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ESCOLA DE ENGENHARIA DE SÃO CARLOS

FELIPE CALSAVARA

A driving simulator experiment towards contributions to studies on driver behaviour under foggy conditions

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A driving simulator experiment towards contributions to studies on driver behaviour under foggy conditions

Master Dissertation submitted to the University of São Paulo in partial fulfilment of the requirements for the degree of Master of Science in the Transportation Engineering Graduate Program at São Carlos School of Engineering.

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Advisor: Prof. Ana Paula Camargo Larocca

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Ao meu padrinho que hoje observa
minhas conquistas do céu.

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Abstract

CALSAVARA, FELIPE. **A driving simulator experiment towards contributions to studies on driver behaviour under foggy conditions**. 65p. Master of Science. Dissertation – Department of Transportation Engineering, São Carlos School of Engineering, University of São Paulo, São Carlos, 2022.

Visibility is essential for the driving task, and its reduction influences the behavior of drivers, which must be understood towards the design of adequate accident mitigation strategies. Fog is an example of a weather condition that directly impacts a driver's vision and leads to more severe accidents involving multiple vehicles in comparison with normal visibility conditions. Intelligent Transport Systems based on connected vehicles communication have been increasingly implemented in vehicles towards overcoming the aforementioned issue and potentially helping drivers take actions from externally acquired information, thus warning them of dangerous situations to be avoided. The present study was divided into two different experiments, of which the first investigated the effects of the presence or absence of fog on drivers' visual performance and the second evaluated a driver's speed profile in different scenarios (clear weather, fog weather, and fog with an in-vehicle fog warning system). In both experiments, a driving simulator recreated the real scenarios of a major Brazilian road segment, showing the geometric and weather conditions of a road known for its frequent incidence of fog. The analysis of the results of drivers' visual performance and speed profile in a foggy scenario revealed that (1) the eye tracked area was concentrated in a smaller region, (2) the number of fixations increased, (3) the pupil dilation was shorter, and (4) the fixation duration did not change. (5) The evaluation of the scenario that used connected vehicles technology showed that such technology can substantially improve road safety, since drivers can better adjust speed to enter a fog zone.

Keywords: Driving simulator. Eye-tracking. Fog. Speed profile. Warning-system.

Resumo

CALSAVARA, FELIPE. **Contribuição aos estudos sobre efeito da neblina no comportamento do condutor. Estudo de caso em simulador de direção.** 2022. 65p. Dissertação (Mestrado em Ciências). – Departamento de Engenharia de Transportes, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2022.

A visibilidade é fundamental para a tarefa de condução e a sua redução influi no comportamento dos motoristas, que precisa ser entendido para projetar estratégias adequadas de mitigação de acidentes. A neblina é um exemplo de condição climática que impacta diretamente a visão do motorista. Acidentes nessa condição tendem a ser mais severos e envolver múltiplos veículos, se comparados a condição normal de visibilidade. Uma solução para diminuir o número desses acidentes é a adoção de sistemas de transporte inteligentes, baseados na comunicação entre veículos. Estes sistemas notificam antecipadamente ao motorista sobre as condições possivelmente perigosas da rodovia, possibilitando ao condutor adaptar melhor o seu comportamento de condução. Portanto, este trabalho foi dividido em dois experimentos distintos. O primeiro, investigou os efeitos da presença ou ausência de neblina no desempenho visual dos motoristas. O segundo, avaliou o perfil de velocidade do motorista em diferentes cenários (tempo limpo, tempo de neblina e neblina com sistema de alerta de neblina no veículo). Em ambos os experimentos, um simulador de direção foi utilizado para recriar os cenários reais de um dos principais trechos rodoviários brasileiros, mostrando as condições geométricas e meteorológicas de uma estrada conhecida pela frequente incidência de neblina. A análise dos resultados obtidos no desempenho visual dos condutores e no perfil de velocidade permitiram chegar às seguintes conclusões. Comparado com o cenário sem neblina, no cenário de neblina, (1) a área rastreada pelos olhos concentrou-se em uma região menor; (2) o número de fixações aumentou; (3) a dilatação pupilar foi mais curta; e (4) a duração da fixação não se alterou entre os cenários. (5) A avaliação do cenário que utilizou a tecnologia de veículos conectados com sistemas de alerta indicou que o uso dessa tecnologia poderia melhorar substancialmente a segurança viária, pois os motoristas ajustariam melhor a velocidade ao entrar em uma zona de neblina.

Palavras-chave: Simulador de direção. Rastreamento ocular. Neblina. Perfil de velocidade. Sistema de aviso.

List of publications

Articles that compose the dissertation:

I. **Calsavara, F**.; Kabbach Junior, F.I.; Larocca, A.P.C. Effects of Fog in a Brazilian Road Segment Analyzed by a Driving Simulator for Sustainable Transport: Drivers' Visual Profile. Sustainability 2021, 13, 9448. https://doi.org/10.3390/su13169448

II. **Calsavara, F**.; Kabbach Junior, F.I.; Larocca, A.P.C. Effects of Fog in a Brazilian Road Segment Analyzed by a Driving Simulator for Sustainable Transport: Drivers' Speed Profile under In-Vehicle Warning Systems. Sustainability 2021, 13, 10501. https://doi.org/10.3390/su131910501

List of abbreviations

3D – Three dimensional
AADT – Average Annual Daily Traffic
ADAS – Advanced Driver-Assistance Systems
ANOVA – Analysis of variance
CV – Connected Vehicles
D – Number of accidents with no victims
Denatran – Brazilian National Traffic Department
Df – Degrees of freedom
DMS – Dynamic Message Sign
DPRF – Departamento de Polícia Rodoviária Federal
F – Number of accidents with fatal victims
GPU – Graphics Processing Unit
HUD – Head-Up Display
ITS – Intelligent Transport Systems
M – Mean difference
PNCT – National Traffic Counting Plan
ROI – Region of interest
S – Severity index
S-curve – "S"-shaped highway curve
SE – Standard Error
UPS – Standard Severity Unit
V – Number of accidents with non-fatal victims
V2I – Interaction between vehicles and infrastructure
V2V – Interaction between vehicles and vehicles
VTD – Virtual Test Drive
WSI – Weighted Severity Index

List of symbols

kph	kilometer per hour
®	trademark
m	meter
Hz	hertz
min	minutes
s	seconds

Contents

1. Introduction

Visibility is a critical factor for drivers to perceive roadway information, and fog is an inclement weather condition that directly impacts their vision, since it reduces the overall contrast and visibility of a driving scene. Visual attention has been considered a contributing factor to traffic crashes, and fog-related accidents are prone to be more severe and involve multiple vehicles.

Intelligent Transport Systems based on connected vehicles communication have been increasingly implemented inside vehicles towards overcoming the aforementioned problem, since they promptly notify drivers on potentially dangerous road conditions, such as fog, so that they can better adapt their driving behavior.

Few academic studies have related a driver's behavior with their safety in low-visibility situations, thus leaving gaps on the understanding of a driver's visual search strategy in low-visibility situations and the relationships between speed variations due to the use of in-vehicle warning systems. A broad understanding of driving behavior in low visibility can help researchers and designers improve road safety through more effective safety measures.

A driving simulator is an important tool for evaluating drivers' behavior in low visibility situations. For ethical reasons, conducting a natural driving experiment is unfeasible, since it puts the driver's life at risk. Another key factor that has supported the present research is the studies on the topic have been published in North American and European countries and, therefore, do not correspond to the behavior profile of Brazilian drivers and to the infrastructure conditions of Brazilian highways.

1.1 Objectives

The main objective of this study is to investigate a driver's behavior in low-visibility situations, and the specific objectives are:

a) to check whether the presence (foggy scenario) or absence (clear scenario) of fog significantly affects the driver’s visual profile;
b) to evaluate a driver’s speed profile supported by a fog in-vehicle warning system.

1.2 Dissertation structure

The first chapter briefly introduces both the theme of driver's behavior in low-visibility situations, pointing out the relevance, justification, and approach of the research problem, and the general and specific objectives of the research. Chapters 2 and 3 present two research papers produced during the research and that analyze, respectively, the effects of fog or its absence on drivers' visual performance and the driver's speed profile when driving with the aid of in-vehicle warning systems. Both articles are highly relevant for the study of Brazilian drivers' behavior in low-visibility situations. Chapter 4 closes the dissertation presenting the main conclusions of the research and suggesting new studies.

2. Effects of Fog in a Brazilian Road Segment Analyzed by a Driving Simulator for Sustainable Transport: Drivers' Visual Profile

2.1 Introduction

Adverse weather conditions significantly impact roadway conditions, vehicle performance, visibility distance, driver´s behavior, travel demand, traffic flow characteristics, and traffic safety. Visibility is fundamental for the driving task, and its reduction influences driver behavior, which must be understood toward the design of appropriate mitigation strategies (HASSAN; ABDEL-ATY, 2011; KHAN; GHASEMZADEH; AHMED, 2018).

2.1.1 Visibility Reduction

Ni *et al.* (2012) claim that fog is a climatic condition that directly impacts the driver's vision. Its presence reduces both the contrast and visibility of the scene in which it is directed, hence, details, as the distance view increases. The absence or reduction of long-range visual information is dangerous, since, under normal visibility situations, drivers tend to look further ahead on the road they are traveling than at its edges (SERAFIN, 1994). Therefore, fog increases the risk of accidents because it hides long-range visual information, hampering the prediction of the path to be taken and the anticipation of events such as pileups or vehicle decelerations ahead (ROSEY *et al.*, 2017).

Ahmed *et al.* (2014) explored the viability of using weather information collected from airports in real-time crash-risk assessments on highways. A Bayesian logistic regression approach estimated the probability of crash occurrence, and the results showed the reduction in visibility reported by airport weather stations is associated with crash occurrence.

Previous studies have demonstrated that, although the percentage of accidents under fog is small compared to normal visibility conditions, they tend to be more severe and involve multiple vehicles (ABDEL-ATY et al., 2011; HAMILTON *et al.*, 2014; WHIFFEN; DELANNOY; SIOK, 2004). Abdel-Aty *et al.* (2011) concluded head-on and rear-end crashes are the two most common crash types under fog condition.

Chen *et al.* (2019) described the influence of adverse weather on the perceived risk for drivers during car-following based on a driving simulation experiment. They used an entropy weight method and multiple linear regression to explore the effects of different weather conditions on the perceived risk level of drivers and observed such levels increase in the function of fog intensity due to the reduction in visibility.

A study with a driving simulator conducted by Yan *et al.* (2014b) confirmed that drivers reducing their speed under low-visibility conditions was not enough for them to respond in time to impending changes in road geometries and the speed of the vehicles ahead, or to an emergency event. Although some drivers would keep longer headway distances, rear-end crashes may occur since they may not be able to see the braking lights of the front vehicle (WU *et al.*, 2018a).

The effects of foggy climate during driving have been widely studied; however, gaps on the understanding of the driver's visual search strategy in low visibility sections have been identified. The use of an eye-tracking system for a deep understanding of driving behavior in low visibility can guide researchers and designers toward improving road safety through more effective measures.

