordinates on the track, instant vehicle speed, among others), out of 70 possible ones.

The identification of treatments was necessary for the database lines. Therefore, a separate database contained coordinates related to both beginning and end of each curve and tangent of the complete scenario, divided into tangent, entry, and exit spirals and circular sector and their classifications (small, medium, or large). A code identified the treatment and its classification for all lines through the crossing and comparison of the coordinates of the databases.

The main database file, extracted from the simulator experiments, contains 504 lines resulting from the 28 participants driving through the nine combined treatments twice. Besides the characteristics of both drivers and treatments, each line comprises speed and lateral placement data such as mean value, standard deviation, maximum and minimum values, and maximum difference, among others. The statistical analyses presented in what follows were performed by IBM SPSS 24.0® (IBM, 2016).

3.5 Data Analysis

The analysis of variance (ANOVA) with repeated measures investigated the effects of the geometric characteristics of curves, radii, and approach tangents on the driving speed profiles, trajectories, and eye movements. Since the correct application of ANOVA tests required the verification of a few assumptions (e.g., normal distribution of responses, homogeneity of variances between groups, and independence of observations), the data were previously subjected to Kolmogorov–Smirnov test, which checked if they were normally distributed. They were also subjected to Levene's test, which verified the homogeneity of variance. Since the experiment adopted repeated measures, the hypothesis of independence between the responses under different conditions would be violated. An additional sphericity assumption was necessary to circumvent that failure, and Mauchly test evaluated it (Field, 2011).

- Description of variables:
    - Dependent variables: driving speed, lateral placement, and eye movement information such as number of fixations, fixations' duration, pupil diameter, and gaze direction.
    - Independent variables: approach tangent lengths and curve radii.
- Factorial ANOVA is an analysis of variance involving two or more independent variables, as in our experiment.
- ANOVA with repeated measures consists of an analysis of variance conducted in any design. The independent (predictor) variables were measured using the same subjects under all conditions, as in our experiment. F-statistic from a repeated measures ANOVA is reported as F (df, dferror) = F-value, p = p-value. The first degree of freedom (df) is calculated as the number of conditions minus one, and the second is the product of the first with the number of subjects minus one. The following formula explains the F-ratio:

$$F = \frac{explained\ variance}{unexplained\ variance} = \frac{MS_{conditions}}{MS_{error}} \qquad (1)$$

where MS is the mean squared error or the mean variability in the data.

- The following tests checked whether the assumptions for proceeding with ANOVA with repeated measures had not been violated:
    - Kolmogorov-Smirnov, which evaluates if the distribution of scores is significantly different from a normal one. A significant p-value indicates a deviation from normality.
        - Friedman's ANOVA, which is a non-parametric test also known as the non-parametric version of the one-way repeated measures ANOVA. It compares multiple conditions when the same subjects participate in each condition. The resulting data are not normally distributed.
    - Levene's test, which checks if the variances of a group are significantly different, therefore, a non-significant result indicates the hypothesis has been satisfied.
    - Mauchly test, which assesses the hypothesis the variances of differences between conditions are equal. A significant Mauchly's statistical test (i.e., when it has a probability value less than 0.05), indicates that there are significant differences between the variances of the differences; therefore, the sphericity condition was violated.
        - Greenhouse-Geisser correction, which estimates the distance from sphericity and corrects the degrees of freedom associated with the corresponding F ratio when Mauchly test causes the sphericity condition to be violated.

4. Results and Discussion

4.1 Driving speed

Table 2 shows the summaries of driving speeds in terms of average values and standard deviations for the combination of approach tangent lengths and curves radii, and the significance values of Kolmogorov-Smirnov (K-S) normality test after the removal of visible outliers. Such a removal was justified by the rigorous analysis of the recording footage of the experiment, which revealed the values of the average speed of the outliers did not match the real ones achieved by the drivers and were considered data recording errors. All curve configurations – except the smaller radius with a large approach tangent curve – showed significant results for normal distribution.

Table 2. Driving speed descriptive statistics and normality test for each treatment

Curve configuration		Radius (m)	Approach tangent (m)	Speed (km/h)		K-S
				Average	SD	p-value
1	Rs-Ts	125	50	77.10	1.38	0.20
2	Rs-Tm	125	310	80.79	1.34	0.20
3	Rs-Tl	125	570	82.93	1.31	0.03*
4	Rm-Ts	370	50	96.05	1.61	0.20
5	Rm-Tm	370	310	96.06	1.79	0.20
6	Rm-Tl	370	570	94.00	1.83	0.20
7	Rl-Ts	615	50	101.03	1.41	0.20

Figure 2 displays the treatment boxplots after the removal of outliers. The average speed can be assumed to increase with the increase in the curve radii. The variation in the length of the tangents exerted no apparent effect on the average speed between groups and, as expected, the driving speed developed by volunteers was close to the design equilibrium speed of the curves, since driving below or above the equilibrium speed would impact the safety performance of the curve negotiation.

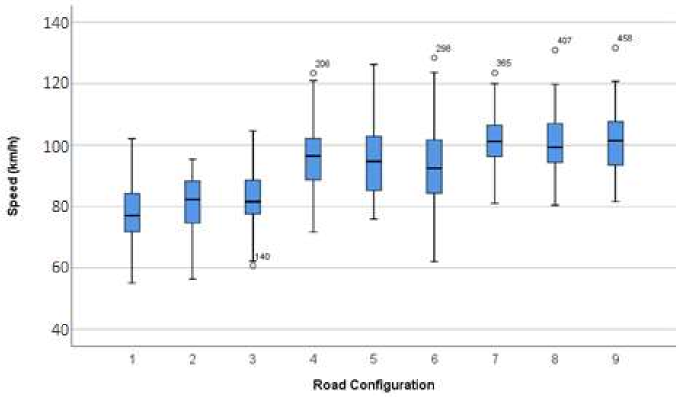


Figure 2. Treatment boxplots

Factorial ANOVA with repeated measures checked the effect of curve radii and approach tangents length on the average driving speed along the curves. Levene's test revealed the homogeneity of the variances was not significantly different across groups F (8, 469) = 1.373, p>0.05 and Mauchly test indicated the sphericity hypothesis was not violated for the main effect of curve radii and approach tangent and was significant for their interaction (χ^2 (9) = 18.37, p <0.05).

Therefore, the degrees of freedom were corrected by Geisser-Greenhouse spherical estimates (ε = 0.58), which also revealed a significant main effect of curve radii F (2, 469) = 145.55, p<0.001, Partial Eta Squared = 0.383, and observed power = 1.000, and a non-significant one for approach tangents F (2, 469) = 0.617, p=0.540, Partial Eta Squared = 0.003, and observed power = 0.153. ANOVA showed the interaction effect between radii and approach tangent was not significant - F (3.466, 173.28) = 2.894, p=0.055, Partial Eta Squared = 0.055, and observed power = 0.729.

