**Universidade de Aveiro** Departamento de Engenharia Mecânica
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**Beatriz da Silva Fernandes**

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Análise da Fiabilidade de um Simulador de Condução para Reprodução da Dinâmica de Veículos do Ponto de Vista Microscópico

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestrado em Engenharia Mecânica, realizada sob orientação científica do Doutor Jorge Filipe Marto Bandeira, Investigador Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro, e da Doutora Eloísa Catarina Monteiro de Figueiredo Amaral e Macedo, Investigadora Doutorada (Nível 1) do Departamento de Engenharia Mecânica da Universidade de Aveiro.

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**Palavras-chave**

Transporte rodoviário, simulador de condução, modelos de emissões, fiabilidade, validação.

**Resumo**

Apesar da constante inovação tecnológica, o sector dos transportes rodoviários continua a ser uma fonte significativa de emissões poluentes. A investigação sobre soluções para aumentar a sustentabilidade dos veículos e reduzir as suas emissões é um tema oportuno. Embora experiências no mundo real possam ser consideradas, estas produzem alguns inconvenientes, como o aumento dos níveis de poluição e dos riscos de acidentes. Assim, as experiências baseadas em simuladores podem ser relevantes para estudar a dinâmica dos veículos e o comportamento dos condutores. Contudo, a utilidade científica e a robustez do simulador ficam seriamente comprometidas se a fiabilidade dos resultados da simulação não for assegurada. A presente dissertação centra-se numa análise exploratória que visa estudar a fiabilidade de um simulador de condução de base fixa para reproduzir os parâmetros de condução para a estimativa de emissões, analisando a acelareção e velocidade de 2 condutores em ambiente de simulação e em ambiente real. Os testes no simulador de condução e no mundo real foram realizados em cenários urbanos e de auto-estrada. Os parâmetros dinâmicos do veículo, tais como velocidade instantânea, aceleração e posição, foram recolhidos usando o software do simulador de condução (simulador Carnetsoft) nos testes virtuais, e um dispositivo OBD (on-board diagnostic) nos testes empíricos. A amostra de dados foi dividida em dez eventos que ocorrem tipicamente em viagens urbanas e de auto-estrada para melhor prosseguir com a avaliação comparativa dos resultados obtidos. As emissões poluentes foram estimadas utilizando a metodologia VSP (Vehicle-Specific-Power). Uma avaliação comparativa e um teste Kolmogorov-Smirnov de duas amostras (teste K-S) foram conduzidos para validar os resultados obtidos e avaliar a fiabilidade de um simulador de condução na reprodução da dinâmica e emissões de veículos. Os resultados desta análise exploratória de validação mostraram que, com um erro relativo de 4% e tendo em conta o pequeno número de participantes, as emissões médias totais de todos os eventos não foram significativamente diferentes (958,39 g para os testes simulados e 998,06 g para os testes empíricos). Os resultados dos testes K-S revelaram que as distribuições do modo VSP não seguiram o mesmo padrão em 4 de 10 eventos, nomeadamente "curva à esquerda depois de um semáforo", "entrar na auto-estrada", "sair da auto-estrada" e "seguir em frente" para o condutor 1 e "curva à direita com prioridade", "ceder passagem", "sair da auto-estrada" e "seguir em frente" para o condutor 2. Isto significa que os condutores apresentaram comportamentos diferentes tanto nos testes simulados como empíricos para esses eventos específicos. Verificou-se que, em geral, o simulador de condução pode replicar a dinâmica do veículo de uma perspectiva microscópica. No entanto, um estudo profundo sobre o comportamento do condutor num simulador, em comparação com um ambiente do mundo real, deveria ser posto em prática para resultados mais rigorosos.

**Keywords** Road transport, driving simulator, emission models, reliability, validation.

**Abstract**

Despite the constant technological innovation, the road transport sector remains a significant source of pollutant emissions. Research on solutions to increase the sustainability of vehicles and reduce their emissions is a timely topic. Although real-world experiments can be considered, these yield some drawbacks, like increased levels of pollution and risks of accidents. Thus, simulator-based experiments can be relevant to studying vehicle dynamics and driver behaviour. However, the scientific usefulness and robustness of the simulator are severely compromised if the reliability of the simulation results is not ensured. The present dissertation focuses on an exploratory analysis that aims to study the reliability of a fixed-based driving simulator to reproduce driving parameters for emission estimation by analyzing the acceleration and speed of 2 drivers in a simulation environment and in a real environment. Tests conducted on both a driving simulator and real-world cases were performed on an urban and a highway scenario. Vehicle dynamic parameters, such as instantaneous speed, acceleration, and position, were collected using the driving simulator software (Carnetsoft simulator) in the simulation tests, while an in-vehicle OBD (on-board diagnostics) device was used under the empirical tests. The data sample was divided into ten events that typically occur on urban and highway trips to better proceed with the comparative evaluation of the obtained results. The pollutant emissions were estimated using the Vehicle-Specific-Power (VSP) methodology. A comparative evaluation and a two-sample Kolmogorov-Smirnov test (K-S test) were conducted to validate the obtained results and assess the reliability of a driving simulator in reproducing vehicle dynamics and emissions. The results of this exploratory validation analysis showed that, with a relative error of 4% and accounting for the small number of participants, the total average emissions of all events were not significantly different (958,39 g for simulated and 998,06 g for empirical tests). The K-S test results revealed that the VSP mode distributions did not follow the same pattern in 4 out of 10 events, namely "left-turn after a traffic light", "entering highway", "exiting highway" and "moving forward" for driver 1 and "right-turn with priority", "give way", "exiting highway" and "moving forward" for driver 2. This means that the drivers displayed different behaviours in both the simulated and empirical tests for those specific events. It was found that in general, the driving simulator can replicate vehicle dynamics from a microscopic perspective. Nevertheless, a deep study on driver's behaviour in a simulator compared to a real-world environment should be put in place for more rigorous results.

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# Nomenclature

| | |
|---|---|
| $CO_2$ | Carbon Dioxide |
| $CO$ | Carbon Monoxide |
| $NO_2$ | Nitrogen dioxide |
| $NO_x$ | Oxides of Nitrogen |
| $O_3$ | Ozone |
| CMEM | Comprehensive modal emission model |
| EC | European Commission |
| EU | European Union |
| GHG | Greenhouse Gases |
| GNSS | Global navigation satellite system |
| HC | Hydrocarbon |
| K-S | Kolmogorov-Sminorv |
| LDDV | Light duty diesel vehicles |
| LDGV | light duty gasoline vehicles |
| LDT | Light-duty trucks |
| LDV | Light-duty vehicles |
| OBD | On-Board Diagnostics |
| PM | Particulate matter |
| RPM | Revolutions per minute |
| VSP | vehicle-specific-power |
| VT-Micro | The Virginia Tech microscopic energy and emission model |

# Chapter 1

# Introduction

## 1.1 Motivation and Relevance

### 1.1.1 Importance of Transport

Transports can be described as activities that involve moving people or things from one location to another in the most practical manner [Dinu, 2018] and have gradually become more essential over the years.

This sector provides direct benefits to businesses, the economy and people. For businesses, it connects them to their customers, markets and other businesses. For the economy, transport-related activities contribute to a country's total economic output, aid in the growth of the national or regional economy [Wood, 2021], enable tourism and connect the global system. For people, transport and, in particular, the ownership of a private vehicle has increased access to the basic requirements of living [Bhardwaj et al., 2019], creating distances and obstacles only it can overcome [Aldred and Woodcock, 2008].

Private vehicles have been the dominant mode of transport for a long time [Velaga et al., 2012] and have overtaken the use of public transport [Berg and Ihlström, 2019]. As supported in Table 1.1, in Portugal, the number of passenger cars in circulation has been increasing since 2012, making the number of passenger cars on Portuguese roads higher than all the other types of road transport. Over the past decades, developing economies' economic growth encouraged the expansion of their transport sectors, resulting in larger vehicle stocks [Bouachera and Mazraati, 2007].

Despite the constant technological innovation in this field, road transport is still responsible for many issues threatening people and the environment, such as excessive fuel consumption, pollutant emissions, traffic accidents and congestion [Black, 2010].

Table 1.1: Motorised road vehicles in circulation in Portugal by type of vehicles. Adapted from PORDATA [2021].

| Year | Passenger Cars | Light Commercial | Buses and Coaches | Heavy Trucks | Others |
|---|---|---|---|---|---|
| 2010 | 4 692 000 | 1 337 373 | 15 425 | 106 893 | 30 360 |
| 2011 | 4 712 354 | 1 321 711 | 15 181 | 101 840 | 30 102 |
| 2012 | 4 258 746 | 1 172 906 | 12 358 | 84 980 | 27 051 |
| 2013 | 4 334 364 | 1 167 306 | 12 119 | 81 940 | 29 235 |
| 2014 | 4 699 645 | 1 259 725 | 14 941 | 88 874 | 32 321 |
| 2015 | 4 722 963 | 1 224 821 | 14 717 | 88 398 | 32 795 |
| 2016 | 4 850 229 | 1 221 913 | 14 850 | 88 561 | 32 797 |
| 2017 | 5 059 472 | 1 240 914 | 15 235 | 95 904 | 35 716 |
| 2018 | 5 282 970 | 1 267 647 | 15 493 | 102 033 | 37 188 |
| 2019 | 5 452 119 | 1 396 653 | 17 819 | 116 384 | 44 616 |
| 2020 | 5 565 963 | 1 290 390 | 15 197 | 105 129 | 44 433 |

### 1.1.2 Challenges Facing Road Transport

#### Safety

Road accidents are one of the most detrimental externalities of transport, and their frequency is impacted by urban density, road infrastructure, as well as individual behaviour [Louro et al., 2021]. Road traffic accidents are the only factor in the top 10 causes of mortality that is not a sickness and are the eighth most prevalent cause of death across all age groups [World Health Organization, 2018]. In 2019, a total of 22 763 road traffic deaths and 948 511 road accidents causing personal injuries occurred on EU-28 roads [European Commission, 2021].