2.1.2 Eye Tracking

Visual attention, which is closely related to eye movements, refers to the way information is processed in an environment, and has been a contributing factor to traffic crashes. The recording of eye movements, considered by Velichkovsky *et al.* (2003) as an appropriate tool for identifying drivers' visual attention, has drawn the interest of the academic community.

Studies have evidenced that the region to which the eyes are pointing is closely related to what is being coded and processed by the driver, and the duration of a look reveals the processing difficulty faced. Chapman and Underwood (1998) demonstrated that drivers require longer durations in complex scenarios, thus, potentially leading to a crash.

According to Zhang *et al.* (2016), the eye movement behavior can be analyzed from glance measures or fixation measures supported by an eye-tracker of sufficient accuracy and precision. Fixation analyses are commonly associated with cognitive processing and applied for evaluations of mental efforts. The length of fixation duration has been found to be connected with the complexity degree of a visual scene, and shorter, but more frequent fixations may reduce processing time.

Eye tracking information is essential for the understanding of the way climatic variations in an external environment impact the driving task. Konstantopoulos, Chapman and Crundall (2010) recorded the eye movements of driving instructors and learner drivers while they drove three virtual routes that included day, night, and rain routes in a driving simulator. The results showed rainy weather significantly affected the drivers´ eye movements, and more frequent and shorter fixations indicated faster driver information processing.

2.1.3 Use of Driving Simulators

Driving simulators are essential in different fields of study and have been widely used for investigations into the impact of individual driver differences, vehicle technology, driver support systems, road projects, and the effectiveness of road safety interventions (FISHER; CAIRD; RIZZO, 2011). They have become versatile toward achieving different objectives (DOLS *et al.*, 2021; FIGUEIRA; LAROCCA, 2020a; LAROCCA *et al.*, 2018), and enable analyses of several factors that influence driver behaviors, e.g., emotional state (BAULK *et al.*, 2008; MATTHEWS, 2002; MATTHEWS *et al.*, 2011), and the use of hallucinogenic substances (GROTENHERMEN *et al.*, 2007; ORTIZ-PEREGRINA; ORTIZ; ANERA, 2021; RAMAEKERS *et al.*, 2011) and distracting devices such as cell phones (STRAYER; DREWS; CROUCH, 2006; SULLMAN; BAAS, 2004; VIEIRA; LAROCCA, 2017).

According to Bella (2008), the advantages of driving simulators include better experimental control, higher efficiency, low cost, safety, and ease of data collection (i.e., they provide sustainability and safety to investigations on infrastructure design associated with driver behavior under fog). Drivers can be repeatedly confronted with different circumstances including specific climatic conditions such as fog and heavy rain with no risk to life and reduced costs, which is a great advantage regarding field tests (LUCAS *et al.*, 2013). Studies with driving simulators under foggy conditions have focused mainly on kinematic aspects of the vehicle guided by the driver, analyzing variables such as average speed, speed variation, acceleration, collision time, and lane position (BELLA; SILVESTRI, 2017; BROOKS *et al.*, 2011; MUELLER; TRICK, 2012; YAN *et al.*, 2014a; YANG *et al.*, 2020). However, few have analyzed the influence of those climatic conditions on the driver's eye movement behavior.

This article studies the driver's behavior under environmental conditions, specifically regarding the influence of fog. It describes a controlled experiment in a driving simulator, a strategy that offers significant benefits for research on road safety and geometric design as test arrangements are shifted to a virtual environment, thus saving time and costs, and providing safety to volunteers. The logistical effort reception of volunteers at the simulator facilities and the production of a wide variety of road scenarios associated with eye track system are significantly reduced. The fog conditions analyzed refer to a curved road segment of a highway with one of the highest worldwide daily volumes of trucks and is characterized by high fog formation. The conditions were faithfully recreated in the driving scenarios employed in the experiments, where the drivers' visual profile was analyzed.

2.2 Methods

2.2.1 Apparatus

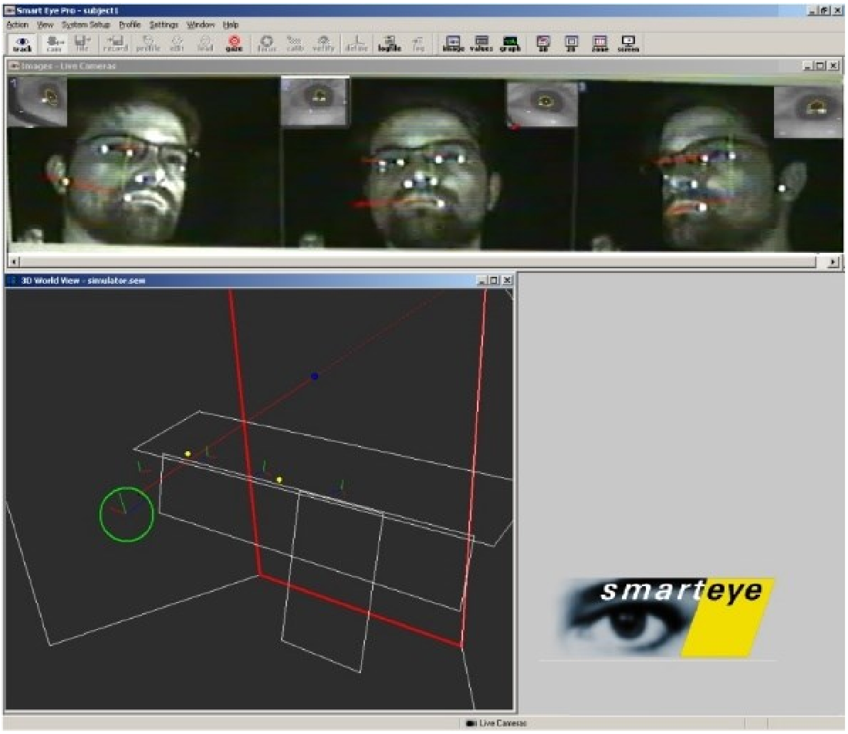
The Sustainable Road Safety Project of the Department of Transportation Engineering at the São Carlos School of Engineering, University of São Paulo, has developed a fixed-base driving simulator from human, vehicle, and traffic research. It is equipped with a driving cockpit with a car seat, a steering wheel with paddle shift and force feedback, and accelerator, brake, and clutch pedals. The simulated environment was projected on a 1.40 x 0.80 m flat panel of 1080 p resolution and 60 Hz projection rate. Rear and lateral mirrors and a speedometer in a head-up display (HUD) were also projected on the panel. Speakers reproduced sounds similar to vehicle engines and wind for deeper immersion (Figure 1). The simulator has been employed in other studies developed in the department (DE CAMPOS *et al.*, 2020; FIGUEIRA; LAROCCA, 2020a, 2020b; LAROCCA *et al.*, 2018; SANTOS *et al.*, 2017; VIEIRA; LAROCCA, 2017).

Figure 1 – Simulator's physical structure

Two computers processed the real-time simulation. The first, responsible for environment rendering and simulation running, was strengthened with two GPUs, whereas the other modeled the vehicle´s dynamics, which included a road–vehicle interaction and mechanical answers to the driver's actions. The vehicle's dynamics were similar to a Brazilian ordinary vehicle version, thus enabling participants to perceive a medium-fidelity immersion with visual and auditory stimuli similar to a real driving experience due to the high computational capacity that modeled and rendered a virtual environment in real time.

Appropriate equipment—model Pro 5.10® Smart Eye—attached to the simulator recorded the eyes' movements. Pro 5.10 is comprised of three front cameras that perform the driver's eye-tracking, and an additional rear camera, which records the scenes seen by the driver. The equipment provides raw data reliability and 3D filtered data, and remotely tracks the direction of the gaze, head position, eyelid opening, blinks, attachment points, and pupil size, among other monitoring and measurements. Figure 2 shows an example of the software interface, which detects the intersection of the driver's gaze with objects created in the environment for better determining the response time and maps the areas on the screen most viewed by the driver. MAPPS® 3.3 software, developed by EyesDX, analyzed data on the eyes' movement.

Figure 2 – Eye tracking recorder software



2.2.2 *Study Segment*

The rural road simulated was a 10 km stretch of a Brazilian highway that connects Sao Paulo to Curitiba and is the main connection between Brazil and other South American countries. The stretch is located in a mountainous region with fog incidence in certain periods. The highway administrator provided the stretch geometric design necessary for virtual modeling, the AADT (Average Annual Daily Traffic) as well as the location, type, and severity of accidents that have occurred in recent years.

The stretch is comprised of 20 curves (Figure 3), and the fog analysis was performed in a segment selected according to the fog car crash statistics of the road from 2011 to 2020. The hypothesis is that the accidents are related to the drivers' inability to react properly under fog conditions at those spots. Considering geometry and crash statistics, the fog analyses were performed between the 6th (C6) and the 7th curves (C7) (Figure 4). Both position and intensity of the fog were fixed in all foggy trials, and passenger vehicles and trucks were distributed proportionately.

Figure 3 – Layout of the section under study and the identification of curves

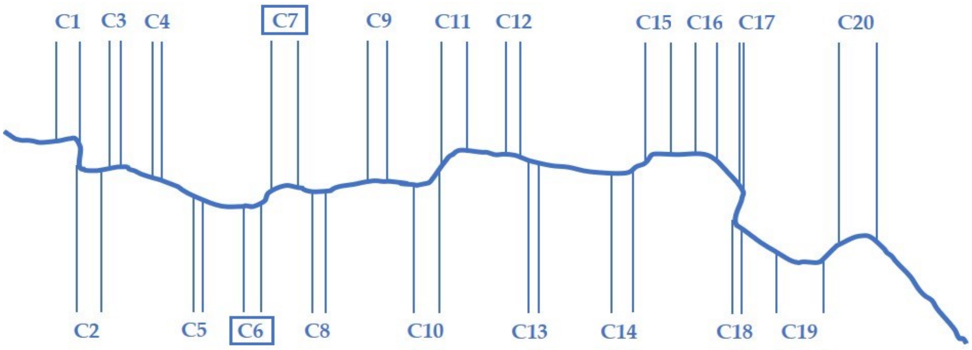
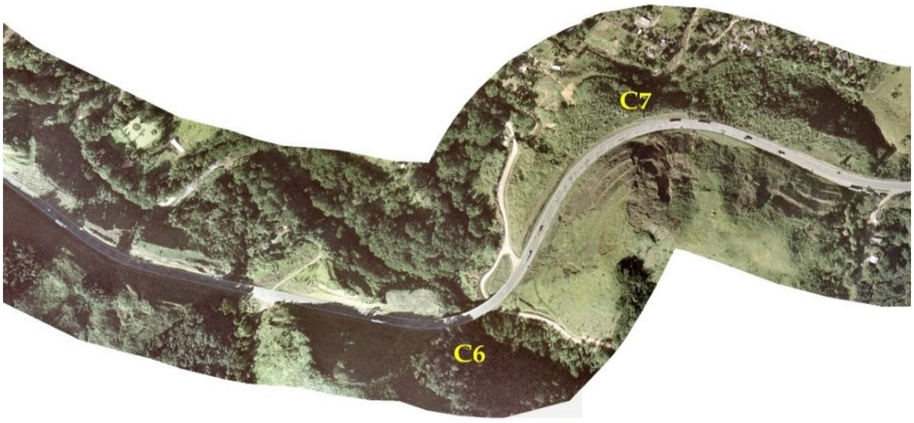