Bonferroni correction was performed for multiple comparisons. Regarding the main effect of curve radii, a pairwise comparison based on post-hoc tests indicated the average speeds recorded for each level were significantly different. As expected, the lowest speeds were recorded on curves with smaller radii (80.29 km/h), followed by medium curves with a 95.37 km/h average speed. This was significantly higher than that of the first group (average difference = 15.07 km/h, p<0.001) and lower in comparison with those of larger radii and 100.91 km/h average speed (average difference = 5.54 km/h, p<0.001). Calvi (2015) reported the average speed increases on curves with a wider radius, which is aligned with our results.

The operation of speed difference along subsequent highway sections is another parameter widely used in safety evaluations (Choudhari & Maji, 2019; Llopis-Castelló et al., 2018; Wang & Wang, 2018). The maximum and minimum speeds reached by the drivers on each curve were extracted from the experiment data for the calculation of maximum speed reduction. If drivers reached the minimum speed on the curve before reaching the maximum, the speed difference assumed a positive value. On the other hand, i.e., if they reached their maximum speed before the minimum one, the speed difference was negative.

The calculated speed differences were grouped into three categories, namely substantial speed decrease (SSD) - for speed difference values lower than -10 km/h, steady speed (SS) - for an absolute value of speed difference lower than or equal to 10 km/h, and substantial speed increase (SSI) - for speed differences larger than 10 km/h. Wang and Wang established such a speed change behavior. Table 3 shows the incidence of the speed change classification for the curves; according to the results, SSD was the most common behavior, with a higher proportion for curves with small and medium radii - those with large radius displayed a more evenly distributed speed change behavior.

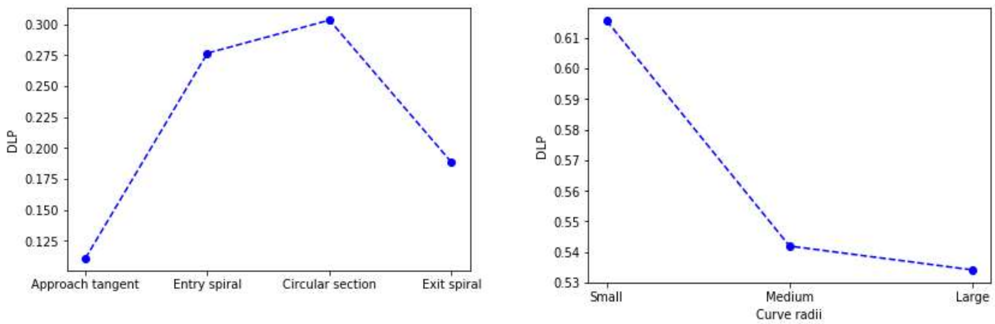
Table 3. Speed change behavior per curve configuration

Curve configuration	**Speed change behavior**					
	SSD		**SS**		**SSI**	
Rs-Ts	32	(61.54%)	16	(30.77%)	4	(7.69%)
Rs-Tm	44	(83.02%)	4	(7.55%)	5	(9.43%)
Rs-Tl	48	(94.12%)	2	(3.92%)	1	(1.96%)
Rm-Ts	22	(44.90%)	13	(26.53%)	14	(28.57%)
Rm-Tm	29	(63.04%)	9	(19.57%)	8	(17.39%)
Rm-Tl	40	(80.00%)	8	(16.00%)	2	(4.00%)
Rl-Ts	14	(28.00%)	16	(32.00%)	20	(40.00%)
Rl-Tm	16	(31.37%)	11	(21.57%)	24	(47.06%)
Rl-Tl	31	(60.78%)	11	(21.57%)	9	(17.65%)
Total	276	(60.93%)	90	(19.87%)	87	(19.21%)

4.2 Lateral placement

The vehicle's lateral position (LP) was calculated as the distance from the vehicle's center of gravity to the central road axis, i.e., the middle of the three lanes. A vector cross product identified the side of the vehicle position, i.e., on the right or the left of the track axis - the lateral position assumes a positive value if the vehicle is on the right side of the lane axis and a negative one if it is on the left side. A code identified the traffic lane on which the vehicle was driving and the moments when it was crossing or drifting on the lanes.

Suh et al. (2006) defined Deviation of Lateral Placement (DLP) as an index representing a driver's steering behavior along a given section of a highway. It can be interpreted as a standard deviation of an individual vehicle's lateral placement along a given highway section that shows a vehicle's overall lateral stability. The analysis of the standard deviation of lateral position revealed a higher value in the circular section than in other stretches, as seen in Figure 3(a), implying driving in curvy sections of a road is more challenging. Furthermore, curves with small radii resulted in a significantly greater mean DLP value, Figure 3(b), consistent with the fact the smaller the radius, the more complex the stability maintenance during curve negotiations.



(a) (b)

Figure 3. Deviation of lateral placement per curve section and curve radius

Similarly to the speed data, those on the deviation of lateral position per curve configuration group were subject to Kolmogorov-Smirnov test, which checked whether they were normally distributed. The significant results shown with p-values ($p<0.05$) in Table 4 revealed the homogeneity hypothesis had been violated.

Table 4. Deviation of lateral placement descriptive statistics and normality test

Curve configuration		Radius (m)	Approach tangent (m)	DLP (m)		K-S
				Average	SD	p-value
1	Rs-Ts	125	50	0.20	0.13	0.015*
2	Rs-Tm	125	310	0.32	0.22	0.013*
3	Rs-Tl	125	570	0.32	0.22	0.006**
4	Rm-Ts	370	50	0.27	0.20	0.000***
5	Rm-Tm	370	310	0.34	0.31	0.000***
6	Rm-Tl	370	570	0.29	0.25	0.000***
7	Rl-Ts	615	50	0.30	0.21	0.000***
8	Rl-Tm	615	310	0.35	0.34	0.000***
9	Rl-Tl	615	570	0.33	0.25	0.000***

*: $P \leq 0.05$, **: $P \leq 0.01$, ***: $P \leq 0.001$

Since Kolmogorov-Smirnov test indicated deviations in data normality for all curve configurations, Friedman's ANOVA, a non-parametric test for several related samples, examined the effect of curve radii and approach tangent length on the deviation of lateral position (DLP), revealing a significant difference across the treatment groups (χ^2 (8) = 35.06, p <0.001).