#### Congestion

In our daily lives, traffic congestion is a major problem [Mandhare et al., 2018], and the urban transportation system is greatly affected by the significant amount of delay and cost caused by it [Wang et al., 2014]. The excessive number of vehicles, population growth, inefficient public transport services and poor roadway conditions are some factors causing traffic congestion [Lomendra et al., 2018]. Besides affecting society and the economy, congestion often causes road accidents and induces high stress and frustration in commuters [Lomendra et al., 2018].

#### Environment

Energy and oil consumption and pollutants emissions from vehicles have a negative impact on the world's sustainability and human health.

The transport sector is responsible for almost 30% of the world's total energy consumption and 65% of world oil products consumption [Solaymani, 2019]. Regarding emissions, around 20% of all GHG emissions in Europe are attributed to the road transport sector [European Commission, 2019], with $CO_2$ emissions rising yearly and making a massive contribution to climate change, as shown in Figure 1.1.

It is essential to highlight that light vehicles represent the primary source of emissions of $CO_2$ within the category of road transport, as shown in Figure 1.2.

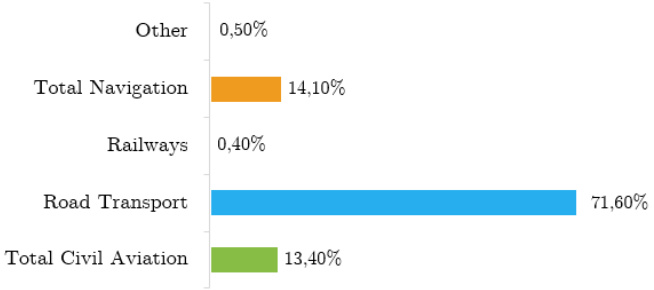


Figure 1.1: Percentages of $CO_2$ emissions by transport type in 2019. Adapted from European Commission [2021].

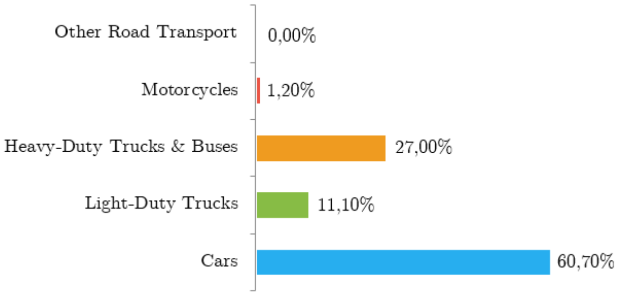


Figure 1.2: Percentages of $CO_2$ emissions by road transport type in 2019. Adapted from European Commission [2021].

Transport activities can be labelled as a source of some other pollutants of significant concern, like nitrogen oxides ($NO_x$), hydrocarbon (HC), carbon monoxide (CO) and particulate matter (PM). These pollutant emissions have significant health consequences, making the concerns caused by this industry go far beyond climate issues [Department for Transport, 2021].

Air pollution is believed to be responsible for several million premature deaths worldwide [Miller and Newby, 2019]. Laboratory studies indicate that exposure to nitrogen dioxide ($NO_2$), ozone ($O_3$), and PM has been correlated with the development of allergic responses [Krzyżanowski et al., 2005]. Moreover, ultrafine particles, such as those from diesel exhaust emissions, are a major source of nanoparticles in urban environments and cause cardiovascular issues [Miller and Newby, 2019]. Studies show a direct relationship between air pollution environmental exposure and the growth of cancerous pathologies and respiratory diseases, whether acute, chronic, or cancerous [Barreira et al., 2018].

In Europe, pollution control regulations are imposed by the Euro emission standards, which aim to promote the automotive industry's adoption of pollution control and energy efficiency mechanisms [Pinto, 2015]. The upward trend of adverse effects due to exposure to air pollution [Maia et al., 2018] represents a complex challenge for the 21st century, along with significantly reduced emissions and increased transport sustainability [European Commission, 2019].

The European Union's (EU) objective of at least a 55% GHG reduction target by 2030 and climate neutrality by 2050 can only be met by implementing more ambitious measures to immediately reduce transport's dependency on fossil fuels in coordination with zero pollution initiatives [European Commission, 2019]. The EC further asserts that for the EU to transition to a climate-neutral economy while also pursuing zero-emission mobility, transport emissions must be reduced by 90% by 2050 [European Commission, 2019].

In this context, it is essential to pay close attention to how to promote sustainability in the operation of these vehicles to rapidly and efficiently make a change and cut off the negative effects associated with road transport, especially regarding transport emissions. Numerous technical advancements and studies have been available for the estimation of road traffic impacts. In particular, various emission models —computer models created to estimate automobile emissions —have been proposed.

## 1.2 Vehicle Emission Models

Emission models are based on mathematical formulations of the existing relationships between emissions and the variables on which these emissions depend [De Blasiis et al., 2012]. These variables vary depending on the object of study, but some examples are speed, acceleration, geometric design of routes, driving cycle and reaction times. Concerning variable aggregation scale, emission models can be divided into three categories, as shown in Figure 1.3, depending on the scale of the parameters they measure - macro, meso, and micro levels.

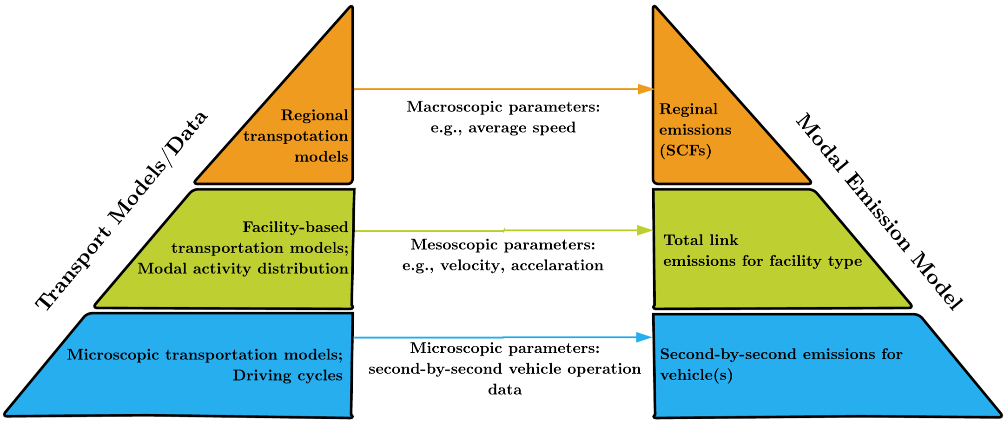


Figure 1.3: Transport emission model interface. Adapted from An et al. [1997]

Emission models can also be divided into static and dynamic models. Static models represent variables' aggregate level of consideration and are generally based on average vehicle speed. Dynamic models have a more detailed representation of the variables under review per second. The difference between these models can be understood with the help of the following diagram (Figure 1.4):

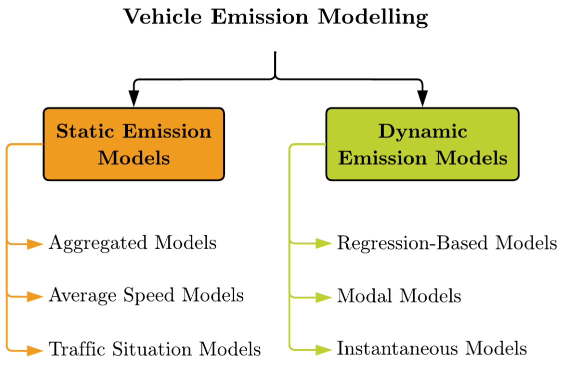


Figure 1.4: Vehicle emission modelling classification. Adapted from Alfaseeh and Farooq [2020]

Dynamic emission models, or modal models, generally consider the driving cycles of vehicles along their trajectory on the road network, i.e., the variation of operating modes at a constant speed, acceleration or deceleration. Thus, the operating conditions of vehicles at a given time, associated with a speed value, are recorded simultaneously with the number of pollutants emitted [Ariotti, 2010].

Instantaneous measurements of traffic characteristics allow for immediate or modal analysis and modelling based on immediate kinematic variables, such as speed and acceleration or on aggregated variables, such as the time the vehicle accelerates, cruises, or stops [Cappiello, 2002]. In general, dynamic emission models have the form of the Equation 1.1:

$$\mathrm{E}_i(t) = \sum\nolimits_j e_i(c_j, x_j(t)) \tag{1.1}$$

where:

$\mathrm{E}_i(t)$ = total emissions generated from pollutant i (or total fuel consumed) for a given analysis period in a given area;

$j$ = vehicle identification;

$c_j$ = Vehicle (j) category

$x_j(t)$ = represents the instantaneous or modal variable of vehicle j at time t. Some models also use historical variables, such as past values of speed or elapsed time since the start of the trip;

$e_i(c_j, x_j(t))$ = represents the emission of pollutant i for vehicle j at time t.

Since studies on the road transport emission impacts considering real-world experiments can entail some risks, mostly associated with the risk of a crash, the use of a driving simulator can be considered a good approach for conducting experiments by simulating a driving environment to study vehicle dynamics and driver behaviour on a microscopic level. Simulation for driving vehicles is a valuable research tool for studying driving in all its complexity. Driving simulators replicate the driving experience, presenting the users with visual, audible, and kinematic information [Rodwell et al., 2019]. This type of equipment has numerous practical applications, ranging from education and training to ecological and safety analysis.

## 1.3 Applications of Driving Simulator

Driving simulators are essential for, e.g., educating inexperienced drivers and have proven to increase the effectiveness of driver education [Rodwell et al., 2020]. These tools are also widely used in other types of training, such as police and emergency services training. The capability to replicate the driving experience without exposing the individuals to its risks make driving simulators excellent tools for training, learning and research outcomes. Thus, research is another important application of driving simulators. Many experiments to study driving behaviour are conducted in simulated environments. Its prominence stems from its ability to eliminate safety and ethical issues and avoid unexpected or risky events [Soares et al., 2020]. This research tool is qualified for many fields, such as human factor studies and studies on the effects of infrastructure on human behaviour. Research driving behaviour simulators are often used in research institutes, universities, and the automotive industry. One of the main advantages is that it allows the study of driving practices under conditions that would be illegal and unethical in an actual driving situation [Yu et al., 2016].