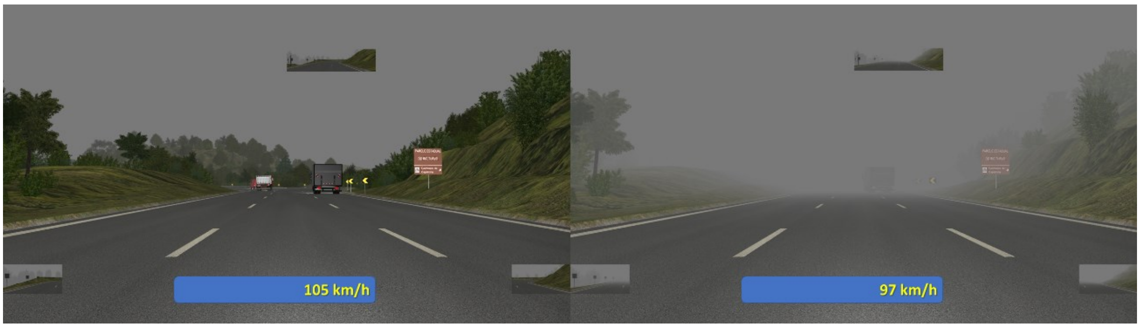
Figure 4 – Aerial image of the curves analyzed



2.2.3 *Simulator Scenario*

The scenarios were modeled and simulated by the Virtual Test Drive (VTD) package developed and marketed by Vires®, according to the data collected (see Figure 5), and then analyzed by Python programming codes. They were designed for analyses in the selected stretch of the test highway, with a heavy x passenger car proportion of the traffic flow respecting the results from the National Traffic Counting Plan (PNCT). The only changes between the scenarios were the presence of independent variables and absence of fog to ensure that no difference would be confused with other factors. Field surveys for the fog visibility calibration in the studied region were not part of this research. Based on previous studies (CHEN *et al.*, 2019; PARK *et al.*, 2019; WU *et al.*, 2018a, 2018c), the heavy fog condition was considered as a critical scenario (visibility distance is shorter than or equal to 200 m), therefore, fog position (settled in the tangent between C6 and C7) and fog intensity according to visibility (50 m) were fixed in all foggy trials.

Figure 5 – Screenshots of the simulated scenarios



Comparison between absence (left) and presence (right) of fog in the stretch after the 6th curve.

A valid interpretation of the results depends on a series of factors related to proper design, execution, and analysis. As suggested by Fisher, Caird and Rizzo (2011), the scenarios were randomized for each participant toward avoiding bias. Randomization ensures an equal distribution of all characteristics among the treatment groups, thereby diminishing the potential for confounding. A pilot data collection was conducted prior to the definitive experiment for saving resources and subjects.

2.2.4 Experimental Design and Procedure

Thirty-eight volunteers were required to have had a driver's license for at least one year and normal or corrected-to-normal vision. The group was formed by 23 men and 15 women, aged between 20 and 36 years old (M = 26.9, SE = 4.0).

A within-subjects' design (repeated measures) was employed, and each subject experimented two visibility conditions, namely clear and foggy, totaling two trials/scenarios for each one. The scenario under clear conditions represents the control group in which the participant drives with no influence of reduced visibility, and will be useful for the analyses of the default behavior of each participant. A scenario under fog is expected to enable analyses of the way the environment outside the car changes the drivers' behavior. The order of the scenarios was randomly sorted for each participant toward avoiding bias as well as accommodating the limited time each participant would spend in the simulator and minimizing possible simulator sickness.

A Protection of Human Subjects in Research approval was obtained from the Brazilian National Health Council prior to the experiments. Upon arrival at the laboratory, each participant signed an informed consent and filled a personal information questionnaire. They were also instructed on the procedures and mechanical operations of the simulator. The instructions did not include any detailed information on the experiments that might potentially influence the driving behavior. The participants were instructed to drive as normally as they usually do in a real car. Subsequently, they drove an adaptation scenario until they had felt adapted to the simulator and comfortable with the simulation. The adaptation simulation lasted at least 5 min for each participant and could be repeated as many times as necessary. A profile for the eye-tracking system was then created and calibrated by Smart Eye® software, and the participants drove for approximately 5 minutes in each of the two experimental scenarios, with a 2-minute interval between them. They were instructed to pull over and stop after they had driven along the data collection segments. The experiment lasted approximately 20 minutes.

2.2.5 Data Analysis

The dependent variables analyzed were number and duration of fixations, pupil diameter, and area tracked by the participants´ eyes. Their individual and combined analyses aimed at finding relevant incorporations for the dealing with such a weather situation. Therefore, the drivers' visual performance patterns in fog weather must be uncovered as a function of the different visibility conditions toward the development of technologies, optimization of the systems' application effectiveness, and correct improvements in the visualization of signaling on highways. The following variables were analyzed in both scenarios: (i) number of fixations, which provides information on sampling rate (i.e., frequency at which the information is collected from the screen); (ii) mean fixation duration, as an indicator of processing time (shorter mean fixation duration means shorter processing times); (iii) pupil diameter, according to which the presence of fog increases contrast visibility, thus decreasing the pupil diameter; and (iv) screen's area tracked, which reflects the visual search spread (i.e., effectiveness of the visual search strategy adopted by the driver).

The lack of visibility can significantly affect a driver's visual strategies before driving in a foggy area. The number of fixations in a foggy zone is expected to be greater, whereas the fixation duration is shorter, thus indicating the drivers' ability to react properly.

A paired t-test analysis was computed by SigmaPlot (v.12) with the paired t-test tool. However, a Wilcoxon test was applied when normality was violated by the Shapiro–Wilk test. The analyses were organized into number of fixations, mean fixation durations, pupil diameter, and area tracked.

2.3 Results and Discussion

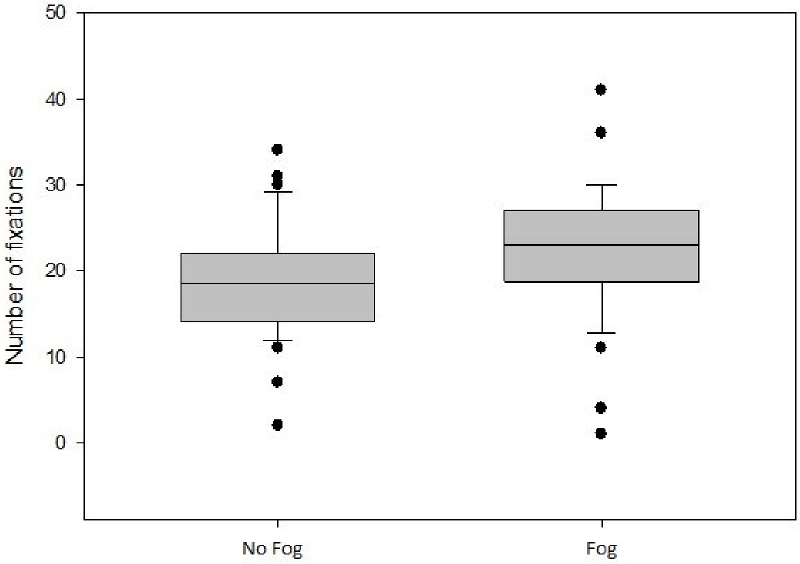
2.3.1 Number of Fixations

Table 1 and the boxplot in Figure 6 show the results of the Wilcoxon test. The number of fixations was calculated for each subject in the two scenarios. Wilcoxon test compared the average number of fixations during driving with and without fog regarding how fog influences such a number. The foggy scenario showed a significantly higher number of fixations (median = 23.00) than the no fog one (median = 18.50), $z = 3.958$, $p < 0.001$, $r = 0.45$, thus indicating that the presence of fog increased the average number of fixations and was statistically significant.

Table 1 – Wilcoxon signed rank test for the number of fixations

Group	N	Missing	Median	25%	75%
No Fog	38	0	18.500	14.000	22.000
Fog	38	0	23.000	18.750	27.000

Figure 6 – Boxplot for number of fixations



The participants performed approximately 23 fixations in the foggy scenario and around 18.5 in a clear one. The change that occurred was greater than expected by chance; a statistically significant difference (P = < 0,001) was detected.

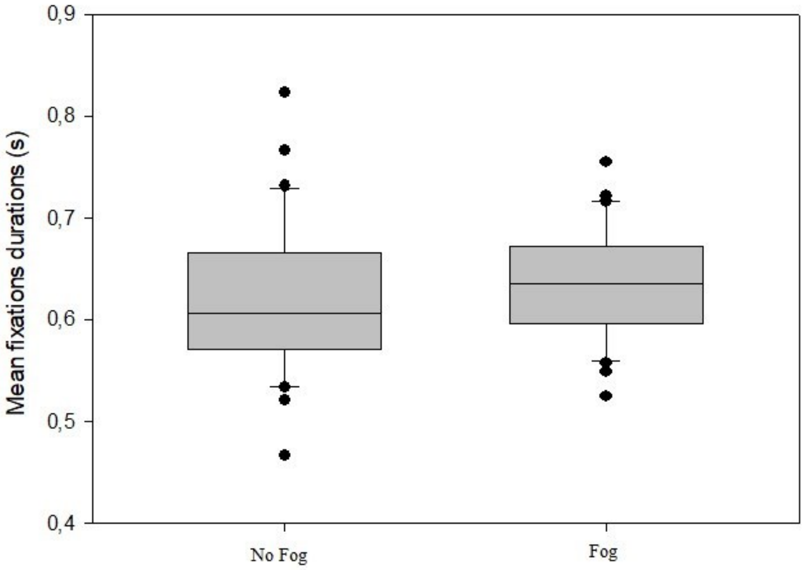
2.3.2 Mean Fixation Durations

A paired t-test compared the average duration of the fixations during driving with and without fog. The Shapiro–Wilk test for normality revealed that data were normally distributed (P = 0.559), and the descriptive analysis indicated that the average durations of fixation were 0.634 seconds (EP = 0.0744) under fog and 0.617 seconds (EP = 0.0525) with no fog. The test results (Table 2 and Figure 7) showed no significant difference in the fixation durations between the scenarios (t (37) = −1.254 and p = 0.218 > 0.05).

Table 2 – Paired t-test for mean fixation durations

Treatment Name	N	Missing	Mean	Std Dev	SEM
No Fog	38	0	0.6170	0.0744	0.0121
Fog	38	0	0.6340	0.0525	0.0085
Difference	38	0	−0.0169	0.0833	0.0135

Figure 7 – Boxplot for mean of fixation durations



Boxplot for mean of fixation durations shows 0.617 seconds in the clear scenario and 0.634 under fog. The change from the treatment was not great enough for excluding the possibility of the difference being due to chance (P = 0.218). Power of performed test with alpha = 0.050: 0.107, which is below the desired power of 0.800, indicating lower probability of detecting a difference when one actually exists.