4.2.1 Driver's classification on curve trajectories

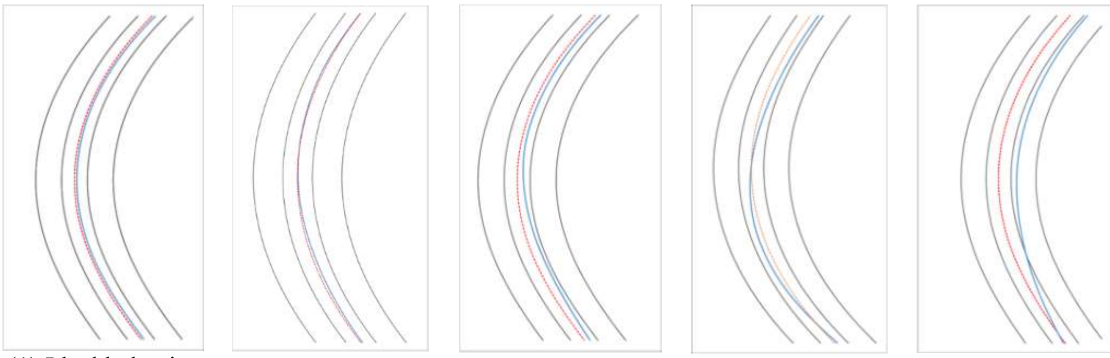
Several combinations of lateral position parameters (e.g., mean value, standard deviation, maximum and minimum values, maximum absolute value, maximum absolute difference, and maximum value of lateral acceleration, calculated as the relation between squared vehicle speed and curve radius) provided vehicle trajectories classifications, as shown in Table 5. The curve path classifications and the boundary values for the parameters were adapted from a literature review conducted by (Mauriello et al., 2018). The path was a three-lane highway with a total separation of flows instead of a two-lane rural highway.

Table 5. Criteria for the classification of driving behavior

Class		Approach tangent	Curve	Total
1. Ideal behavior		$\|LP\|max \leq 0.65$ or $2.95 \leq \|LP\|max \leq 4.25$ $\sigma_{LP} \leq 0{,}35$	$\|LP\|max \leq 0.55$ or $3.05 \leq \|LP\|max \leq 4.15$ $\sigma_{LP} \leq 0{,}20$	
2. Normal behavior		$\|LP\|max \leq 0.9$ or $2.7 \leq \|LP\|max \leq 4.5$ $\sigma_{LP} \leq 0{,}40$ $\|\Delta LP\|max \leq 1.2$	$\|LP\|max \leq 0.9$ or $2.7 \leq \|LP\|max \leq 4.5$ $\sigma_{LP} \leq 0{,}35$ $\|\Delta LP\|max \leq 1.2$	$\sigma_{LP} \leq 0{,}50$
3. Intermediate behavior	3.1 Driving close to the centerline	$\|LP\|max \leq 1.0$ or $2.6 \leq \|LP\|max \leq 4.6$ $\sigma_{LP} \leq 0{,}40$ $\|\Delta LP\|max \leq 1.1$	$\sigma_{LP} \leq 0{,}30$ LPmean > 0.5	
	3.2 Driving outside in curve approach	$1.0 < \|LP\|max < 2.6$ or $\|LP\|max > 4.6$	$\|LP\|max \leq 1.0$ or $2.6 \leq \|LP\|max \leq 4.5$ $\sigma_{LP} \leq 0{,}35$ LPmean ≤ 0.5	
4. Cutting	4.1 Right curves lane 1 lane 2 lane 3	 LPmin < -3.70 LPmin < -0.10 LPmin < 3.50	 LPmax > -3.2 LPmax > 0.40 LPmax > 4.00	
	4.2 Left curves lane 1 lane 2 lane 3	 LPmax > -3.50 LPmax > 0.10 LPmax > 3.70	 LPmin < -4.00 LPmin < -0.40 LPmin < 3.20	
5. Correcting behavior	5.1 in approach	$\sigma_{LP} > 0{,}30$ alat_max > 4m/s²	-	
	5.2 on the curve	-	$\sigma_{LP} > 0{,}30$ alat_max > 4m/s²	
	5.3 multiple corrections	Combination of behaviors 5.1 and 5.2		

The following five major classes were defined: (1) Ideal behavior, which represents trajectories almost perfectly parallel to any of the lanes' axis, (2) Normal behavior, which is similar to the previous one, but with greater values for the classification criteria, representing a behavior with no significant errors, (3) Intermediate behavior, characterized by a significant offset toward either the centerline, or the outside in the approach section, (4) Cutting, which represents a conscious driving maneuver to balance centrifugal acceleration by following a trajectory with a radius greater than the geometric one, and (5) Correcting behavior, an unconscious track behavior displayed due to an underestimation or overestimation of road curvature. Trajectories not included in such classes were classified as "others".

Figure 4 shows examples of the trajectories' classifications extracted from different drivers' files (gray lines represent road edges, red line is the middle line axle, and the blue one is the vehicle's center of gravity path).



(1) Ideal behavior (2) Normal behavior (3) Intermediate behavior (4) Cutting (5) Correcting behavior

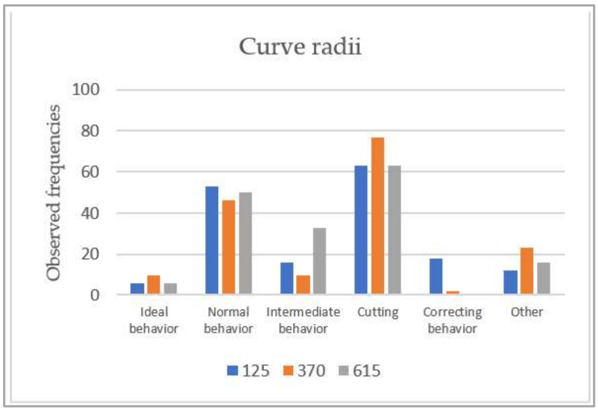
Figure 4. Examples of different driving behavior paths

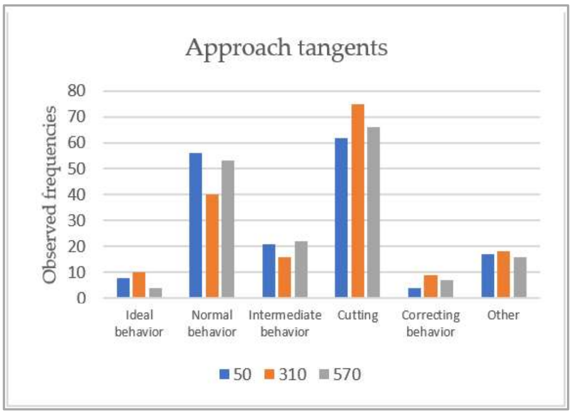
As expected from the literature review, the curve trajectory classification resulted in a small proportion of ideal behavior (4.37%). Cutting was the most common behavior, observed in 40.28% of trajectories, followed by normal and intermediate behaviors, with 29.56% and 11.71%, respectively. Correcting behavior was the least common result and the most dangerous one, displayed in 3.97% of the instances. Curve trajectories classified as "others" were also quite common (10.12%), suggesting the classification criteria can be improved.