This dissertation focuses on a different application of driving simulators: eco-driving. This concept deals with the change of driving behaviour practices to improve fuel efficiency and, subsequently, reduce the emissions of road vehicles, and it has been demonstrated to have great potential in reducing fuel consumption and emissions [Martin et al., 2012]. As shown in Figure 1.5, the driver behaviour factor has, along with other vital factors, great relevance when it comes to vehicle energy consumption, and eco-driving has excellent potential for energy savings [Xu et al., 2021]. Driving behaviour accounts for up to 30% of the total energy consumption [Xu et al., 2021]. Simple changes in the driving technique, such as taking into consideration the best speed to achieve the best fuel economy, reducing idling conditions and shifting up as soon as possible, can considerably reduce vehicle emissions.

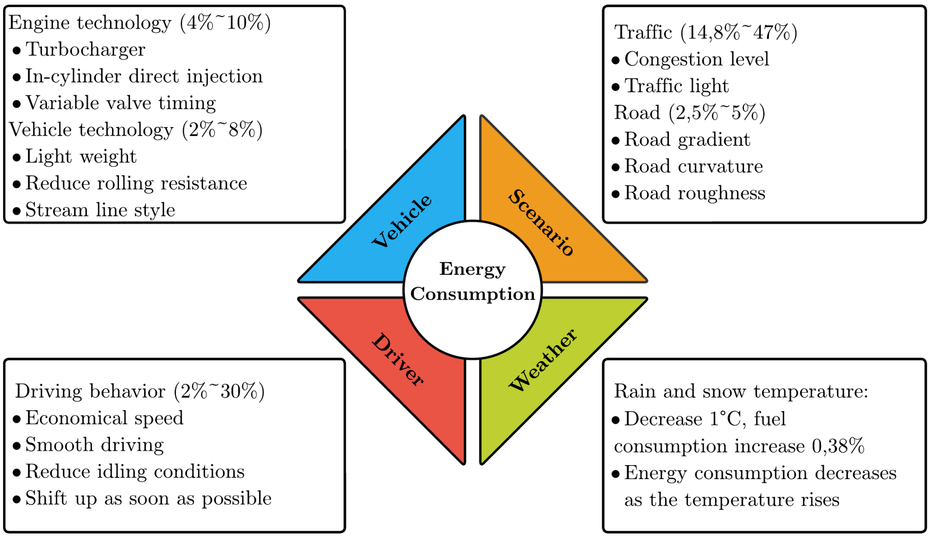


Figure 1.5: Primary factors affecting vehicle energy consumption. Adapted from Xu et al. [2021].

It has been reported that eco-driving could, on average, reduce fuel consumption by between 5% and 10% [Martin et al., 2012]. It is also seen as an economical and environmentally friendly strategy that reduces air and noise pollution and saves fuel [Beloufa et al., 2019]. Countries like Germany and Japan have already promoted eco-driving techniques by advising their citizens on simple but efficient ways of changing their driving behaviour to reduce the ecological footprint of their vehicles, such as keeping their speed constant and limiting the use of air conditioners [Hiraoka et al., 2009]. However, there is a lack of studies focusing on driving simulation to analyse vehicle emissions.

## 1.4 Objectives

This dissertation aims to evaluate the potential of a driving simulator to accurately reflect the impacts of vehicle emissions using the VSP emission model. In order to address this, this exploratory analysis seeks to validate data from tests conducted on both a driving simulator and the real world. These empirical and simulated tests are intended to show not only the variations in vehicle emissions but also the variations in drivers' actions in the simulator and on the road, as well as along various types of routes. Vehicle dynamic parameters, such as instantaneous speed, acceleration, and position, provided by the driving simulator software and the Global Navigation Satellite System (GNSS), will be analysed.

## 1.5 Dissertation Outline

This dissertation comprises six chapters.

Chapter 1 presents an overview of the current picture of the road transport impacts, mostly focused on pollutant emissions. It also introduces how road transport emission impacts are usually estimated. Then, this study's purpose, significance, and critical subjects are discussed, and finally, the objectives of this work are presented.

Chapter 2 describes the state-of-the-art regarding, factors that influence emissions, vehicle emission models and driving simulation, that are thoroughly reviewed considering earlier research on the topic.

Chapter 3 is devoted to the description of the methodology followed in this work, covering each phase, which includes the selection of participants, data collection methods, and emission-related calculation methodologies.

Chapter 4 presents an overview and description of the entire data set obtained through the simulator and empirical tests.

Chapter 5 presents the analysis and discussion of the results, broken down by scenario (urban and highway) as well as the analysis of the participants driving behavior. In the end, a microscopic analysis validation is executed.

Chapter 6 presents the conclusions of this exploratory validation analysis, and finally, the limitations of this exploratory analysis and suggestions for improving future research in this area will be made.

# Chapter 2

# State-of-the-art

The present literature review is conducted to establish the context and relevance of the proposed exploratory validation analysis. First, Section 2.1, mentions some important factors that influence vehicle's emissions. Then, in Section 2.2, there is an introduction to different types of emission models (dynamic and static), their importance, and what distinguishes each type. It is also discussed previous research focused on microscopic vehicle emission modelling. The following Section (Section 2.3) is devoted to an overview and discussion of different approaches to using driving simulation in the research field. Special attention is given to the analysis of the driving simulation validation, a subject within this field that deserves further investigation. Then, different studies using the same driving simulator used in this research are presented and discussed. At the end of this chapter, some limitations of the existing studies and research gaps are identified (Section 2.4).

## 2.1 Factors that Influence Emissions

It is important to analyse what factors influence vehicle emissions to promote environmentally friendly driving practices. Sivak and Schoettle [2012] studied the decisions that a driver can make to influence the on-road fuel economy of light-duty vehicles and divided these decisions into three categories- strategic decisions (vehicle selection and maintenance), tactical decisions (route selection and vehicle load), and operational decisions (driver behaviour). Results showed that the strategic decision of vehicle selection had the biggest effect. Nonetheless, the remaining variables that a driver has control over can result in a loss of the on-road fuel efficiency per driver of roughly 45%; these are:

### Driving Speed

The lowest fuel consumption is achieved when driving at a constant speed (Pietra et al. [2021]; Andrzejewski et al. [2020]). For example, El-Shawarby et al. [2005], discovered that keeping the speed in the 60 to 90 km/h range significantly reduced emissions per unit of distance. In 2021, Pietra et al. concluded that when driving at high speed, it is convenient to maintain the velocity value under a certain limit, which was set to 110 km/h.

**Use of Cruise Control**

Sivak and Schoettle [2012] concluded the use of cruise control increases highway mileage by roughly 7%. Simulation testing Ahn et al. [2011] showed that, on average, the eco-cruise control system could save 10% in fuel consumption and $CO_2$ emissions for different vehicle types.

**Use of Air Conditioner**

Pietra et al. [2021] concluded that the air conditioner compressor may consume up to 6 kW of power, this is similar to driving steadily at around 55 km/h in medium-sized automobiles. However, Haworth and Symmons [2001] when not using the air conditioner is paired with opening the window(s), the increased aerodynamic drag can more than make up the fuel savings above a certain speed.

**Idling**

In 2013, Rahman et al. conducted a study reviewed the impact of diesel vehicles idling on fuel consumption and exhaust emission, concluding that fuel consumption and emissions during idling are very high compared to the driving cycle and that idling reduction technologies reduce fuel consumption and emissions significantly.

**Aggressive Driving**

Aggressive driving can be categorized by a quick and frequent change in speed (strong acceleration and deceleration). Adamidis et al. [2020] assessed the impact of adopting smooth driving habits on traffic and emissions. With this study, it was determined that smooth driving leads to a statistically significant reduction in the emissions of the most important air pollutants. However, this is not always true. According to some studies (Saerens and Van den Bulck [2013]; Xia et al. [2013]), using harder accelerations to attain the required velocity more quickly might result in fuel and emissions savings.

Studies, such as the ones mentioned above, that analyse the influence of driving behaviour on vehicle emissions are becoming more common each year and are crucial for the increase of sustainability of vehicles. This type of research resorts to vehicle emission models to estimate the vehicle emissions from the obtained driving data; this is another imperative topic in this field.

## 2.2 Vehicle Emission Models

In 2012, De Blasiis et al. conducted a study to analyse emission factors using both static and dynamic models from driving simulator outcomes. This study aimed to understand the influence of driving behaviour on emission factors. Results showed a significant difference between the two categories of models, showing lower emission rate values of static models compared to dynamic ones. From that, different relationships between average speed and emission factors were investigated. The authors highlighted that, for dynamic models, drivers' behaviour strongly influenced emission parameters. Hence, the average speed value should be considered a non-representative emission phenomenon parameter. The second analysis of this research focused on driving behaviour in different scenarios concerning emission factors, and the authors found that the emission factors were independent of the average speed. In contrast, a good correlation was revealed between an increase in emission factors and an increase in speed changes (assessed by the standard deviation of speed). Finally, this research concluded that the complexity of geometry and interfering flow increases the emission rates exponentially in dynamic models.

As described in the Chapter 1, emissions models can also be characterised by the scale of aggregation of the variables, splitting the models into three levels - macroscopic, mesoscopic, and microscopic. The following subsection will summarise some of the most well-known microscopic vehicle emission models; these models are VT-Micro (Ariotti [2010], Rakha et al. [2004] and Rakha et al. [2003]), CMEM (Rakha et al. [2004], Scora and Barth [2006] and Barth et al. [2001]) and VSP (Jimenez-Palacios [1998], Coelho et al. [2009], Yu et al. [2016], Jimenez et al. [1999] and Song et al. [2012]).