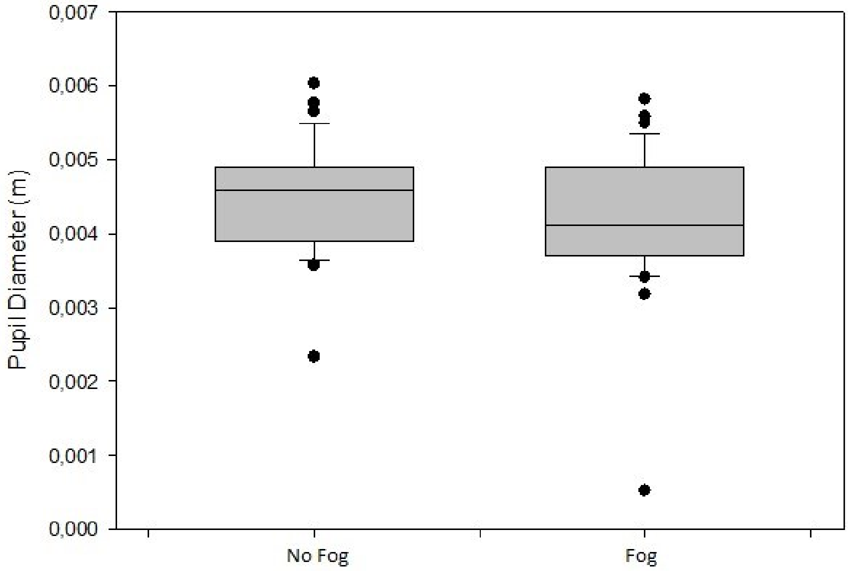
2.3.3 *Pupil Diameter*

Table 3 and the boxplot in Figure 8 show the results of the Wilcoxon test, which compared the average pupil diameter during driving with and without fog. It was significantly lower (median = 0.00411 m) in the foggy scenario in comparison with that of no fog (median = 0.00458 m). z = −3.676. p < 0.001. r = −0.42, indicating that the presence of fog decreased the average pupil diameter and was statistically significant.

Table 3 – Wilcoxon signed rank test for pupil diameter

Group	N	Missing	Median	25%	75%
No fog	38	0	0.00458	0.00390	0.00491
Fog	38	0	0.00411	0.00369	0.00490

Figure 8 – Boxplot for pupil diameter



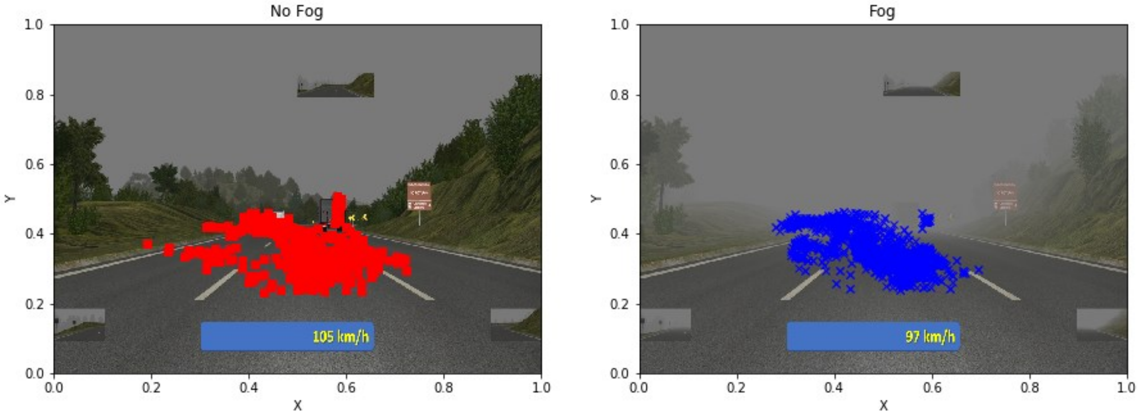
The participants´ pupil diameters were approximately 0.411 cm in the foggy scenario and around 0.458 cm in the clear one. The change from the treatment was greater than that expected by chance, showing a statistically significant difference (P = < 0.001).

According to Ni *et al.* (2012), the presence of fog reduced the overall contrast and visibility of the driving scene, resulting in reduced visible details as a function of increasing distance. Contrast reduction is evident when a decrease in the pupil diameter is verified in the foggy scenario, limiting the amount of light reaching the retina.

2.3.4 Area Tracked

Figure 9 shows a comparison of clear (red) and foggy (blue) scenarios. Changes were expected in the distribution of visual attention as a direct consequence of the degree of visual information available to drivers. Since the purpose of the study was to compare the regions of the external environment tracked, the points of interest internal to the vehicle (i.e., mirrors and head-up display) were excluded from the analysis area. The figure shows scatter graphs for a volunteer in each scenario and an overview of the visual spatial distribution for each condition.

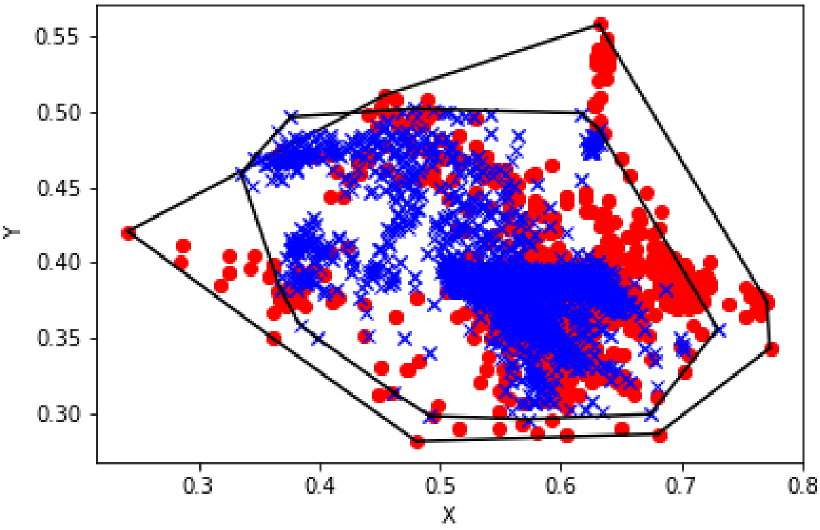
Figure 9 – Example of a comparative spread



The upper image shows an example of a comparative spread of search between clear (left) and foggy (right) scenarios for one of the participants, and the picture behind indicates the regions where the illustrated fixations might be allocated.

Despite the similarity of the fixation patterns, the clear area tracked showed broader regions than the foggy scenario, hence, statistical differences. As exemplified in Figure 10 below, for one of the participants, the polygon's area shaped by the extreme points in blue (foggy) was 0.061 m² and the area shaped by the extreme points in red (clear) was 0.090 m².

Figure 10 – Example of polygons shaped by points tracked in clear (red) and foggy (blue) scenarios for one of the participants.

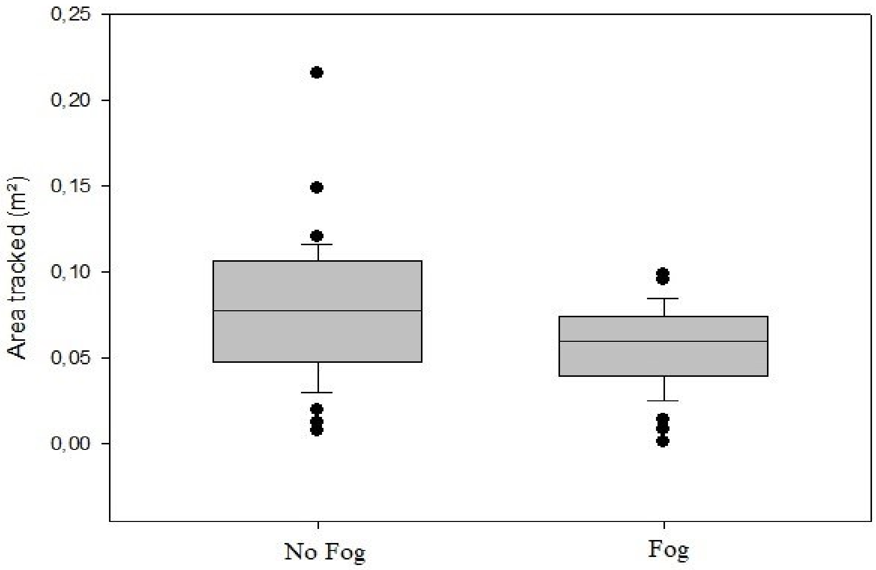


A paired t-test compared the area tracked during driving in clear and foggy scenarios (see Table 4 and Figure 11 for the results). Shapiro–Wilk test for normality revealed data were normally distributed (P = 0.080), and the descriptive analysis indicated that the average areas tracked were 0.0789 m² (EP = 0.0404) under clear condition, and 0.0561 m² (EP = 0.0234) under fog. The test results showed a significant difference in the area tracked between the scenarios (t (37) = 3.548) and a statistically significant change (P = 0.001).

Table 4 – Paired t-test for the area tracked

Treatment Name	N	Missing	Mean	Std Dev	SEM
No fog	38	0	0.0789	0.0404	0.00655
Fog	38	0	0.0561	0.0234	0.00380
Difference	38	0	0.0228	0.0396	0.00642

Figure 11 – Boxplot for area tracked



The participants tracked approximately 0.0561 m² of screen in the foggy scenario and around 0.0789 m² in the clear one. The change from the treatment was greater than that expected by chance, showing a statistically significant change (P = 0.001).

2.4 Conclusions and Future Research

Apart from the knowledge of differences in the behaviors of a driver´s eyes while driving under clear and foggy conditions, the reasons for such differences must also be known toward the design of interventions in highway projects that provide safety for drivers driving under foggy conditions.

Fixation duration is a good indicator of difficulties in a driver´s processing of some information. Although no statistical difference has been found for the mean fixation duration, this can also be understood as a result, since under foggy conditions, the duration of the drivers' fixations (i.e., their information processing time) is the same of that in a scenario with no fog.

On the other hand, if the processing time remains the same, the amount of information processed leads to a significant difference, clearly shown by the increased number of fixations in the foggy scenario over the clear one. Despite a smaller field of vision, the driver searches for more visual information and spatial references in a foggy scenario for either staying on the track, or a better understanding the situation.

Regarding differences in the spread of view, the drivers' areas tracked were reduced under foggy conditions, and a great number of visualizations were provided in the center of the screen, indicating that drivers do not see much beyond the shoulders.

Our results can enable designers to reconsider the design of edge lines for assuring they are visible in fog, or even design fog warnings with short messages on gantries over the roadway. Such possibilities can improve both the drivers' processing capacity and variables (e.g., processing time of autonomous vehicle algorithms), since they will be able to learn the image's locations to focus on when analyzing a scene under fog weather.

Although some studies have addressed driving under foggy conditions, the literature lacks research on eye tracking as a dependent variable. This is one of the first studies to have used driving simulators for the understanding of the driving infrastructure's environment under fog in the Brazilian scenario.