Table 6 shows the proportion of the different classes of trajectory disaggregated concerning approach tangents length and curve radii. Pearson chi-square test revealed a significant association between curve radius and trajectories classification results, χ^2 (10) = 51.204 ($p<0.001$); however, it accepted the null hypothesis of non-association between approach tangent lengths and trajectories classification χ^2 (10) = 9.837 ($p=0.455$). The testing of the association between the trajectories behaviors with the nine curve configurations classes resulted in lower limits of expected frequencies to rely on Pearson chi-square test.

Table 6. Disaggregated proportions of driving behaviors

Behavior	Ts			Tm			Tl			Total		
	Rs	Rm	Rl	Rs	Rm	Rl	Rs	Rm	Rl	Rs	Rm	Rl
1 Ideal behavior	5.36	3.57	1.79	5.36	7.14	5.36	3.57	7.14	0.00	3.57	5.95	3.57
2 Normal behavior	41.07	28.57	25.00	30.36	21.43	30.36	28.57	21.43	39.29	31.55	27.38	29.76
3 Intermediate behavior	7.14	3.57	17.86	10.71	1.79	5.36	19.64	23.21	16.07	9.52	5.95	19.64
4 Cutting	32.14	44.64	35.71	41.07	50.00	46.43	37.50	39.29	35.71	37.50	45.83	37.50
5 Correcting behavior	7.14	14.29	10.71	0.00	1.79	1.79	0.00	0.00	0.00	10.71	1.19	0.00
6 Others	7.14	5.36	8.93	12.50	17.86	10.71	10.71	8.93	8.93	7.14	13.69	9.52
Total	100	100	100	100	100	100	100	100	100	100	100	100





(a) **(b)**

Figure 5. Driving behavior frequencies per curve radius (a) and approach tangent (b).

The trajectories were grouped into three macro-classes for a better visualization of the effect of different approach tangent lengths and curve radii on curve negotiation. The safest curve negotiation behavior was G1 and included ideal and normal behaviors; macro-class G2 represents the intermediate behavior, and G3 included cutting and correcting behaviors representing the most dangerous behavior.

According to Figure 6, the safest behavior (G1) was more evident in the small approach tangent and radius combination, explained by the higher concentration level demanded on this type of curve. As expected, it was followed by medium and large radii combined with a large approach tangent, since the negotiation of wider curves tends to be easier. Intermediate behavior (G2) is slightly more frequent on curves with large radii. Concomitantly, the incidence of the most dangerous one (G3) significantly decreases in function of curve radius, which is consistent with crash statistics that show a notably higher crash rate on small radii curves.

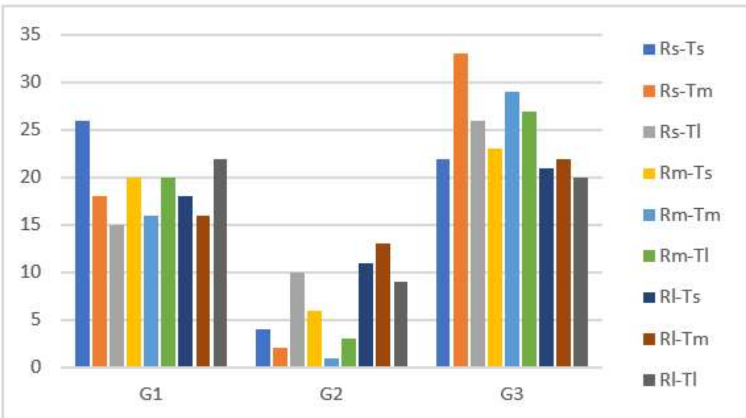


Figure 6. Classification of macro-classes trajectories per curve configuration

Pearson chi-square test showed a significant association between the combination of curves radii and approach tangents length with the macro classification results, χ^2 (24) = 33.235 ($p < 0.05$).

The results revealed trajectories as an emerging safety indicator on horizontal curves, since a significant correlation was found between the trajectories identified as dangerous and the radii of the curves. The understanding of local driver behavior and identification of driver profiles can significantly contribute to measures for ensuring and improving road safety; besides, the use of a driving simulator has been highly advantageous for such studies. Research has demonstrated different ways to analyze driving performance, evidencing analyses can be shared or replicated, raising reflections upon proposals of regulatory changes by road managers, whether private or governmental agencies.

4.3 Eye-movements data analysis

This section addresses pertinent statistical analyses for a better comprehension of variables to be used and that suit the assumption driver's eye movements differ on curves with distinct geometric characteristics. It also discusses the results and their agreement with what is expected.

The variables extracted from the simulation experiment by Pro 5.10® Smart Eye equipment were number of fixations, their durations, pupil size, and gaze directions regarding the driver's visual attention. They were assessed in two different ways, i.e., calculated as the polygon area formed by the drivers' gaze dispersion for each curve configuration and adopting the relation between the standard deviations of the eye-tracking in the X and Y axes.

4.3.1 Fixations

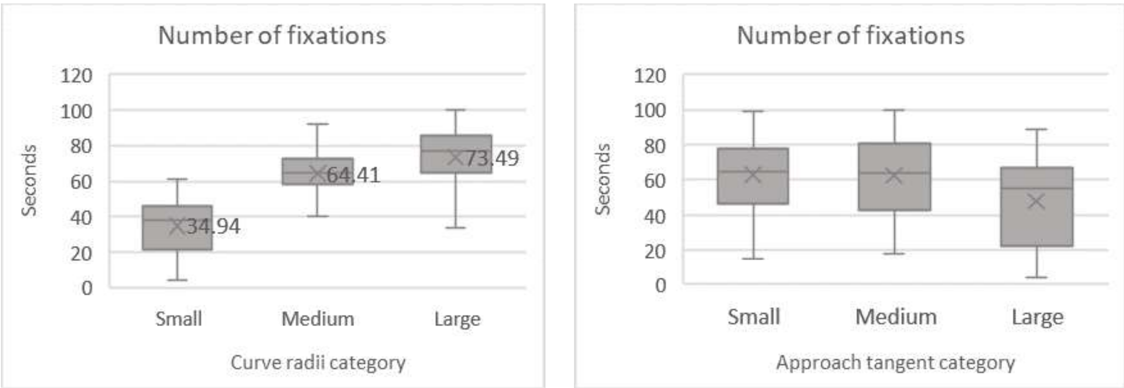
The number of fixations was calculated for each subject in both runs and for the nine possible curve configurations (see Table 7 for the mean results). Kolmogorov-Smirnov test indicated deviations in data normality for most curves' configurations. According to the boxplots, the number of fixations is directly proportional to the curve radius increase (Figure 7(a)) and differs among the studied approach tangent lengths, mainly for the largest one compared to the others. Such significant differences were confirmed by non-parametric test

Friedman's ANOVA, which revealed relevant effects on the average number of fixations of the curve's radii (χ^2 (2) = 120.139, p <0.001) and approach tangents (χ^2 (2) = 76.712, p <0.001).