### 2.2.1 The Virginia Tech microscopic energy and emission model (VT-Micro model)

As the name suggests, this microscopic emission model was developed at Virginia Tech, USA. The model consists of linear regressions developed using chassis dynamometer data on nine light-duty vehicles [Rakha et al., 2004]. These vehicles were selected to provide an average vehicle that matches average vehicle sales in terms of engine capacity, unladen weight, and vehicle type [Rakha et al., 2004]. The test data were grouped into tables that present the amounts of pollutants, in g/s, as a function of speed and acceleration. To avoid estimating negative values of emission rates, the model calculates the logarithm of the emission rate [Ariotti, 2010].

In 2003, Rakha et al. compared different types of emissions models for estimating hot-stabilized light-duty gasoline vehicle (LDGV) emissions. After validation, the VT-Micro model appeared to be accurate in estimating hot-stabilised, light-duty, normal vehicle tailpipe emissions, providing emission estimates consistent with trends with laboratory measurements. Furthermore, compared with other drive cycles, the VT-Micro model accurately captured emission increases for aggressive acceleration drive cycles.

### 2.2.2 Comprehensive modal emission model (CMEM)

This model, developed in 1995 at the University of California Riverside, estimates emissions from light-duty vehicles (LDVs) and light-duty trucks (LDTs) as a function of the vehicle's mode of operation. The term "comprehensive" refers to the model's ability to predict emissions for various LDVs and LDTs in different operating states (e.g. properly functioning, damaged, defective). To develop the CMEM model, extensive data were collected for engine exhaust and tailpipe emissions from over 300 vehicles, including more than 30 high-polluting vehicles. The model consists of six modules that predict engine power, engine speed, air-fuel ratio, fuel consumption, emissions from the engine and catalyst fraction. Vehicle and operating variables (such as speed, acceleration and road gradient) and model-calibrated parameters (such as cold start coefficients and engine friction factor) are used as input data for the model [Rakha et al., 2004]. Vehicles were categorised in the CMEM model based on the total emission contribution of a vehicle, and 28 vehicle categories were created based on several vehicle variables.

Among the most recent validation work comparing CMEM results with independent emission tests (independent in vehicles and driving cycles) is the 2001 study by Barth et al.. Based on this recent validation analysis, CMEM output performed well within the range of vehicles tested. One-sample t-tests were conducted to determine how well CMEM represents the tested vehicles. The results also showed that CMEM means the average well in most cases, with some exceptions, especially for the high emission vehicles. For high-emission vehicles, CMEM tends to underrepresent the emissions. When comparing the three models, it was found that, in general, all three predict about the same at low to medium speeds. More significant deviations were found at very low and very high speeds; in particular, CMEM showed higher HC emissions and lower $NO_x$ emissions at high speeds, and at very low speeds, it indicated lower values for all emissions when compared to the other studied models.

### 2.2.3 Vehicle-Specific-Power (VSP)

This last model can estimate emissions using the vehicle's specific power, VSP. The VSP value can be estimated from second-by-second speed, acceleration and slope values; thus, the VSP-based approach has been widely used for emission estimation in recent years.

When the new definition of vehicle-specific power's value for pollution and remote sensing research was determined in 1998 by Jimenez-Palacios, it was demonstrated that VSP is an influential explanatory variable for real-world emission rates for LDGVs. The study Coelho et al. [2009] intended, among other things, to ascertain if the VSP methodology previously established for gasoline cars could also be applied to light-duty diesel vehicles (LDDVs). It was shown to be suitable for LDDVs because of the VSP's strong correlation with the variability in diesel vehicles' instantaneous pollutant emissions.

In 2019, Fernandes et al. develop an empirical approach that integrates second-by-second vehicle activity and emission rates for diesel passenger vehicles. In this research, the authors assessed the effect of variation of VSP on $CO_2$ and $NO_x$ emission rates. Results of the study showed that VSP is a good predictor of emission rates.

## 2.3 Driving Simulation

Driving simulation has been widely used for research proposes, and nowadays, around 13 000 articles can be found that use this equipment as an asset for their study. For instance, within the **scientific clinical research** field, studies can be found using a driving simulator to evaluate the driving behaviour of injured people [Ku et al., 2002] or to help treat disorders like fear of driving [Kaussner et al., 2020]. This field can also take a **psychological approach** with studies concerning the influence of stereotypes on driving behaviour [Lambert et al., 2016] or the study of peer influence while driving [Jackson and Blackman, 1994].

Another valuable way to use driving simulation is to study how **road infrastructures** influence drivers' behaviour. For example, a 2007 study conducted by Van Der Horst and De Ridder used a driving simulator to prove that drivers tended to move away laterally from safety barriers when they first approached them and that on a rural road with an 80-km/h speed limit, trees do not affect the speed of the driver unless they are close to the road edge.

In summary, widespread applications of the driving simulator have confirmed that it is an effective and powerful tool for studying road design, driving behaviour, and various safety issues when a massive collection of real-world data is technically hard to collect. The existing research mostly uses driving simulation to analyse specific driving behaviour's risks and safety implications. This dissertation will use driving simulator experiments to particularly focus on the ability to use simulator-based data to analyse the driving behaviour impacts in terms of **emissions**.

### 2.3.1 Advantages of Driving Simulation Studies

Over the years, studies that use a driving simulator have grown dramatically in number. This is because driving simulation has proven to be an effective and safe approach for assessing driving behaviour impacts.

A study dedicated to discussing the advantages and disadvantages of the use of driving simulators for research purposes [De Winter et al., 2012] highlighted that driving simulators had good controllability, reproducibility, and standardisation, which means that these tools allow controlling virtual traffic, weather conditions, and road layout, creating purposefully developed scenarios. This is very important in studies as it allows the researcher to manage requirements and situations without waiting for them to happen; hence participants in different physical locations can drive under the same conditions. Another benefit of using the driving simulation mentioned in this study is the possibility of encountering dangerous driving conditions without putting the driver at risk. Flach et al. [2008] stated that simulators "offer an opportunity to learn from mistakes in a forgiving environment". Exploring dangerous environments and situations is critical to reducing traffic accidents, on-the-road injuries, and deaths. Another easily identifiable advantage is the ease of data collection. A driving simulator can measure performance accurately and efficiently, while a real vehicle makes it far more cumbersome to obtain complete, synchronised, and accurate measurement data [Wynne et al., 2019].

Driving simulators offer several benefits, yet their use in real-world driver assessment is scarce and more evidence is needed to support their use since unrealistic driving behaviour can be obtained and invalid research outcomes can be produced. Therefore, validation is one of the most important topics to be studied in the driving simulation since all driving simulation studies' viability depends on it.

### 2.3.2 Validation

Validity is the capacity of a simulator to simulate actual driving reliably [Wynne et al., 2019]. Mudd and McCormick are pioneers in the validation of driving simulators and advocate two measurements for validating this device. The first is to measure the subject's driving behaviour in a driving simulator and compare it to the conduct of an on-road driving assessment. The second is the validity of the physical components of the simulator, which include the layout and dynamic characteristics of the simulator and similarities to the real vehicle ([Mudd, 1968]; [McCormick, 1970]). Although there are many approaches to validating a driving simulator, it is fundamental that driving behaviour is validated against on-road driving assessments.

In 2015, a study to validate a laboratory-based driving simulator was developed. The study by Meuleners and Fraser [Meuleners and Fraser, 2015] provided early support for the relative validity of the driving simulator, which was considered adequate for various road safety outcomes with reduced risk of harm to participants. For this research, participants were instructed to drive a selected route on-road; that same route was programmed in the driving simulator using the UC/Win-road software. The on-road driving behaviours of participants and driving behaviours in the simulator were assessed by an occupational therapist and two trained researchers using an assessment form. Paired t-tests were used to evaluate differences in driving performance between the simulator and on-road assessments.

A general procedure for validating a driving simulation environment was conducted to analyse gap-acceptance behaviour [Rossi et al., 2020]. This study tested whether a synthetic indicator of gap-acceptance behaviour showed significant differences when computed based on field observations versus observations collected in the simulated environment. Results showed that the mean critical gap estimated in the field and the mean critical gap estimated in the virtual environment are not significantly different, concluding that the driving simulator environment can be considered to be validated with reference to the chosen case study.

A study by Faschina et al. [2021] aimed to investigate the reliability of a driving simulator with regard to its capacity to forecast drivers' actions based on participants' observed driving mistakes and individual driving characteristics. For that, 41 participants executed tests on a simulator and the open road, and the correlation between observed driving mistakes was looked at using linear modelling. Results demonstrated the reliability of the driving simulator in terms of both self-reported and observed driving behaviour.

One research that fits very well into this theme is the 2016 study conducted by Yu et al., which proposed to test and validate the feasibility and applicability of the driving simulator approach in generating vehicle activity data to produce VSP values for estimating emissions. In this study, each participant drove a vehicle in the actual network and the driving simulator in the laboratory environment to ensure consistent driving performance. Based on the analysis results as well as feedback from the 20 participating drivers, the study concludes that the driving simulator is a viable test tool for the development of VSP and, thus, for estimating vehicle emissions, especially for scenarios where the driving time is relatively short, and the network and traffic conditions are less complex. The results show that the calibration errors of the estimated emissions can be reduced to about 50% of the total emissions. In comparison, the validation error of the total emissions is less than 2%. The approach was tested in two cases and shown to be suitable for estimating vehicle emissions from driving simulator tests using the VSP-based model approach.

The present exploratory analysis will use the two-sample Kolmogorov-Smirnov test (K-S test) to explore the validity of the driving simulator results. This study will apply the test to analyse the VSP mode distributions resulting from the empirical and simulated trips.

The findings of previous studies that evaluated the behavioural validity of driving simulators found these are valuable tools for assessing a variety of driving measures.