The driving simulator guarantees realistic experiences for safe driving under different dangerous conditions such as fog. Its potential has been confirmed for testing under controlled road virtual environments, since it enables repeatability of specific combinations of features and cost reduction. Investigations on driving in a specific scenario can also be more effective than that in the real world as well as safer, because of the absence of physical risk, regardless of the driver´s performance. The eye track system association provided a realistic extract of a driver´s behavior, and data from almost forty drivers who covered 760 kilometers in a virtual scenario could be analyzed in a sustainable manner.

3. Effects of Fog in a Brazilian Road Segment Analyzed by a Driving Simulator for Sustainable Transport: Drivers' Speed Profile under In-Vehicle Warning Systems

3.1 Introduction

Intelligent Transport Systems (ITS), based on connected vehicles communication, help drivers take actions from externally acquired information by, for example warning them of a potentially dangerous situation to be avoided by automatic braking or automatic steering. The development of information technology promotes traffic efficiency and safety through real-time information interaction between vehicles (V2V) and vehicles and infrastructure (V2I).

External factors like weather conditions impact roadway situations and traffic safety (HASSAN; ABDEL-ATY, 2011), and adverse phenomena, such as fog reduce visibility, contributing to traffic crashes. Fog increases the risk of accidents since it hides long-range visual information and hampers the prediction of the path to be taken and events, e.g., pileups or vehicle decelerations (ROSEY *et al.*, 2017).

In Brazil, according to the annual traffic statistics of road traffic crashes issued by the federal highway patrol, fog was a probable cause for 11,753 accidents between 2011 and 2020, which represent 5% of the total number of crashes occurred under adverse weather conditions (rain, fog, snow, strong wind, etc.) (DPRF, 2021). Although the percentage of accidents under fog is smaller than those under normal visibility conditions, they tend to be more severe and involve multiple vehicles (HASSAN; ABDEL-ATY, 2011; PARK *et al.*, 2019; WU *et al.*, 2018a).

According to Mueller and Trick (2012), reduced visibility increases the risk of collision. However, not all drivers are affected in the same way—some are more likely to make safety-related adaptations, which can be measured primarily by speed compensation and ability to follow a car or stay in the lane. Speed compensation is the most typical adjustment to driving behavior under fog conditions. Previous studies have confirmed drivers tend to make safety-related adaptations, such as slowing down, to compensate for insecurity due to the limited visual field (BROUGHTON; SWITZER; SCOTT, 2007; NI; KANG; ANDERSEN, 2010).

However, a study with a driving simulator conducted by Yan *et al.* (2014b) confirmed driver's reduction in speed under low-visibility conditions is not enough to respond in time to impending changes in road geometries, speed variation of vehicles ahead, and an emergency event. Although some drivers would keep longer headway distances, rear-end crashes may still occur, since they may not be able to see the breaking lights of the front vehicle (WU *et al.*, 2018b).

Efforts have been devoted to solving the traffic safety problems in a fog area. The warning system that alerts drivers about a fog location helps them improve their speed adjustment before entering the fog zone. The most typical warning systems that provide drivers with real-time traffic alerts are located in the highway infrastructure Dynamic Message Sign (DMS), and inside Connected Vehicles (CV), called in-vehicle information systems. Liu and Khattak (2016) claim vehicles sharing their status information with other vehicles or with the infrastructure leads to better-planned actions during driving, earlier identification of hazards, and safer responses.

Several studies on DMSs in fog situations have been conducted. Using a driving simulator, Boyle and Mannering (2004) analyzed drivers' speed adjustments under four different scenarios of advisory information under foggy conditions. According to the findings, although warning messages lead to significant speed reductions in the low-visibility area, drivers tend to increase speed downstream, when such adverse conditions no longer exist. Al-Ghamdi (2007) studied traffic crashes caused by fog and concluded although the DMS warning system was ineffective in reducing speed variability, the mean speed was reduced by approximately 6.5 kph in fog sections. Wu *et al.* (2018b) conducted an empirical driving simulator study to assess the effectiveness of real-time fog warning systems, and the results showed drivers are more likely to reduce their speed or brake harder under thicker fog.

In recent years, due to the significant development of CV technology, investigations into the effectiveness of V2V systems have increased. Zhao *et al.* (2019) used a connected vehicle test platform to analyze the speed adjustment of drivers after receiving warning information at different fog concentrations. The results indicated the warning system effectively led to speed reductions in all fog scenarios. Chang *et al.* (2019) used a fixed-based driving simulator to investigate the effectiveness of fog warning systems in driving performance. According to the results, scenarios with fog warning systems significantly improved safety due to speed reduction prior to a fog area over the no warning system scenario. Wu *et al.* (2018c) conducted a driving simulator study to evaluate the effectiveness of the Head-Up Display (HUD) warning system in drivers' braking behaviors. The results indicated the system can help decrease drivers' reaction time and reduce the probability of accidents.

The information exchange between the CV technology and the driver is critical content to be studied, especially due to the benefits it can offer to highway management, reducing investments for the elimination of stretches with high accident indexes like s-curves, i.e., complex curves with a generally small radius and short tangent (LI; YAN; WONG, 2015).

The road geometry of curves is complex, thus hampering driving and often violating a driver's expectations. Milosevic and Milic (1990) investigated drivers' perception of vehicle speed in curves and reported drivers tend to underestimate their speed. Speed underestimation on curved roads can significantly contribute to sudden speed variations, hence, accidents. Good accident-prevention measures must, therefore, be selected according to the characteristics of the curves for preventing drivers from misperceiving their speed.

Although previous studies have analyzed the effects of fog warning systems on drivers' speed maneuvers, few have compared drivers' behaviors while driving in curved segments in different weather scenarios.

Multiple ADAS implementation positively impacts drivers' behavior but still lacks the ability to address some issues when there is foggy weather condition by assessing the relationship between human behavior and a single ADAS (fog warning system). This research analyzes the effects of an in-vehicle fog warning on a driver's speed profile on a stretch of road with critical geometric (s-curves) and weather (fog) conditions. An experiment conducted in a driving simulator considered the benefits of its use since it helps evaluations of the effectiveness of inclement weather warning technologies due to their capacity to provide real-world scenarios at a relatively low cost (compared to real-world experiments) and no risks to the driver's life (LUCAS *et al.*, 2013).

Countries have different climates, traffic compositions, and road geometries, and these different characteristics may influence driving behavior. A broad understanding of low visibility driving behavior in different countries can help researchers and designers improve road safety through more effective safety measures. The scenarios employed were in a simulated rural Brazilian road known for its several s-curves and frequent incidence of fog. A Weighted Severity Index (WSI) methodology defined the critical segment.

3.2 Methods

3.2.1 Apparatus

The simulator is part of the Sustainable Road Safety Project of the Department of Transportation Engineering from the São Carlos School of Engineering, University of São Paulo—Brazil. It can support driving simulations in several rural traffic environments under laboratory control according to different experimental purposes and was used in previous studies (CALSAVARA; KABBACH JUNIOR; LAROCCA, 2021; DE CAMPOS *et al.*, 2020; FIGUEIRA; LAROCCA, 2020a, 2020b; LAROCCA *et al.*, 2018; SANTOS *et al.*, 2017; VIEIRA; LAROCCA, 2017). It is comprised of a driving cockpit with a car seat, a steering wheel with paddle shift and force feedback, accelerator, brake, clutch pedals, and speakers to reproduce vehicle engines and wind sounds (Figure 12). A flat panel projected the simulated environment, lateral mirrors, rear mirrors, and a HUD (for speed and fog warning information).

Two computers process the real-time simulation—one is responsible for environment rendering and simulation running, and the other models the vehicle's dynamics, including a road-vehicle interaction and mechanical responses to the driver's actions.

Figure 12 – Simulator's physical structure (scheme)

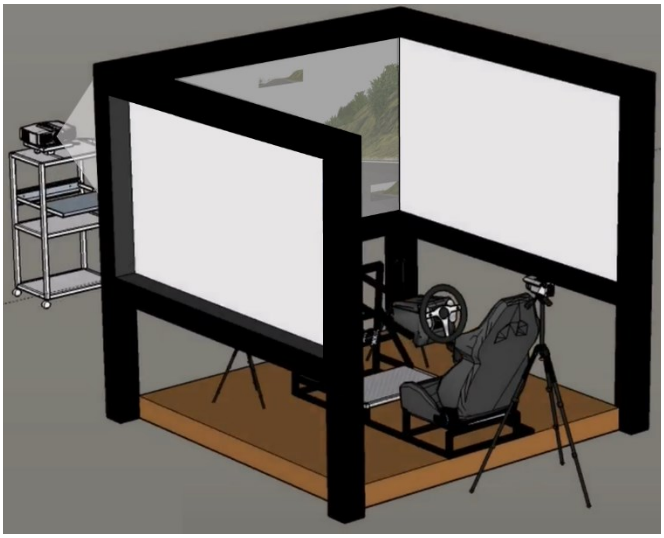
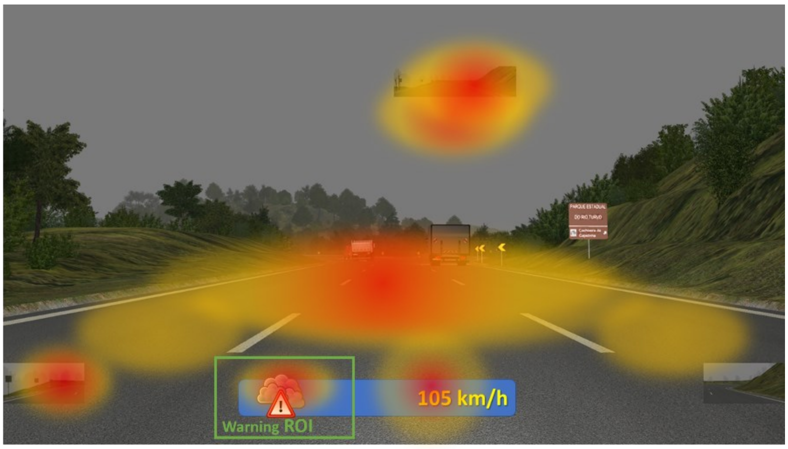


Figure 13 – Representative screen and head-up display (with heat map and fog warning region of interest displayed)



In addition to the components described above, appropriate equipment—model Pro 5.10® Smart Eye—was attached to the simulator to record eye movements. Pro 5.10 is comprised of three front cameras that perform the driver's eye-tracking, and an additional rear camera, which records the scenes seen by the driver. The equipment provides raw data reliability and 3D filtered data, and remotely tracks the direction of the gaze calculated automatically based on X and Y coordinates.

MAPPS® 3.3 software, developed by EyesDX (Coralville, IA), analyzed data on the eyes' movement. A frame-by-frame analysis was conducted on a video with the eye's position overlaid on the field of view to identify participants' attention allocation on HUD when the fog warning was displayed. In order to investigate how often and when the participants inspected the HUD, the fog warning region in HUD was defined as one region of interest (ROI), and only the participants whose fixation in the warning moment fell within this area were part of the sample of this research. Figure 13 shows an example of the software interface, which detects the intersection of the driver's gaze with objects created in the environment for better determining the response time and maps the areas on the screen most viewed by the driver on a heat map.