Table 7. Number of fixations descriptive statistics and normality test

Curve configuration		Radius (m)	Approach tangent (m)	Number of fixations		K-S
				Average	SD	p-value
1	Rs-Ts	125	50	44.34	10.87	0.077
2	Rs-Tm	125	310	41.22	9.01	0.126
3	Rs-Tl	125	570	19.26	4.99	0.002**
4	Rm-Ts	370	50	64.39	12.04	0.000***
5	Rm-Tm	370	310	71.39	14.98	0.000***
6	Rm-Tl	370	570	57.43	11.57	0.000***
7	Rl-Ts	615	50	79.65	16.44	0.000***
8	Rl-Tm	615	310	74.34	18.44	0.000***
9	Rl-Tl	615	570	66.48	15.80	0.000***

**: P ≤ 0.01, ***: P ≤ 0.001



(a) **(b)**

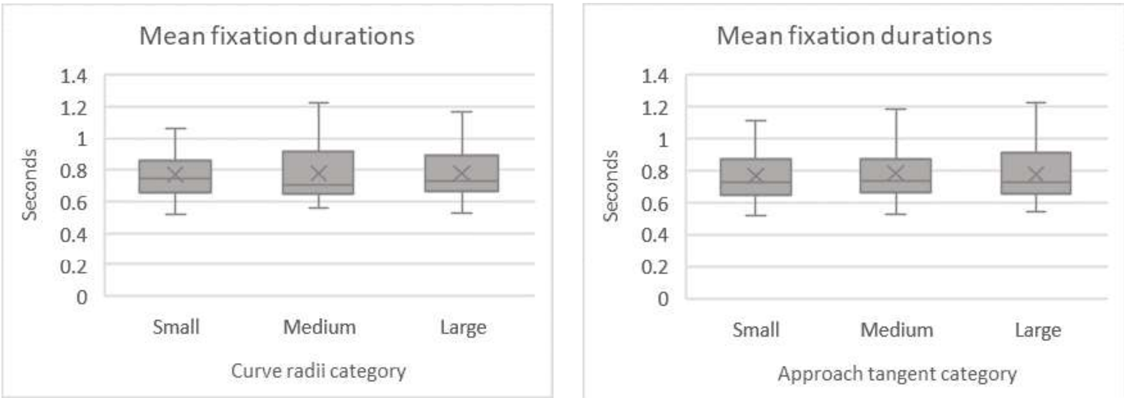
Figure 7. Mean number of fixations per curve radius (**a**) and approach tangent (**b**).

Similarly, non-parametric test of Friedman's ANOVA compared the average duration of the fixations during driving throughout the different curve configurations for the mean fixation duration. Kolmogorov-Smirnov test revealed the homogeneity hypothesis had been violated. The boxplots show no clear differences and, accordingly, Friedman's ANOVA retained the null hypothesis the mean fixations durations did not change across the radii of the curves (χ^2 (2) = 1.246, p =0.536) and approach tangents groups (χ^2 (2) = 2.094, p =0.351).

Table 8. Mean fixation duration descriptive statistics and normality test

Curve configuration		Radius (m)	Approach tangent (m)	Fixation duration (s)		K-S
				Average	SD	p-value
1	Rs-Ts	125	50	0.752	0.137	0.200
2	Rs-Tm	125	310	0.764	0.146	0.000***
3	Rs-Tl	125	570	0.793	0.152	0.011*
4	Rm-Ts	370	50	0.778	0.171	0.003**
5	Rm-Tm	370	310	0.792	0.198	0.011*
6	Rm-Tl	370	570	0.767	0.169	0.021*
7	Rl-Ts	615	50	0.773	0.142	0.000***
8	Rl-Tm	615	310	0.796	0.166	0.002**
9	Rl-Tl	615	570	0.772	0.162	0.000*

*: $P \leq 0.05$, **: $P \leq 0.01$, ***: $P \leq 0.001$



(**a**) (**b**)

Figure 8. Mean fixation durations per curve radius (**a**) and approach tangent (**b**).

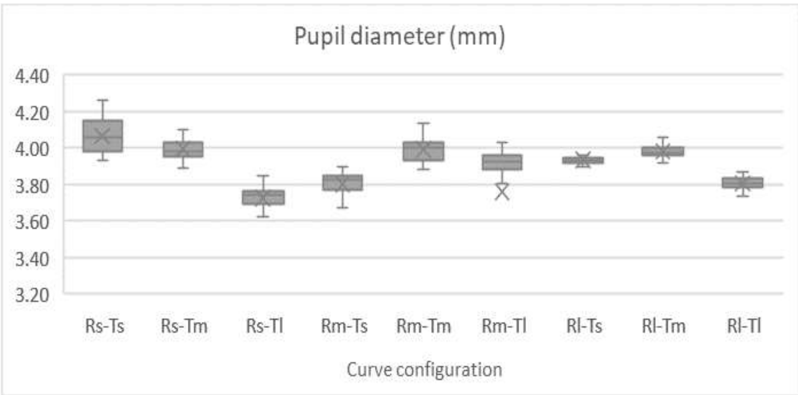
4.3.2 Pupil diameter analysis

Pupil diameter, another eye measurement recorded during the experiment, is strongly connected with the driver's cognitive abilities. Kolmogorov-Smirnov test indicated deviations in data normality, pointing to Friedman's ANOVA for examinations of the effect of curve's configurations on drivers' pupils' sizes. Analyses of the curve radii and the approach tangent lengths revealed significant differences between the observed mean pupil diameters (χ^2 (2) = 14.174, p<0.001) and (χ^2 (2) = 29.656, p<0.001), respectively.