## 2.4 Summary

After carefully examining prior research in this field, it has been determined that driving behaviour significantly impacts vehicle emissions. Since driving behaviour depends on so many various factors and private automobiles are always evolving, research on this topic must be continuous. Over the past few years, many initiatives have been developed to assess vehicle emissions. For estimating emissions, emissions modelling is essential, and more models are being developed. In earlier research, the VSP emissions model was shown to be a reliable and simple method of predicting emissions, producing precise results. However, compared to other methods, this method is utilized by a very small number of studies, highlighting the significance of the current work.

Studies using driving simulators are a great way to learn about automotive-related subjects. Since simulation may be used to reproduce reality without having any practical consequences and makes data collecting simple, it is frequently used in studies. Nevertheless, the validity of this devices for emission assessment purposes is often neglected. This is critical to ensure that all studies conducted with this type of equipment are reliable and accurate. The work in this dissertation stands out from previous studies because, to the author's knowledge, no similar research has been carried out in the European context.

# Chapter 3

# Methodology

## 3.1 Proposed Methodology

Figure 3.1 displays the framework of the entire research process of this dissertation. As it may be inferred from the diagram, this research revolves around two distinct groups of data, one from the simulated tests and the other from the empirical tests. Two different drivers executed both tests, and velocity and acceleration were collected at every second. After that, the emissions were estimated with the VSP emissions model, and finally, the reliability of the driving simulator to reproduce vehicle emissions was studied.

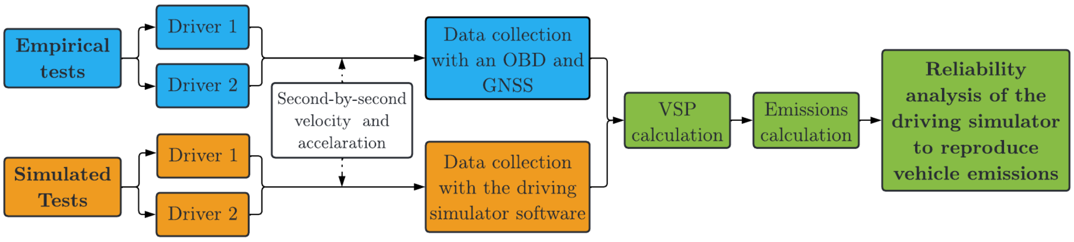


Figure 3.1: Research process framework.

The driving simulator and vehicle used for this research are described in Sections 3.2 and 3.3. In Section 3.4 there is a description of the two scenarios chosen, urban and highway, both for the simulated and the real road and Section 3.5 is dedicated to the participants of this exploratory analysis. The calculations required to determine the second-by-second VSP and emissions will be described in Section 3.6. Finally, in Section 3.7 and 3.8 is explained how the data will be analysed and validated.

## 3.2 Driving Simulator Experiments

The Carnetsoft research simulation software [*Research Driving Simulator*, 2019] was used in this study to perform the experiments under a simulation environment. The desktop driving simulator consists of a computer with a GeForce GTX 770 GPU, an Intel Core I7-10700 CPU @2.90GHz, 16 GB RAM, and a Windows 7 Pro 64 bits operating system. It has a multi-monitor display (left, middle and right), a monitor for data analysis, and a Logitech G29 steering wheel, shifter and pedals to better reflect an in-vehicle environment. The setup also included two cameras for monitoring the driver during the simulation tests to highlight possible signs of, e.g., simulator sickness or fatigue. In Figure 3.2, there is a representation of the desktop driving simulator used in this study.

Figure 3.2: Carnetsoft Driving Simulator desktop.

The research team developed a specific routine to extract second-by-second data associated with driving performance and vehicle dynamics. After each test, an excel spreadsheet was created with instantaneous data from the required variables, such as speed, acceleration, time and position coordinates.

## 3.3 On-road Experiments

For the road tests, it was necessary to use a vehicle that matched the specifications collected in the driving simulator. After a brief analysis of the RPM obtained using a vehicle from the simulator, with values varying between 2000 and 3000 RPM, it was concluded that the most suitable car would be a diesel-fueled vehicle of a similar category of a Renault Clio (Figure 3.3). Thus, a Renault Clio was chosen for the on-road experiments since the research team already has emission factors for this vehicle type derived from several on-road emission measurements using a Portable Emissions Measurement System (PEMS) - 3DATX ParSYNC integrated PEMS.

The vehicle was equipped with an On-Board Diagnostics (OBD) device (OBDII-ELM) that allows getting access to data that can be further used to self-diagnose and report the car's working status (such as voltage, fuel level, engine load, and engine speed) [Wen et al., 2020]. The device (Figure 3.4) was plugged into the vehicle and then synchronised

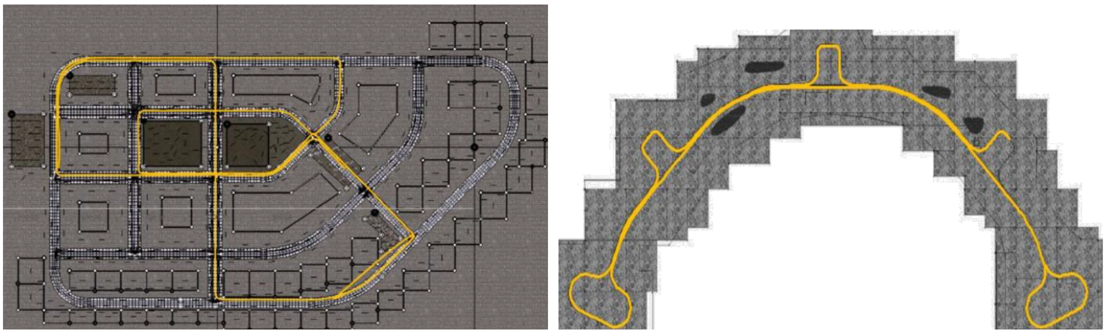
Figure 3.3: Renault Clio 5p.

Figure 3.4: OBDII-ELM.

via Wi-Fi with a mobile app called "TORQUE", which enabled access to the vehicle performance data. The position of the vehicle was also continuously recorded with this mobile app using the global navigation satellite system (GNSS). After the recording, all data was saved as an excel spreadsheet.

## 3.4 Case Study Scenarios

For this research, two scenarios were chosen from the Carnetsoft software: an urban scenario (Figure 3.5a) and a highway scenario (Figure 3.5b).



(a) City map.

(b) Highway map.

Figure 3.5: Maps of the virtual trips.

Buildings surrounded the virtual city roads, and numerous pedestrians were walking and crossing the streets. Traffic lights, speed limits, speed bumps, and special events like congestion and pedestrians crossing outside of the road were also incorporated into the design of the streets.

The virtual highway was also composed of speed limits (the same limits as in the real trips), multiple exits and enters, and long distances to move forward.

It was important that the empirical scenarios matched as much as possible the simulated ones, from infrastructure and traffic to weather conditions and also with similar road singularities. All tests were performed in the city of Aveiro, near the University of Aveiro Campus. Tests were conducted during daylight hours, with sunny weather. Figure 3.6 displays an example of the empirical (Figure 3.6a) and simulated (Figure 3.6b) urban scenario.

(a) Empirical Trip. (b) Simulated Trip.

Figure 3.6: Snapshots from (a) an empirical and (b) a simulated urban trip.

## 3.5 Study Participants

Volunteers were invited to collaborate in the present study by carrying out experiments under the simulation and real environments; they were asked to drive as they normally do, and training sessions were conducted so that volunteers get familiarised with all the apparatus (especially regarding the simulator environment).

This dissertation is limited to two drivers, making this an exploratory analysis, even though the sample is small. The two drivers performed all the experiments, providing this research with data on different driving patterns. As detailed in Table 3.1, the drivers had similar driving experience, but Driver 2 (male) had no previous experience driving in the city of Aveiro, where this exploratory analysis was conducted, and thus, was somewhat unfamiliar with its traffic patterns.

Table 3.1: Information about drivers 1 and 2.

| | Driver 1 | Driver 2 |
|---|---|---|
| Age | 23 | 23 |
| Gender | Female | Male |
| Has a driving license? | Yes | Yes |
| Years of driving experience | 3 | 4 |
| Used to driving a simulator? | Yes | Yes |
| Used to driving in Aveiro? | Yes | No |

## 3.6 Emission Estimation

In this study, a microscopic-level model will be used to estimate the emissions taking into consideration the data collected either through the simulation or the on-road experiments. The model in question is the Vehicle-Specific Power (VSP) model [Frey et al., 2002]; it was chosen because it allows estimating pollutants on a second-by-second basis using vehicle speed and acceleration data, taking into account aerodynamic drag, tire rolling resistance and road grade [Zhai et al., 2008]. Besides this, it is a method that the VSP value has shown a high correlation with the variability of emissions on different types of vehicles, including the one used in this research (light passenger diesel vehicle) [Coelho et al., 2009; Fernandes et al., 2019].

For this research, it is essential to understand the concept of VSP, which is the tractive force a vehicle must employ to move itself and its cargo or passengers [Nam and Giannelli, 2005]. VSP is an effective parameter for estimating vehicle emissions since it can be directly interpreted physically and has a strong statistical correlation with vehicle emissions [Song et al., 2012]. The VSP value for light commercial vehicles is calculated using Equation 3.1, which is derived from the results of Jimenez et al. [Jimenez et al., 1999]:

$$VSP = v \cdot 1.1 \cdot a + 9,81 \cdot grade(\%) + 0,132v + 0,000302 \cdot v^3 \tag{3.1}$$

where:
VSP is the Vehicle Specific Power (kW/ton);
v is the second-by-second vehicle speed (m/s);
a is the second-by-second vehicle acceleration (m/s$^2$);
grade represents the road grade (slope) (%).