3.2.2 Simulated Location

The rural road simulated is a 5 km stretch of an important Brazilian highway that connects Sao Paulo to Curitiba and is the primary connection between the south and southeast regions (Figure 14). The stretch is in a mountainous region with high fog incidence and a large number of s-curves in its geometry. The highway administrator provided the stretch geometric design necessary for virtual modeling, the AADT (Average Annual Daily Traffic), as well as the location, type, and severity of accidents that have occurred in recent years.

The period for the simulation was the month of June, and the time was set to 6 am, which, according to data from federal highway patrol (DPRF, 2021), is the most frequent period for accidents under fog weather (Figure 15). Such findings are in line with the results of Abdel-Aty *et al.* (2011) who, in a detailed study of traffic accidents in the state of Florida (US), observed fog was the main cause of collisions in rural areas, during the winter months and in the early hours of the morning.

Figure 14 – Distribution of accidents under fog in Brazilian federal highways, with predominance in South and Southeast regions, which together represent approximately 80% of such accidents

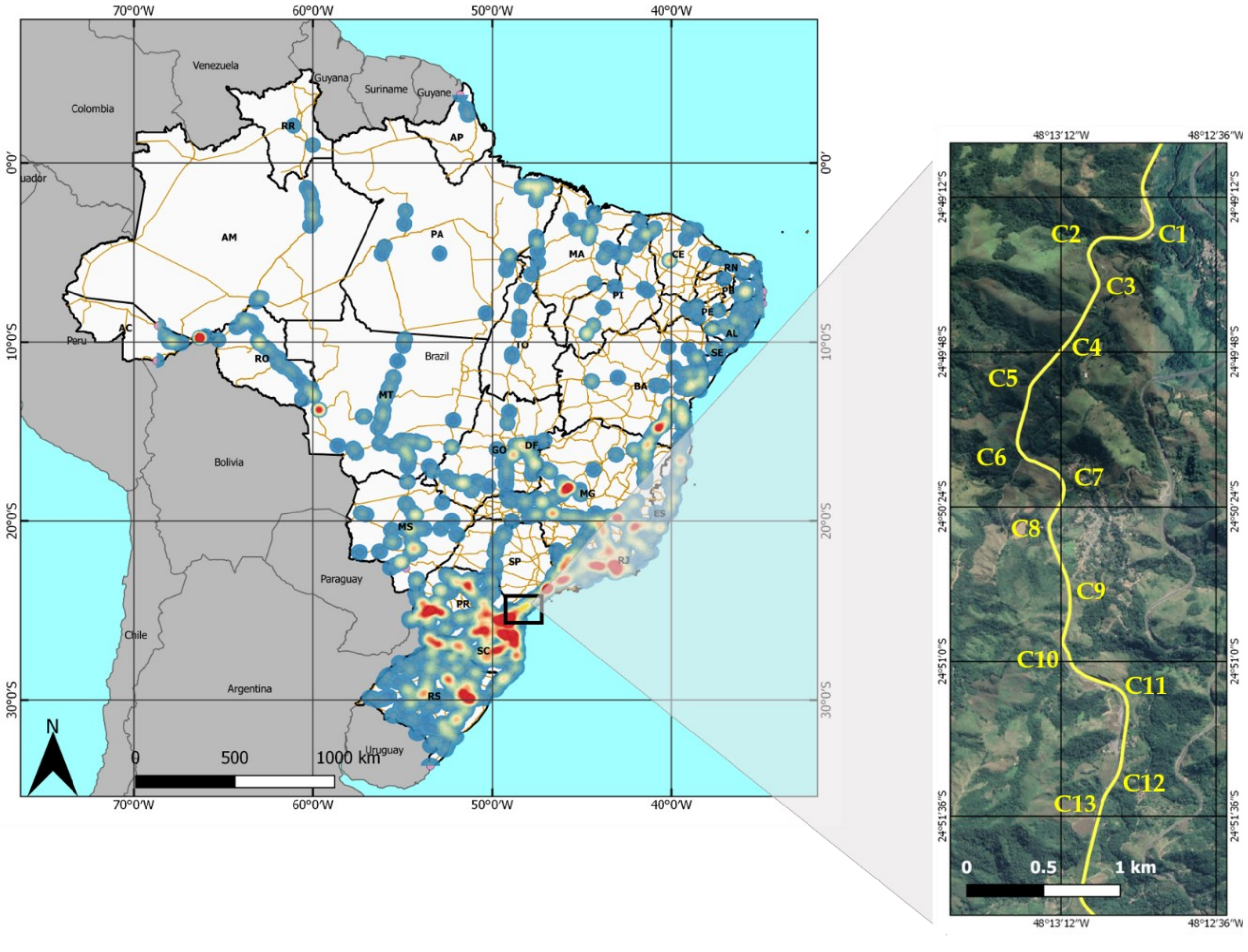
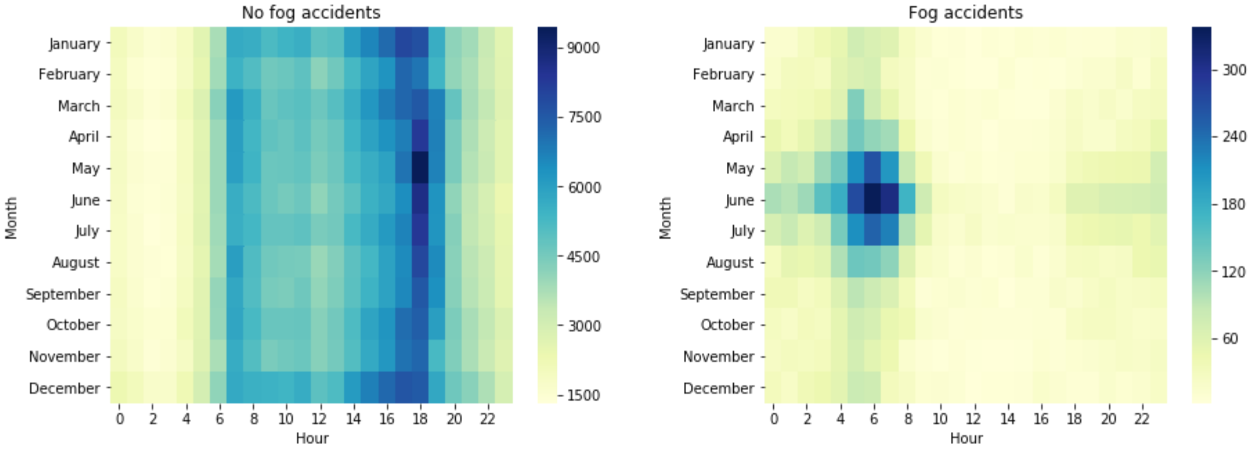


Figure 15 – Distribution of accidents in Brazilian federal highways along year and day over the past ten years: under fog weather (right) and under no fog weather (left)



3.2.3 *Analyses of Curve*

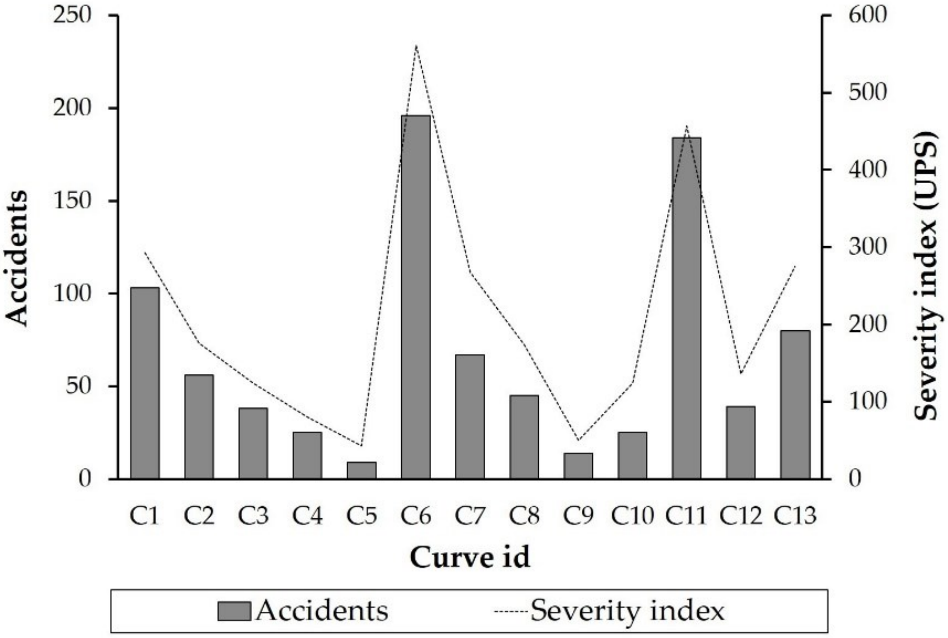
The 5 km stretch comprises 13 curves, and the fog analysis was performed in a segment selected according to the fog car crash statistics of the stretch from 2011 to 2020. The high number of traffic accidents is usually associated with inadequate driving maneuvers of the driver induced by the road geometry (LI; YAN; WONG, 2015)—in this case, by the s-curves of the analyzed section.

Apart from the absolute indices of victims and/or traffic accidents, a Weighted Severity Index (WSI) methodology identified the most critical curves in the segment. WSI is a numerical method of the Brazilian National Traffic Department (Denatran) that attributes weight to the types of accidents according to the severity of the damage caused. In Brazil, Denatran (1987) recommends the following weights and respective expression (Equation 1) for determining the severity index (S), measured in UPS (Standard Severity Unit), where D, V, and F represent the number of accidents with no victims (with only material damage), with non-fatal victims, and with fatal victims, respectively.

$$S = 1 \times D + 5 \times V + 13 \times F \quad (1)$$

WSI was determined for each curve of the stretch (see Figure 16) with the accidents reported over the last ten years. The 6th curve (C6) showed a higher number of accidents and severity index. Both the curve and the posterior one (C7) are complex curves with a small radius and short tangents (previous C6 tangent length: 275 m; C6 curve sector: 245 m length and 130 m radius; afterward C6 tangent length: 50 m; C7 curve sector: 340 m length and 180 m radius), classified as s-curves.

Figure 16 – Car crash statistics and severity index identified by curves



The hypothesis is that accidents are related to drivers' inability to react properly under fog conditions at those spots. According to geometry and crash statistics, the analyses of fog were performed between C6 and C7.