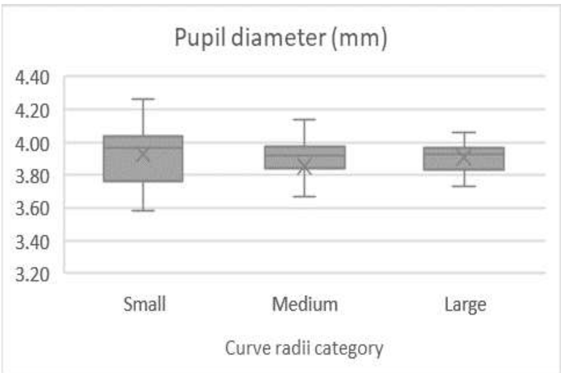
Table 9. Pupil size descriptive statistics and normality test

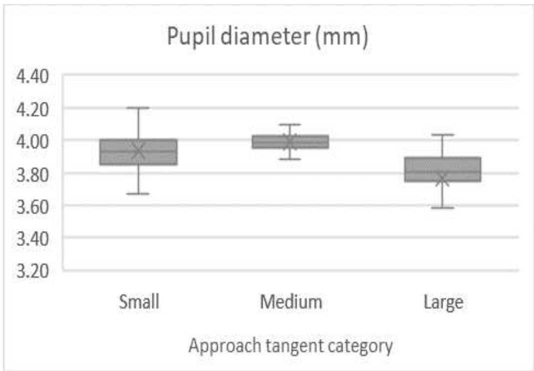
Curve configuration		Radius (m)	Approach tangent (m)	Pupil diameter (cm)		K-S
				Average	SD	p-value
1	Rs-Ts	125	50	0.418	0.023	0.200
2	Rs-Tm	125	310	0.403	0.018	0.005**
3	Rs-Tl	125	570	0.382	0.011	0.004**
4	Rm-Ts	370	50	0.363	0.018	0.000***
5	Rm-Tm	370	310	0.407	0.011	0.200
6	Rm-Tl	370	570	0.403	0.024	0.000***
7	Rl-Ts	615	50	0.382	0.009	0.000***
8	Rl-Tm	615	310	0.398	0.015	0.005**
9	Rl-Tl	615	570	0.393	0.027	0.000***

**: $P \leq 0.01$, ***: $P \leq 0.001$



(a)





(b) **(c)**

Figure 9. Mean pupil diameter per curve configuration (**a**), radius (**b**), and approach tangent (**c**).

Bonferroni correction adjusted significance values. Regarding the main effect of curve radii, a pairwise comparison based on post-hoc tests indicated the average pupil diameter recorded for the small level was significantly different from the others ($p<0.05$), whereas the difference between medium and large radii was not ($p=1.000$). Similarly, the pairwise comparison conducted for the main effect of approach tangents indicated the average pupil diameter recorded for the small level was significantly different from the others ($p<0.001$). In contrast, the difference between medium and large approach tangents was insignificant ($p=0.993$). As expected, since the higher the pupil diameter, the higher the attention devoted to the task, higher pupils' diameters were recorded on curves with smaller radii and approach tangent (0.418 cm).

4.3.3 Gaze analysis

Gaze direction was widely explored for driver's visual attention. Figure 10 shows a comparative search spread between the studied curve configurations for two participants.

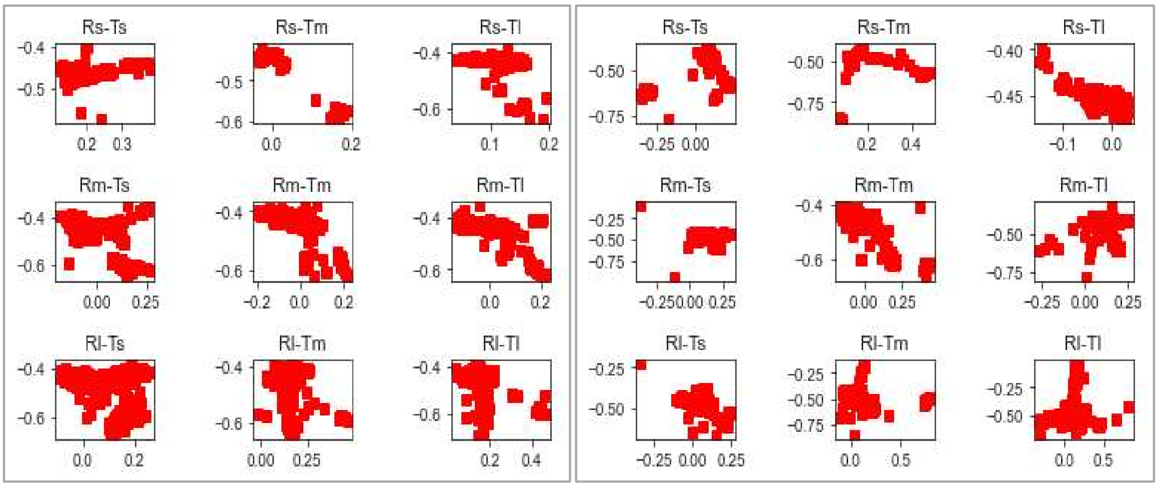


Figure 10. Spread of search per curve configuration for two subjects

The calculation of the polygon's area shape, which are shown in the following sequence of images, was used by the extreme points of the scatter graphs of each participant for the different curve configurations towards evaluations of the effect of curves radii and approach tangent lengths on the drivers' visual attention.