Since the scenarios available for the urban and highway experiments in the simulator can be considered flat roads, real-world cases were also selected to comprise this. Thus, the road grade is assumed to be zero, and then, the VSP expression can be simplified as follows (Equation 3.2):

$$VSP = v \cdot (1,1 \cdot a + 0,132) + 0,000302 \cdot v^3 \tag{3.2}$$

Since VSP is consistently recognized as the most important explanatory variable for each pollutant, VSP modes were produced using it [Frey et al., 2003]. Emission rates can be assigned to modes considering VSP as representative variables for each driving mode. For the particular case of a light-duty (diesel) vehicle, VSPs have been grouped into a range of 14 modes as suggested in Frey et al. [2003]. While applying this methodology: (1) each mode should have an average emission rate statistically significantly different from any other mode, and (2) no single mode should predominate the estimation of total emissions for a typical trip. This methodology allows for an easy way of depicting the driving modes: idle, acceleration, cruise, and deceleration. After data collection on vehicle dynamics variables, the VSP can be calculated, and for each second of driving, it is assigned to a VSP mode and an average of the emissions, yielding an emission factor for each particular bin, following the association reported in Table 3.2. By employing conversion factors based on the premise that fuel consumption and $CO_2$ emissions are linearly related, it is possible to link every mode with instantaneous $NO_x$ emissions.

Table 3.2: VSP mode and corresponding power requirements and instantaneous emissions. Adapted from Frey et al. [2003] and Fernandes et al. [2019].

| VSP mode | W/kg | $CO_2$ (g/s) | $NO_X$ (g/s) |
|---|---|---|---|
| 1 | VSP<-2 | 2,09 | 0,02 |
| 2 | -2≤VSP<0 | 1,90 | 0,02 |
| 3 | 0≤VSP<1 | 1,65 | 0,02 |
| 4 | 1≤VSP<4 | 1,85 | 0,02 |
| 5 | 4≤VSP<7 | 2,10 | 0,02 |
| 6 | 7≤VSP<10 | 2,59 | 0,03 |
| 7 | 10≤VSP<13 | 3,07 | 0,04 |
| 8 | 13≤VSP<16 | 3,52 | 0,04 |
| 9 | 16≤VSP<19 | 4,38 | 0,05 |
| 10 | 19≤VSP<23 | 4,79 | 0,05 |
| 11 | 23≤VSP<28 | 5,63 | 0,06 |
| 12 | 28≤VSP<33 | 6,08 | 0,08 |
| 13 | 33≤VSP<39 | 6,53 | 0,09 |
| 14 | VSP≥39 | 7,73 | 0,10 |

## 3.7 VSP Analysis

Before presenting the study results and their discussion in 4, it is important to highlight some details regarding how the VSP was further examined in the analysis.

Figure 3.7 illustrates these details, unravelling the importance of the acceleration and speed across each VSP mode.

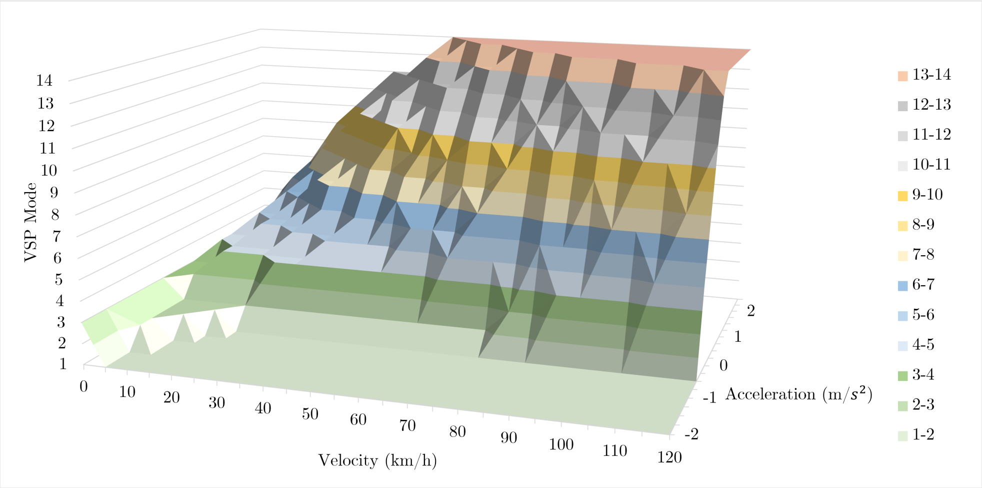


Figure 3.7: VSP Components Relative Weight.
Adapted from Fontes et al. [2014]

This plot was made considering the values of acceleration from -2 to 2 m/s$^2$, with an interval of 0,25 m/s$^2$ and of speed from 0 to 120 km/h with an interval of 5 km/h. For each combination of acceleration and speed, the VSP mode was calculated, creating the graph above. Based on the information depicted in this plot, the following conclusions can be drawn: (1) When the vehicle is stationary, in idle conditions, or when it starts to move, the VSP mode turns out to be close to 3; (2) When the vehicle is moving at a constant speed, data suggest the VSP mode can belong to one of the following speed-based classes: 3 (≈ 1-20 km/h), 4 (≈ 21-60 km/h), 5 (≈ 61-85 km/h), 6 (≈ 86-95 km/h), 7 (≈ 96-110 km/h) or 8 (≈ 111-120 km/h); (3) When the car is decelerating, the VSP mode is 1, but for small decelerations, it can also equal 2, for speeds up to 75 km/h, 3, for speeds ≈ 76-85km/h, 4, for speeds ≈ 86-105km/h and 5, for speeds ≈ 106-120km/h. (4) When the vehicle accelerates, the VSP mode value can range from 4 to 14; this value is directly proportional to the acceleration and speed values; in general, the faster the car moves and harder it accelerates, the larger the VSP mode is.

## 3.8 Validation

The main objective of this study is to analyse the reliability of a driving simulator to accurately reproduce driving parameters for emission estimation. For that purpose, the data obtained from both simulation and real-world environments were subject to analysis so that findings that either reinforce or do not provide evidence of trustful results can be made. The validation process conducted here is based on the comparison between the empirical and simulated speed, acceleration and VSP values, analysing the driving patterns in the two environments and, consequently, the emissions.

Validation will also go through analysing the empirical and simulated VSP mode distributions. This step tries to respond to whether or not drivers react similarly while driving on a real road versus in a simulator when considering practically the same driving conditions [Shechtman, 2010].

The two-sample Kolmogorov-Smirnov (K-S) test for a 95% confidence level is used to evaluate the discrepancy between the estimated and observed VSP modes distributions. The goodness of fit testing using the K-S test quantifies the distance between the empirical and the cumulative distribution functions of two samples [Sheskin, 2003]. In this research, this test was applied, for both drivers, for the VSP mode average frequency distribution of each event. For this test, the null distribution of the two-sample K–S test is calculated under the null hypothesis that the empirical and simulated VSP modes are drawn from the same distribution [LUIZ et al., 2021]; this hypothesis is then rejected or not after the following steps:

1. The cumulative probability of each VSP mode is calculated for the simulated and empirical results;

2. The maximum difference between simulated and empirical cumulative probability is discovered (D-value);

3. The D-critical, for this research's size of samples, is found using the following equation (Equation 3.3):

$$D - critical = 1,36\sqrt{\frac{(n+m)}{(n \cdot m)}} \tag{3.3}$$

where:

n = empirical sample size;

m = simulated sample size.

The total of all VSP modes frequencies in each test constitutes the size sample for each event.

If the D-value exceeds the D-critical, the null hypothesis is rejected, indicating that neither sample follows the same distribution and that the driver does not behave similarly in both simulated and real-world tests.

As it is sensitive to variations in both location and form of the cumulative distribution functions of the two samples, the K-S test is one of the most practical and broad nonparametric approaches for comparing two samples [LUIZ et al., 2021].

# Chapter 4

# Organization of Data

This chapter is devoted to a description of how the data gathered within the experiments conducted, either in the driving simulator or the on-road, were organised and pre-processed to perform the subsequent analysis. To conduct a more thorough investigation, the researcher chose a sample of frequently occurring events to be examined. These events, and correspondent distances, runs and duration will be presented and explained in Section 4.1. Next, the simulated (Section 4.2) and empirical (Section 4.3) events locations will be depicted as well as how each event's distance was marked.

## 4.1 Selection of Events and Distances

The case studies focus on exploring urban and highway trips using a driving simulator scenario and a real-world on-road environment. The urban trip was divided into seven events (Table 4.1), while for the highway scenario, only three events were selected (Table 4.2). The chosen events for the studied scenarios took place in both simulated and empirical experiments to allow for a comparative evaluation. The present study aims to analyse the driver's actions when approaching and leaving commonly found events such as those reported in the tables. For each one of these situations, a certain critical distance was selected to comprise the context of the event, and the data from every second it took the driver to travel that distance will be subject to analysis.

Table 4.1: Events chosen for an urban trip.

| **Event** | **Distance** | **Distance Description** |
|---|---|---|
| Right-turn with priority | 60 meters | 30 meters before and after the turn |
| Left-turn without priority | 60 meters | 30 meters before and after the turn |
| Right-turn after a traffic light | 150 meters | 100 meters before the car stops, and 50 meters after |
| Left-turn after a traffic light | 150 meters | 100 meters before the car stops, and 50 meters after |
| Right-turn after a stop sign | 60 meters | 30 meters before and after the car stopped |
| Left-turn after a stop sign | 60 meters | 30 meters before and after the car stopped |
| Give way | 60 meters | 30 meters before and after the car stops |

Table 4.2: Events chosen for a highway trip.

| **Event** | **Distance** | **Distance Description** |
|---|---|---|
| Entering highway | 300 meters | 150 meters before and after entering highway |
| Exiting highway | 300 meters | 150 meters before and after exiting highway |
| Moving forward | 300 meters | 300 meters of the vehicle moving forward on the highway |

Two factors were taken into account when choosing the distance for each event shown in Tables 4.1 and 4.2: (1) have the minimum distance necessary to observe changes in driving behaviour before and after the event, such as the speed profile; and (2) the maximum distance was constrained by the need to avoid the influence of other events or singularities in the surroundings. For instance, events involving traffic lights had to occur far in advance of the actual traffic light because the location where the vehicle stops depends on the volume of traffic at that precise time.