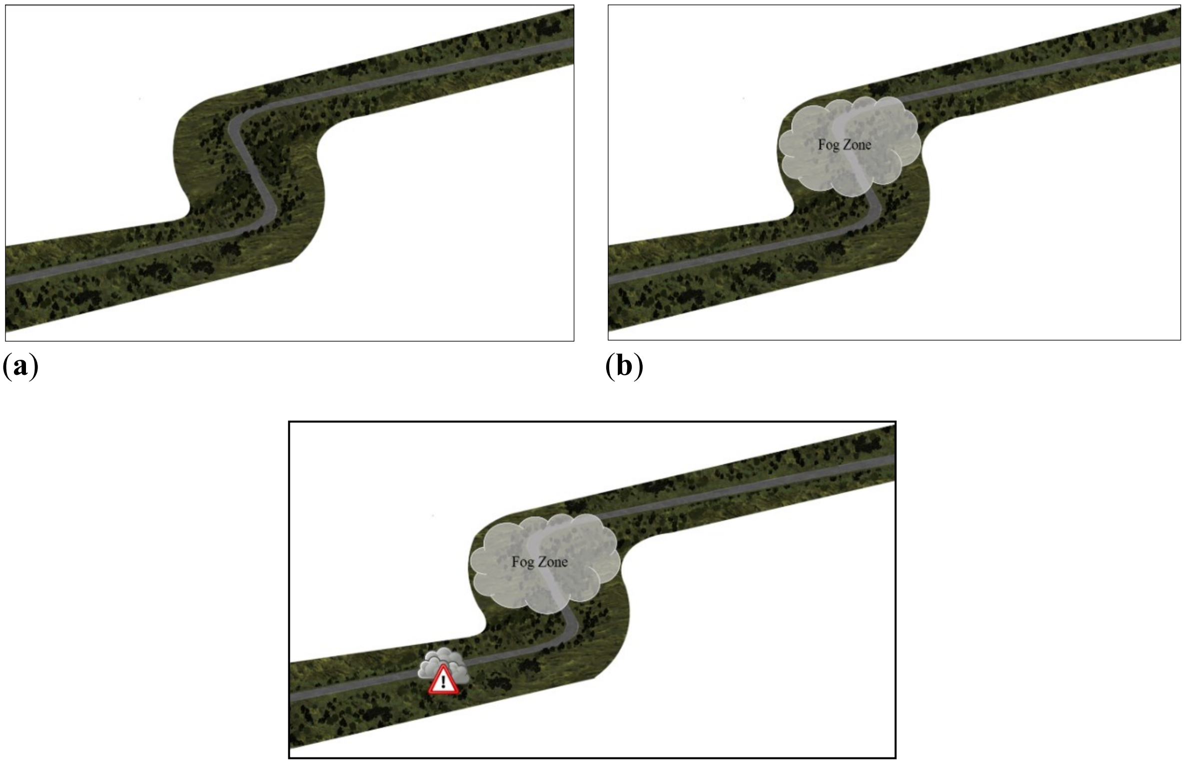
3.2.4 Scenarios

The scenarios were modeled and simulated by Virtual Test Drive (VTD) package developed and marketed by Vires®(Bad Aibling, Germany), according to the data collected. The data sets obtained were then analyzed by Python 3.6 programming codes. All scenarios were designed for analyses in the selected stretch, with a heavy x passenger car proportion of the traffic flow respecting the results from National Traffic Counting Plan (DNIT, 2018), at 6:00 am under a cloudy sky. Traffic was deactivated prior to the driver's entering the fog study area for avoiding the influence of nearby cars.

The only changes between the scenarios were the presence or absence of fog and fog warning for ensuring differences would not be confused with other factors. Fog position (settled in the tangent between C6 and C7) and fog intensity based on visibility (50 m) were fixed in all foggy trials. Fog warning was settled 400 m prior to the driver´s entering fog position.

Figure 17 illustrates the three scenarios analyzed, i.e., clear weather (Figure 17a), fog weather (Figure 17b), and fog weather with an in-vehicle fog warning system, referred to as “Fog&CV” (Figure 17c).

Figure 17 – View of simulated C-6 and C-7 geometry scenarios. (**a**) clear weather, (**b**) fog weather, and (**c**) fog&CV.



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

(**c**)

3.2.5 *Experimental Design and Procedure*

Trials were conducted with twenty-eight participants, who were required to have had a driver’s license for at least one year and normal or corrected-to-normal vision. The group of volunteers was formed by 18 men and 10 women, aged between 21 and 33 years old (M = 25.4, SE = 4.0).

A repeated-measures ANOVA design was employed, and each participant experienced clear weather, fog weather, and fog weather with fog warning, thus totalizing three trials/scenarios for each one. The clear weather scenario (Figure 5a) represents the baseline group and will be useful for analyses of drivers' default behavior. The other two scenarios (Figure 17b,c) are expected to enable analyses of the way both fog and CV technologies inside the car change the drivers' behavior. The order of the scenarios was randomly sorted for each participant towards avoiding bias, as well as accommodating the limited time each participant would spend in the simulator and minimizing possible simulator sickness.

A Protection of Human Subjects in Research approval (number 2.611.849) was obtained from the Brazilian National Health Council prior to the experiments. Upon arrival at the laboratory, each participant signed informed consent and filled out a personal information questionnaire. They were also instructed on procedures and mechanical operations of the driving simulator. The instructions did not include any detailed information on the experiments that might potentially influence the driving behavior. The participants were asked to drive as normally as they usually do in a real car. Subsequently, they drove an adaptation scenario until they had felt adapted to the simulator and comfortable with the simulation. The adaptation simulation lasted at least 5 min for each participant and could be repeated as many times as necessary. After the adaptation scenario, the participants drove for approximately 5 min in each of the three experimental scenarios, with a 2-min interval between them. They were instructed to pull over and stop after they had driven through the data collection segments. The experiment lasted approximately 30 min.

3.2.6 Data Analysis

A two-way repeated-measures ANOVA is often used to compare two or more groups evaluated at different moments. In this research, 3 groups (scenarios) were compared at 2 different moments (before and after the 6th curve). The ANOVA test was applied by Jamovi (version 1.1) software for the analysis of the effect of different scenarios conditions on speed. All follow-up analyses used Tukey test correction for multiple comparisons. Normality was fulfilled with the Shapiro-Wilk test for all scenarios, and descriptive statistics (mean and standard deviation) for speed are shown in Table 5.

Table 5 – Speed mean and standard deviation before and after C6 per scenario

Scenario	Speed (km/h)			
	Before C6		After C6	
	Mean	SD *	Mean	SD *
Clear	92.1	6.3	77.8	10.4
Fog	88.7	10.1	68.6	8.8
Fog & CV	78.8	16.1	57.5	10.9

* SD = Standard deviation.

3.3 Results and Discussion

3.3.1 General Results

Figure 18 shows the color path of all participants' average speed changes in each scenario—the speed along the curve was not constant and was adjusted according to the curve geometry, as observed by Li, Yan and Wong (2015). The average speed was higher before and after C6 in the clear weather scenario compared to other scenarios. The color path figure (Figure 18) is consistent with the graphic displayed in Figure 19, where the comparison of speeds between scenarios is easier. After C6, the speed is significantly decreased in the three scenarios, due to the influence of the road geometry. In presence of fog, the speed decrease was greater in the scenario with CV warning.

Figure 18 – Color path of all participants´ average speeds (km/h) when performing the 6th curve (C6) and 7th curve (C7) in each scenario

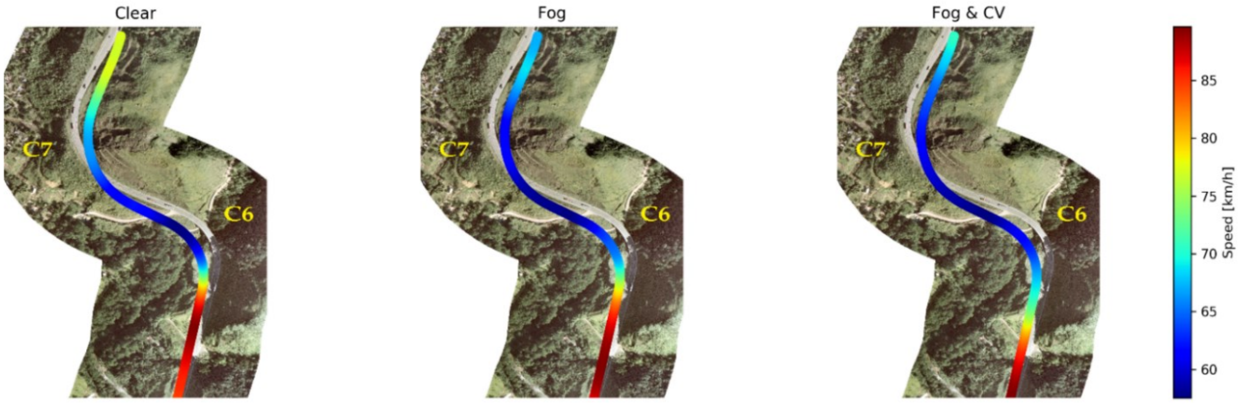
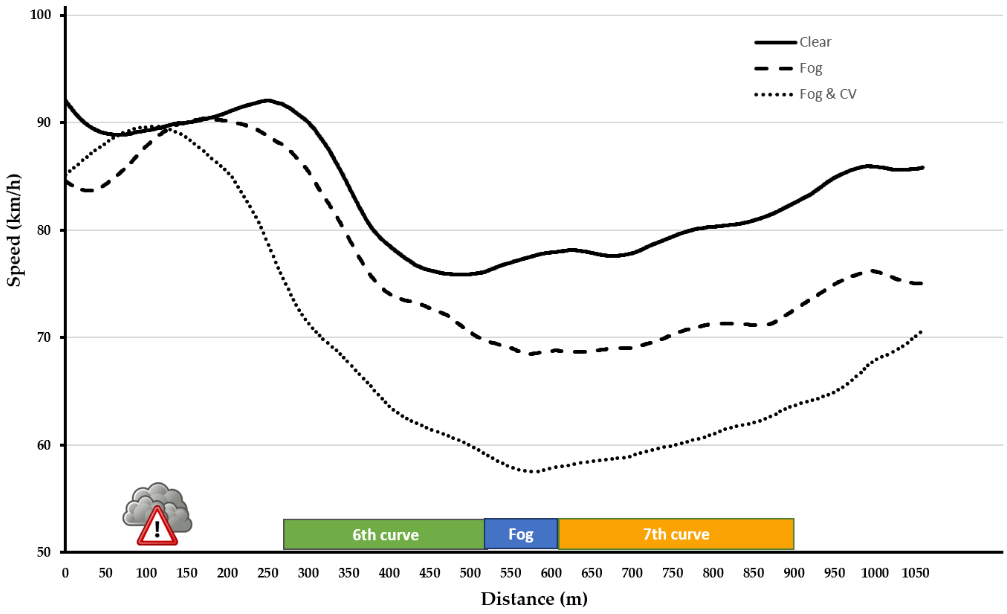


Figure 19 – Comparison of all participants´ average speeds (km/h) in each scenario



3.3.2 *Summary Statistics*

The average speeds at which the participants drove under clear weather in the simulator were 92.1 km/h before C6 and 77.8 km/h after C6. The average speeds driven under fog weather were 88.7 km/h before C6, and 68.6 km/h after C6. Finally, in the fog & CV scenario, the average driving speeds were 78.8 km/ h before C6 and 57.5 km/h after C6. Table 5 shows the means and standard deviations speeds.