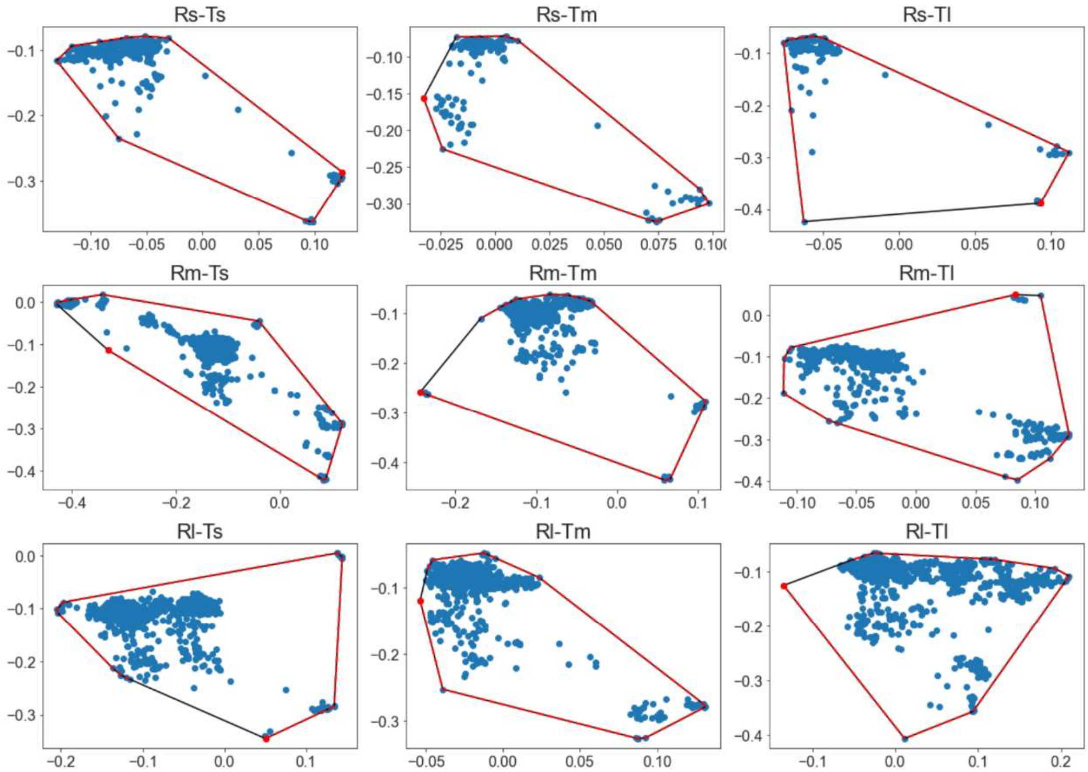


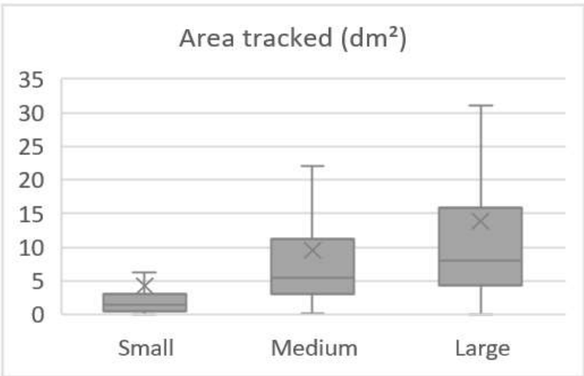
Figure 11. Gaze distributions areas

Friedman's ANOVA test compared the areas tracked during driving in the different curve configurations. Kolmogorov-Smirnov revealed data were not normally distributed, as shown in the following table and according to the average areas tracked. The significance of differences was statistically proved by the test, which showed (χ^2 (8) = 156.664, p<0.001). In general, the average areas tracked increased with radius and approach tangent increase. A smaller spread of drivers' field of view is related to their greater focus while performing the curves, indicating the result is in line with the literature, since shorter curves and tangents tend to demand more attention from drivers.

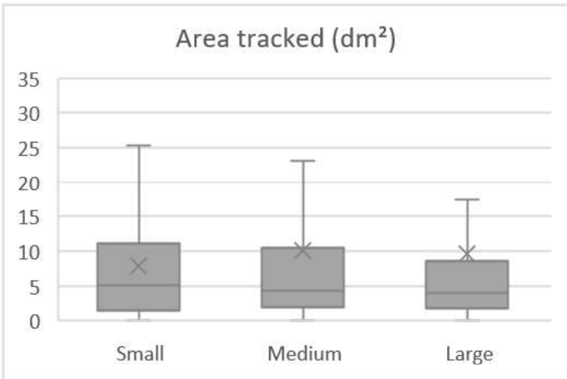
Table 10. Area tracked descriptive statistics and normality test

Curve configuration		Radius (m)	Approach tangent (m)	Area (m²)		K-S
				Average	SD	p-value
1	Rs-Ts	125	50	0.030	0.033	0.000***
2	Rs-Tm	125	310	0.040	0.073	0.000***
3	Rs-Tl	125	570	0.056	0.241	0.000***
4	Rm-Ts	370	50	0.090	0.087	0.007**
5	Rm-Tm	370	310	0.091	0.113	0.000***
6	Rm-Tl	370	570	0.121	0.192	0.000***
7	Rl-Ts	615	50	0.126	0.136	0.000***
8	Rl-Tm	615	310	0.167	0.316	0.000***
9	Rl-Tl	615	570	0.124	0.147	0.000***

**: $P \leq 0.01$, ***: $P \leq 0.001$



(**a**)



(**b**)

Figure 12. Mean area tracked per curve radius (**a**) and approach tangent (**b**)

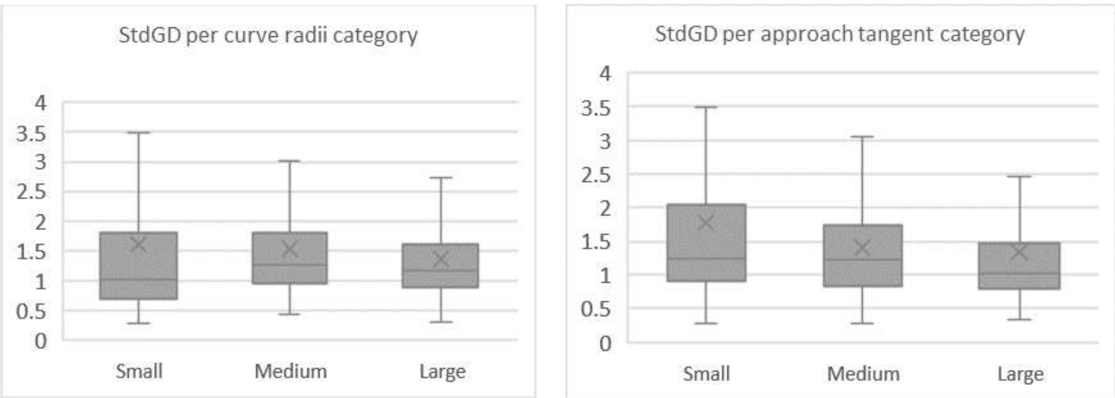
Similarly, the average results from the relation of the standard deviation of the gaze distributions from axes X and Y (StdGD Index) were not normally distributed, according to Kolmogorov–Smirnov test (Table 11). Friedman's ANOVA revealed the index significantly changes between the studied curve configurations (χ^2 (8) = 22.483, p = 0.004).

Table 11. Deviation of gaze distributions index descriptive statistics and normality test

Curve Configuration		Radius (m)	Approach Tangent (m)	StdGD		K-S
				Average	SD	*p*-Value
1	Rs-Ts	125	50	2.07	3.60	0.000 ***
2	Rs-Tm	125	310	1.42	0.92	0.000 ***
3	Rs-Tl	125	570	1.36	1.02	0.000 ***
4	Rm-Ts	370	50	1.69	0.87	0.023 *
5	Rm-Tm	370	310	1.41	0.65	0.004 **
6	Rm-Tl	370	570	1.51	1.31	0.000 ***
7	Rl-Ts	615	50	1.56	0.81	0.009 **
8	Rl-Tm	615	310	1.39	0.75	0.045 *
9	Rl-Tl	615	570	1.13	0.59	0.000 ***

*: $p \le 0.05$, **: $p \le 0.01$, ***: $p \le 0.001$.