Because a vehicle travels faster on highways than in an urban setting, and to satisfy the first consideration mentioned above, the distance chosen for highway events is much greater than the distances of the urban events.

In this research, each driver took the four simulated and real trips for both the city and the highway about six times each (six runs). All experimental tests were filmed in order to validate and explain potential extraordinary events that affect the results (incident, congestion, simulation errors, etc).

Tables 4.3 (for driver 1) and 4.4 (for driver 2) show, for each event, the number of occurrences being considered for the analysis, along with the corresponding total duration and distance of all those occurrences.

Table 4.3: Number of events that are being examined for driver 1, along with their total duration and distance.

| | Empirical | | | Simulated | | |
|---|---|---|---|---|---|---|
| | Number | Time (s) | Distance (m) | Number | Time (s) | Distance (m) |
| Right-turn with priority | 19 | 240 | 1140 | 5 | 51 | 300 |
| Left-turn without priority | 13 | 183 | 780 | 15 | 279 | 900 |
| Right-turn after a traffic light | 8 | 348 | 1200 | 5 | 211 | 750 |
| Left-turn after a traffic light | 6 | 367 | 900 | 5 | 232 | 750 |
| Right-turn after a stop sign | 7 | 99 | 420 | 10 | 164 | 600 |
| Left-turn after a stop sign | 17 | 324 | 1020 | 5 | 74 | 300 |
| Give way | 11 | 180 | 660 | 20 | 325 | 1200 |
| Entering highway | 6 | 119 | 1800 | 6 | 80 | 1800 |
| Exiting highway | 6 | 98 | 1800 | 6 | 77 | 1800 |
| Moving forward | 9 | 122 | 2700 | 7 | 86 | 2100 |

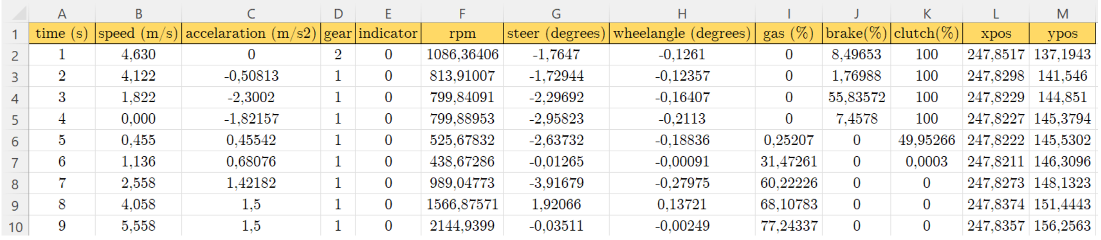
Table 4.4: Number of events that are being examined for driver 2, along with their total duration and distance.

| | Empirical | | | Simulated | | |
|---|---|---|---|---|---|---|
| | Number | Time (s) | Distance (m) | Number | Time (s) | Distance (m) |
| Right-turn with priority | 14 | 201 | 840 | 5 | 58 | 300 |
| Left-turn without priority | 5 | 71 | 300 | 11 | 201 | 660 |
| Right-turn after a traffic light | 5 | 301 | 750 | 5 | 198 | 750 |
| Left-turn after a traffic light | 4 | 309 | 240 | 5 | 237 | 300 |
| Right-turn after a stop sign | 5 | 77 | 300 | 7 | 94 | 420 |
| Left-turn after a stop sign | 11 | 385 | 660 | 5 | 86 | 300 |
| Give way | 5 | 75 | 300 | 12 | 209 | 720 |
| Entering highway | 6 | 117 | 1800 | 6 | 88 | 1800 |
| Exiting highway | 6 | 96 | 1800 | 6 | 93 | 1800 |
| Moving forward | 10 | 169 | 3000 | 14 | 209 | 4200 |

## 4.2 Data from simulated tests

As previously explained in Section 3.2, the driving simulator software provided a spreadsheet file with all the crucial data for this research after each simulated test.

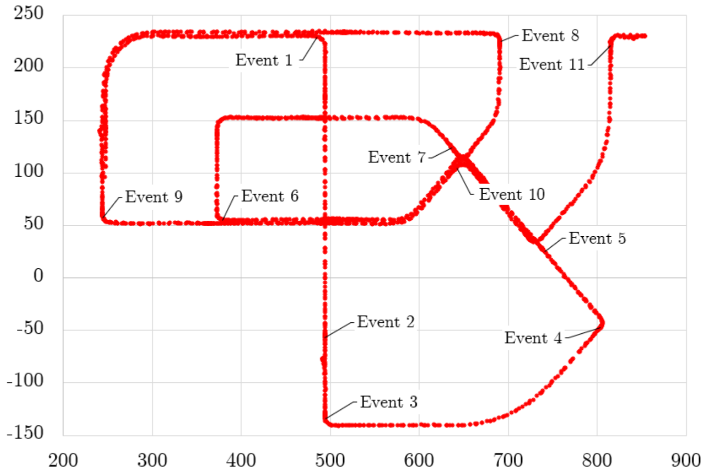
Figure 4.1 shows an example of provided data during 10 seconds of driving in the CarnetSoft driving simulator.



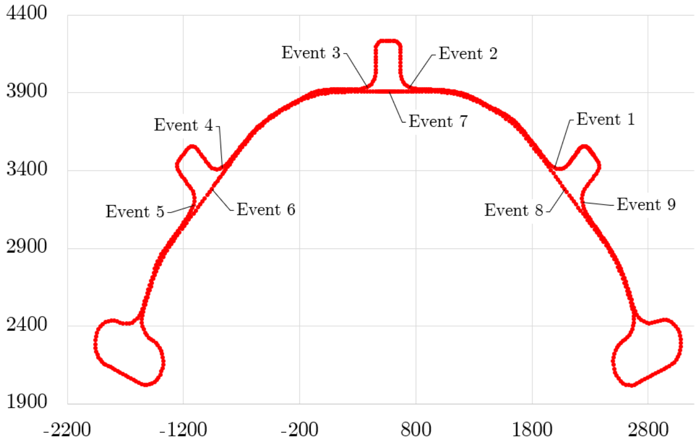
| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | time (s) | speed (m/s) | accelaration (m/s2) | gear | indicator | rpm | steer (degrees) | wheelangle (degrees) | gas (%) | brake(%) | clutch(%) | xpos | ypos |
| 2 | 1 | 4,630 | 0 | 2 | 0 | 1086,36406 | -1,7647 | -0,1261 | 0 | 8,49653 | 100 | 247,8517 | 137,1943 |
| 3 | 2 | 4,122 | -0,50813 | 1 | 0 | 813,91007 | -1,72944 | -0,12357 | 0 | 1,76988 | 100 | 247,8298 | 141,546 |
| 4 | 3 | 1,822 | -2,3002 | 1 | 0 | 799,84091 | -2,29692 | -0,16407 | 0 | 55,83572 | 100 | 247,8229 | 144,851 |
| 5 | 4 | 0,000 | -1,82157 | 1 | 0 | 799,88953 | -2,95823 | -0,2113 | 0 | 7,4578 | 100 | 247,8227 | 145,3794 |
| 6 | 5 | 0,455 | 0,45542 | 1 | 0 | 525,67832 | -2,63732 | -0,18836 | 0,25207 | 0 | 49,95266 | 247,8222 | 145,5302 |
| 7 | 6 | 1,136 | 0,68076 | 1 | 0 | 438,67286 | -0,01265 | -0,00091 | 31,47261 | 0 | 0,0003 | 247,8211 | 146,3096 |
| 8 | 7 | 2,558 | 1,42182 | 1 | 0 | 989,04773 | -3,91679 | -0,27975 | 60,22226 | 0 | 0 | 247,8273 | 148,1323 |
| 9 | 8 | 4,058 | 1,5 | 1 | 0 | 1566,87571 | 1,92066 | 0,13721 | 68,10783 | 0 | 0 | 247,8374 | 151,4443 |
| 10 | 9 | 5,558 | 1,5 | 1 | 0 | 2144,9399 | -0,03511 | -0,00249 | 77,24337 | 0 | 0 | 247,8357 | 156,2563 |

Figure 4.1: *Excel* sheet provided by CarnetSoft Software.

Figure 4.2 illustrates the urban (Figure 4.2a) and highway (Figure 4.2b) simulated trips. These maps were plotted using the *Excel* software through the second-by-second coordinates (Figure 4.1), provided by the software. A mark at each event was added for better visualisation and understanding of the routes.



(a) Urban.



(b) Highway.

Figure 4.2: Routes and event locations in the a) urban and b) highway scenarios.

The following tables depict each event marked on the urban (Table 4.5) and highway (Table 4.6) maps.

Table 4.5: Urban trip

| | |
|---|---|
| Event 1 | Right-turn with priority |
| Event 2 | Give way |
| Event 3 | Left-turn without priority |
| Event 4 | Left-turn without priority |
| Event 5 | Give way |
| Event 6 | Right-turn after a stop sign |
| Event 7 | Left-turn after a traffic light |
| Event 8 | Left-turn after a stop sign |
| Event 9 | Left-turn without priority |
| Event 10 | Right-turn after a traffic light |
| Event 11 | Right-turn after a stop sign |

Table 4.6: Highway trip

| | |
|---|---|
| Event 1 | Entering highway |
| Event 2 | Exiting highway |
| Event 3 | Entering highway |
| Event 4 | Exiting highway |
| Event 5 | Entering highway |
| Event 6 | Moving forward |
| Event 7 | Moving forward |
| Event 8 | Moving forward |
| Event 9 | Exiting highway |

To study each event over its established distance, the researcher must first know the distance travelled at each second.

Vehicle movement deals with the kinematics part of mechanics. Kinematics is the geometrical description of movement employing mathematical functions. It uses only the concepts of geometry (space) associated with time [Alonso and Finn, 2018].