3.3.3 *Two-Way Repeated Measures ANOVA*

Two-way ANOVA with repeated measures analyzed the average speed variations during the experiment before and after C6 and its interaction with the scenarios (Within Subjects Effects) shown in Table 6. The scenarios interaction (Between Subjects Effects) was also analyzed and is shown in Table 7. The hypothesis testing in the analysis was based on a 0.05 significance level.

Both scenario (Clear/Fog/Fog&CV) [F (2, 81) = 27.1; $p < 0.001$] and the curve moment (After/Before) [F (1, 81) = 217.63; $p < 0.001$] significantly influenced the average speed. The analyses also revealed an effect of the interaction between scenario and curve moment on speed

[F (2, 81) = 6.96; p = 0.002]. Post hoc comparisons were performed with a Tukey test for identifying differences (Table 8).

Table 6 – Repeated Measures ANOVA for within-subjects effects

Source	Sum of Squares	df	Mean Square	F	*p*
C6 moment	12,984	1	12,984	217.63	<0 .001
C6 moment × Scenario *	830	2	415	6.96	0.002
Residual	4833	81	59.7	-	-

Note. Type 3 Sums of Squares. (*) interaction between scenario and moment in 6th curve.

Table 7 – Repeated Measures ANOVA for between-subjects effects

Source	Sum of Squares	df	Mean Square	F	*p*
Scenario	9452	2	4726	27.1	<0 .001
Residual	14,146	81	175	-	-

Note. Type 3 Sums of Squares.

Table 8 – Post Hoc Comparisons — C6 moment × Scenario

Comparison								
C6 moment	Scenario	C6 moment	Scenario	M *	SE	df	*t*	p_{tukey}
Before	Clear	Before	Fog	3.41	2.89	130.6	1.178	0.847
-	-	Before	Fog & CV	13.35	2.89	130.6	4.614	< 0.001
-	-	After	Clear	11.33	2.06	81.0	5.487	<0 .001
-	-	After	Fog	23.57	2.89	130.6	8.149	< 0.001
-	-	After	Fog & CV	34.60	2.89	130.6	11.960	<0.001
-	Fog	Before	Fog & CV	9.94	2.89	130.6	3.436	0.010
-	-	After	Clear	7.92	2.89	130.6	2.738	0.075
-	-	After	Fog	20.17	2.06	81.0	9.769	<0.001
-	-	After	Fog & CV	31.19	2.89	130.6	10.783	<0.001
-	Fog & CV	After	Clear	−2.02	2.89	130.6	−0.698	0.982
-	-	After	Fog	10.23	2.89	130.6	3.536	0.007
-	-	After	Fog & CV	21.25	2.06	81.0	10.295	<0.001
After	Clear	After	Fog	12.25	2.89	130.6	4.234	<0.001
-	-	After	Fog & CV	23.27	2.89	130.6	8.045	<0.001
-	Fog	After	Fog & CV	11.02	2.89	130.6	3.811	0.003

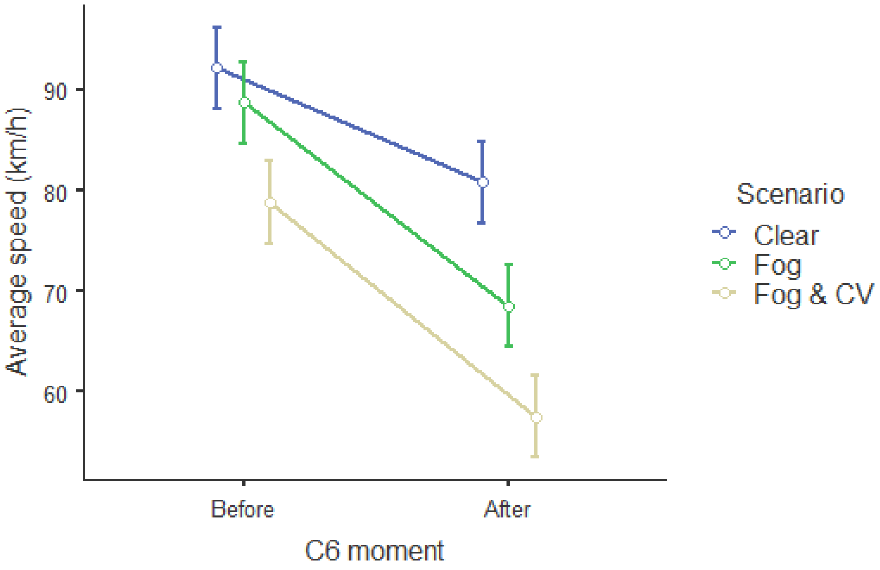
* M = Mean difference; SE = Standard Error; df = Degrees of freedom.

The Post hoc analysis concerned the impact of each scenario’s conditions and the curve moment of the measurement (before/after) on the average speed of the participants.

Towards a better understanding of the interaction effect, the changes in the presence/absence of fog and fog warning in each scenario at the beginning of the curve were compared. Before entering C6 and under clear weather conditions, the participants experienced the same average speed as those in the Fog scenario (M = 3.41) $p = 0.847 > 0.05$, which was expected, since no change occurred between the scenarios, and fog would occur only after the curve. However, before entering C6, the participants under fog weather condition experienced a different average speed of those in the Fog&CV scenario (M = 9.94) $p = 0.010 < 0.05$. Furthermore, before entering C6, the participants under clear weather conditions also experienced a different average speed in comparison to those in the Fog&CV scenario (M = 13.35) $p < 0.001$, possibly indicating the warning led to a speed reduction.

Similarly, the way the presence/absence of fog and fog warning changed in each scenario after C6 was also compared. The participants under clear weather conditions experienced a different average speed in comparison to those in the fog scenario (M = 12.25) $p < 0.001$ and those in the Fog&CV one (M = 23.27) $p < -0.001$. After C6, the participants under fog condition experienced a different average speed compared to those in the Fog&CV scenario (M = 11.02) $p = 0.003 < 0.05$. The results show the participants in each scenario drove at different speeds after performing the curve and entering the fog zone (see Figure 20).

Figure 20 – Estimated Marginal Means of average speed (km/h) in each scenario and curve moment



3.4 Conclusions and Future Research

This study aims at spurring safety improvements in regions of visibility problems caused by fog, reducing their environmental impact, and preserving drivers' lives. This is one of the first studies that use driving simulators to understand the driving infrastructure's environment under fog in the Brazilian scenario

A two-way ANOVA with repeated measures revealed both fog and in-vehicle fog warning systems can effectively reduce drivers´ driving speed. According to a paired comparison with Tukey's correction, the warning shown on the HUD led to an earlier speed reduction in the Fog&CV scenario. The average driving speeds reduced from 78.8 km/h before C6 to 57.5 km/h after C6, which represents a reduction of approximately 27%. This reduction before and after the curve is more significant than the reductions of 15.5% and 22.7% observed in the clear and fog scenarios, respectively. Therefore, a vehicle with an in-vehicle warning system enables drivers to drive at lower speeds in a fog region.

Although in fog weather drivers tend to drive more cautiously and at lower speeds, this is not sufficient to compensate for the hazards imposed by adverse weather. A CV technology would substantially improve road safety since drivers would better adjust speed to enter a fog zone and proceed to a successive curve.

An in-vehicle warning system can improve the speed profile of drivers performing s-curves. Efficient CV technologies would lead to lower-cost changes in road safety in comparison to those in the highway infrastructure.

Connected vehicles technologies can potentially transform our way to drive. However, prior to their broad implementation, several technical challenges must be overcome. Countries and regions must harmonize their research, standards, policies, and technology; the use of different communications standards, for instance, will hamper the application of connected vehicle technology, since the one used in a certain region may not work in another.

Such technology can also decrease crash risk through the incorporation of drivers' personal characteristics in warning systems, and improve traffic safety under fog conditions. This study was limited to analyzing the drivers' speed profile to detect differences due to the use of a single ADAS. Future research should investigate the effects of different delivery times of warning messages under fog conditions, different designs of the head-up display, and the implementation of multiple ADAS combined.

4. Conclusions

This chapter addresses the major conclusions from simulator tests on drivers' behavior in low-visibility situations according to their visual performance and speed profile.

4.1 Research Paper of Chapter 2

A driving simulator investigated whether fog (presence or absence) significantly affects the visual profile of a driver performing a winding stretch under fog and clear conditions.

Regarding differences in the spread of view, the drivers' areas tracked were reduced under foggy conditions and a large number of visualizations was provided in the center of the screen, indicating drivers do not see much beyond the highway shoulders.

Under foggy conditions, the duration of the drivers' fixations (i.e., their information processing time) is the same as that in a scenario with no fog. On the other hand, the amount of information processed leads to a significant difference clearly shown by the increased number of fixations in the foggy scenario over the clear one.

Our results can enable designers to reconsider traffic signs' locations towards ensuring they are visible in a foggy scenario (e.g., on gantries over the roadway) and helpful for car manufacturers to design in-vehicle warning systems that enhance the effectiveness of the system's application. Similarly, the knowledge on number of fixations and their processing times can help improve image identification algorithms in autonomous vehicles. Developers can increase the accuracy of such algorithms by indicating regions that require a better visualization by the driver.

4.2 Research Paper of Chapter 3

The literature lacks studies on the influence of fog in-vehicle warning systems on drivers' performance; therefore, this research examines the effects of fog on the driver's speed profile in a driving simulator experiment.

In the first stage, geographic analyses of accidents that occurred under low visibility conditions and the identification of critical periods were conducted. In comparison with crashes under clear conditions, fog-related ones often occur in Brazil's southern region, in winter months and during the first hours of the day.

The main conclusion from the use of connected vehicle technology is it substantially improves road safety, since drivers can better adjust their speed to enter a foggy zone. In an in-vehicle fog warning system scenario, the average driving speed is reduced from 78.8 km/h prior to the curve to 57.5 km/h after it, thus representing an approximately 27% reduction, which is greater than reductions in clear and foggy scenarios.

The implementation of in-vehicle warning systems can avoid or reduce the need for major infrastructure interventions, such as geometric design, through investments in new intelligent transport systems. When vehicles share their status information with other vehicles or with the infrastructure, actions during driving can be better planned, hazards can be earlier identified, and safer responses can be obtained.

4.3 Recommendations for Future Studies

The implementation of in-vehicle warning systems can avoid or reduce the need for major infrastructure interventions such as geometric design, through investments in new intelligent transport systems. Although some studies have addressed driving under foggy conditions, the literature lacks research on eye-tracking as a dependent variable.

Suggestions for future research include new analyses, such as those presented in this study, towards the understanding of a driving behavior after a fog warning has been sent by the vehicle and investigations on the effects of different delivery times of warning messages under fog conditions, different warning designs on the head-up display, different types and sizes of letter, audible warnings, and implementation of multiple in-vehicle technologies combined.

This study is one of the first on the use of driving simulators with realistic representations of a road infrastructure and its surroundings for the understanding of driving under fog in the Brazilian scenario. Countries and regions must harmonize their research, standards, policies, and technology, since those used in a specific region may not suit another.

Finally, such in-vehicle technology can also decrease crash risks through the incorporation of drivers’ personal characteristics such as age, sex, and driving experience in warning systems towards improving traffic safety under fog conditions.

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