The boxplots in Figure 13 show the index value reduced with the increase in the approach tangent length; however, no clear relation between the index and the curve radius is observed. Evaluating the main effects of curve radii and approach tangents lengths separately for the StdGD index, the Friedman's ANOVA results demonstrated that the differences observed in the second group were strongly supported with a p-value lower than 0.001, (χ^2 (2) = 9.368, p = 0.009) and (χ^2 (2) = 17.170, p < 0.001), respectively.



(a) (b)

Figure 13. Mean Standard Deviation of gaze distributions per curve radius (**a**) and approach tangent (**b**)

5. Conclusions

This chapter provided the major conclusions from analyses of the influence of the geometric characteristics of horizontal curves on driving behavior. Data were obtained by an experiment performed in a fixed-base driving simulator of the Department of Engineering and Transportation (STT) of São Carlos School of Engineering (EESC) at the University of Sao Paulo (USP), which is medium-fidelity immersion equipment with visual and auditory stimuli. The experiment involved 28 drivers running two sequences of nine combinations of curve radii and approach tangents, which resulted in more than 500 curves to be analyzed and classified.

The main objective of the research was to explore drivers' behavior concerning their trajectories, speed profiles, and eye movements, as well as their relationship with the geometric characteristics of the curves towards a better understanding of the differences in the performance parameters under different geometric conditions and proposed behavioral classifications. The comprehension of drivers' behavior and validation of the models in driving simulators are useful and sustainable techniques to improve road safety.

Initially, speeds descriptive analyses and a speed change behavior classification were presented. The lowest speeds were observed on curves with smaller radii, followed by medium- and wider-radius curves, revealing the average driving speed increased on those with a wider radius. Repeated measures ANOVA confirmed the effect of the curve radii on the average driving speed ($F (2, 469) = 145.55$, $p<0.001$), and Bonferroni post-hoc test indicated average speeds were significantly different among the curve radii. Speed change behaviors were assessed by the maximum speed reduction achieved by the drivers on each curve, revealing a substantial decrease in speed is the most common behavior for curved configurations with larger radii.

Drivers' lateral position was also analyzed, and curve trajectory's classification criteria have been proposed for a three-lane highway. The lateral position of the vehicles, assessed by their standard deviation as an index of the driver's lateral stability, achieved higher values for circular sections compared to other highway stretches and for curves with small radii compared to medium and large curves. Friedman's ANOVA confirmed the index was significantly different among the treatments (χ^2 (8) = 35.06, p <0.001). The curve trajectories were classified according to lateral position parameters. The incidence of the most dangerous behavior decreased with the increase in the curve radius, supporting the study conducted by (Mauriello et al., 2018) and consistent with crash statistics, as reported elsewhere.

Regarding differences in the spread of view, the drivers' areas tracked were increased with radius and approach tangent increase, indicating drivers demand more attention while performing shorter curves. The duration of the drivers' fixations (i.e., their information processing time) was not significantly different among the studied groups of curves configurations; however, the amount of information processed led to a substantial difference shown by the increased number of fixations and decreased pupil diameter size on curves with smaller radii.

Overall, the findings were in line with those from the literature; moreover, relevant statistical analyses performed ensured the significance of the observed effects of curve radii and approach tangent on drivers' performance while negotiating curves. The studied measures, namely speed, deviation of lateral placement, number of fixations, pupil size, and gaze directions regarding driver's visual attention showed significantly associated with curves radii. Nevertheless, Papadimitriou et al. (2019) ranked curves radii as the riskiest factor related to road alignment infrastructure elements. Further research is necessary to extend these results and practical suggestions are presented at next sub-section.

The results of this study are promising and demonstrated the effectiveness of the driving simulator for research on road design and driving behavior due to its flexibility for the implementation of different scenarios, which is highly expensive and time-consuming in real-world conditions. The simulator also generates data sufficiently numerous for studies and poses no risk to drivers. Simulation experiments provided a very large amount of data, which can be treated in different research and aspects, as demonstrated in this dissertation, evidencing the validity of continued work towards no great waste of data and efforts.

5.1 Recommendations for Future Studies

This dissertation presents an investigation on the effects of horizontal curve geometry on drivers' lateral placement, speed profiles and visual performance. Further research is required toward extending the results that were previously presented. Suggestions for future research include the improvement of trajectories classification and speed profiles categories, such as using clusters for grouping drivers' behaviors with similarity for different parameters.

As addressed elsewhere, identification questionaries were applied during the experiment, the subjects were asked about the frequency they drive of and their perspective regarding to the experience and driving style (cautious, confident, and insecure). An interesting extend analysis would be crossing the classifications obtained in the research with the self-declaration data from the questionaries and evaluate its correlation. Even more, the questionaries also provide information about the sex and age of the drivers, which are data also liable to be crossed with the results.

The performance parameters were treated individually since here, and the variables associated to them were (i) speed and its average, maximum, minimum and its difference values, (ii) the lateral position, assessed by the mean, maximum, minimum and its difference, and standard deviation values of lateral placement, and (iii) the eye movements, in terms of number of fixations, mean fixation duration, pupil size and gaze distributions areas.

Next steps can also cover including multivariate statistical analyses, such as ordinal logistic regression and inclusion of socioeconomic variables), adding considerable value to the survey, since the correlation between the three studied behavioral parameters is a lack in the literature and is valuable because can provide traffic engineers practical suggestions when implementing traffic control devices to increase safety on curved sections.

This research is expected to be improved applying the same method to another Brazilian roadway in mountainous terrain and evaluating the driver's behavioral classification on curves towards information for the update of manuals of geometric design. Providing a better comprehension of drivers' behavior is helpful for identifying local risky behaviors and then hardly work on their prediction and anticipation, so this study corroborates with previous and further studies on road safety and policies through improvements in driving laws and regulations for future road designs and existing highways (Kolekar et al., 2020).

Finally, the results already achieved showed that lateral position, assessed by drivers' trajectories, is an encouraging surrogate measure for the achievement of driving performance and a road infrastructure safety indicator in horizontal curves. The correlation between behavioral parameters and drivers' eye movement, when thorough cared, can provide traffic engineers several practical suggestions to increase safety in curve sections. For example, the knowledge on the number of fixations and their processing times allows improvements in image identification algorithms in autonomous vehicles, so that developers can increase the accuracy of such algorithms by indicating regions that require a better visualization by the driver.

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