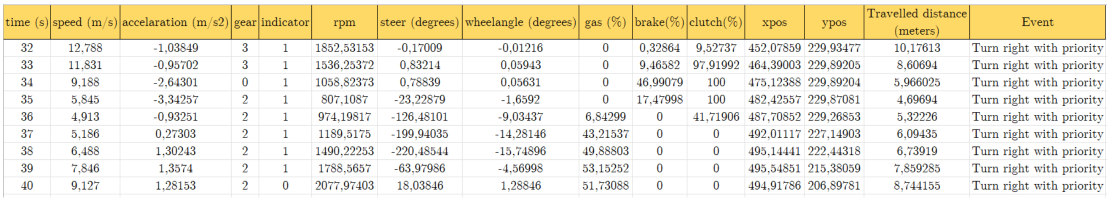
The third kinematics formula calculates the distance travelled in a specific time interval (Equation 4.1).

$$\Delta x = v_0 t + \frac{1}{2} a t^2 \tag{4.1}$$

This formula requires the object in motion, in this case, the vehicle, to move with a constant acceleration during the chosen time gap. Since the time gap is 1 second, the acceleration can be considered stable. The formula can then be simplified to Equation 4.2:

$$\Delta x = v_0 + \frac{1}{2} a \tag{4.2}$$

A column with the travelled distance at each second can now be added to the spreadsheet file. It is possible to separate the data by events based on the coordinates where the events occur and the travelled distance. The following figure (Figure 4.3) provides an example of the data from the urban trip event "Right-turn with priority" obtained with this method.

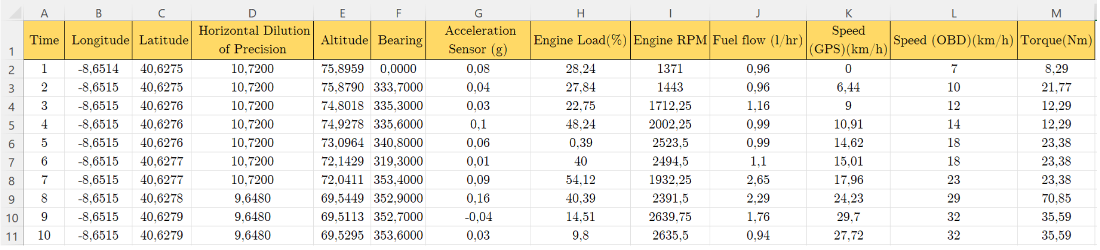


| time (s) | speed (m/s) | accelaration (m/s2) | gear | indicator | rpm | steer (degrees) | wheelangle (degrees) | gas (%) | brake(%) | clutch(%) | xpos | ypos | Travelled distance (meters) | Event |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | 12,788 | -1,03849 | 3 | 1 | 1852,53153 | -0,17009 | -0,01216 | 0 | 0,32864 | 9,52737 | 452,07859 | 229,93477 | 10,17613 | Turn right with priority |
| 33 | 11,831 | -0,95702 | 3 | 1 | 1536,25372 | 0,83214 | 0,05943 | 0 | 9,46582 | 97,91992 | 464,39003 | 229,89205 | 8,60694 | Turn right with priority |
| 34 | 9,188 | -2,64301 | 0 | 1 | 1058,82373 | 0,78839 | 0,05631 | 0 | 46,99079 | 100 | 475,12388 | 229,89204 | 5,966025 | Turn right with priority |
| 35 | 5,845 | -3,34257 | 2 | 1 | 807,1087 | -23,22879 | -1,6592 | 0 | 17,47998 | 100 | 482,42557 | 229,87081 | 4,69694 | Turn right with priority |
| 36 | 4,913 | -0,93251 | 2 | 1 | 974,19817 | -126,48101 | -9,03437 | 6,84299 | 0 | 41,71906 | 487,70852 | 229,26853 | 5,32226 | Turn right with priority |
| 37 | 5,186 | 0,27303 | 2 | 1 | 1189,5175 | -199,94035 | -14,28146 | 43,21537 | 0 | 0 | 492,01117 | 227,14903 | 6,09435 | Turn right with priority |
| 38 | 6,488 | 1,30243 | 2 | 1 | 1490,22253 | -220,48544 | -15,74896 | 49,88803 | 0 | 0 | 495,14441 | 222,44318 | 6,73919 | Turn right with priority |
| 39 | 7,846 | 1,3574 | 2 | 1 | 1788,5657 | -63,97986 | -4,56998 | 53,15252 | 0 | 0 | 495,54851 | 215,38059 | 7,859285 | Turn right with priority |
| 40 | 9,127 | 1,28153 | 2 | 0 | 2077,97403 | 18,03846 | 1,28846 | 51,73088 | 0 | 0 | 494,91786 | 206,89781 | 8,744155 | Turn right with priority |

Figure 4.3: Sample of simulator second-by-second data organized in the spreadsheet for the urban trip event "Right-turn with priority".

## 4.3 Data from empirical tests

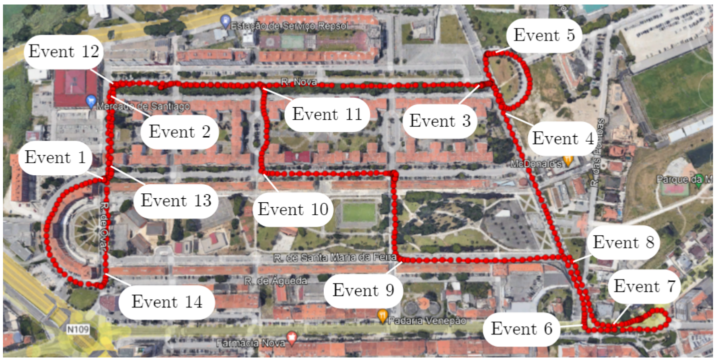
Following each empirical test, the mobile phone app "Torque" allowed export data to a spreadsheet with all the data acquired from the OBD. Figure 4.4 shows a sample of the provided data during 10 seconds of driving.



|  | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Time | Longitude | Latitude | Horizontal Dilution of Precision | Altitude | Bearing | Acceleration Sensor (g) | Engine Load(%) | Engine RPM | Fuel flow (l/hr) | Speed (GPS)(km/h) | Speed (OBD)(km/h) | Torque(Nm) |
| 2 | 1 | -8,6514 | 40,6275 | 10,7200 | 75,8959 | 0,0000 | 0,08 | 28,24 | 1371 | 0,96 | 0 | 7 | 8,29 |
| 3 | 2 | -8,6515 | 40,6275 | 10,7200 | 75,8790 | 333,7000 | 0,04 | 27,84 | 1443 | 0,96 | 6,44 | 10 | 21,77 |
| 4 | 3 | -8,6515 | 40,6276 | 10,7200 | 74,8018 | 335,3000 | 0,03 | 22,75 | 1712,25 | 1,16 | 9 | 12 | 12,29 |
| 5 | 4 | -8,6515 | 40,6276 | 10,7200 | 74,9278 | 335,6000 | 0,1 | 48,24 | 2002,25 | 0,99 | 10,91 | 14 | 12,29 |
| 6 | 5 | -8,6515 | 40,6276 | 10,7200 | 73,0964 | 340,8000 | 0,06 | 0,39 | 2523,5 | 0,99 | 14,62 | 18 | 23,38 |
| 7 | 6 | -8,6515 | 40,6277 | 10,7200 | 72,1429 | 319,3000 | 0,01 | 40 | 2494,5 | 1,1 | 15,01 | 18 | 23,38 |
| 8 | 7 | -8,6515 | 40,6277 | 10,7200 | 72,0411 | 353,4000 | 0,09 | 54,12 | 1932,25 | 2,65 | 17,96 | 23 | 23,38 |
| 9 | 8 | -8,6515 | 40,6278 | 9,6480 | 69,5449 | 352,9000 | 0,16 | 40,39 | 2391,5 | 2,29 | 24,23 | 29 | 70,85 |
| 10 | 9 | -8,6515 | 40,6279 | 9,6480 | 69,5113 | 352,7000 | -0,04 | 14,51 | 2639,75 | 1,76 | 29,7 | 32 | 35,59 |
| 11 | 10 | -8,6515 | 40,6279 | 9,6480 | 69,5295 | 353,6000 | 0,03 | 9,8 | 2635,5 | 0,94 | 27,72 | 32 | 35,59 |

Figure 4.4: *Excel* sheet provided through the mobile app "Torque".

This set of data includes the coordinates of the journey, which were entered into the software *Google Earth* (Figure 4.5) to map the urban (Figure 4.5a) and highway (Figure 4.5b) trips. A mark at each event was added for better visualisation and understanding of the routes.



(a) Urban.

(b) Highway.

Figure 4.5: Routes and event locations in the a) urban and b) highway scenarios.

The events labelled on the urban (Table 4.5) and highway (Table 4.6) maps are described in the following tables.

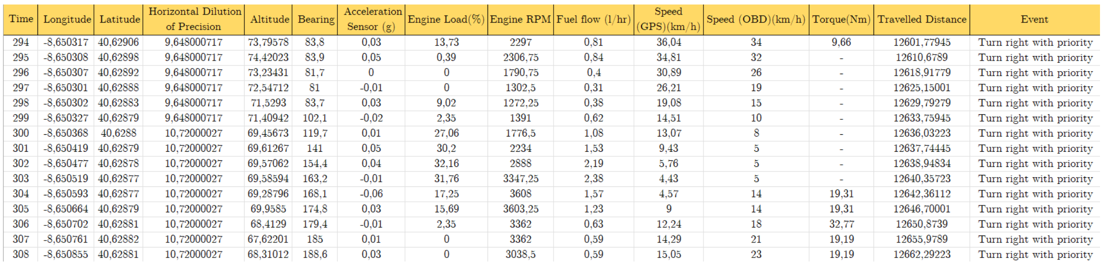
Table 4.7: Urban trip

| | |
|---|---|
| Event 1 | Left-turn after a stop sign |
| Event 2 | Right-turn with priority |
| Event 3 | Left-turn after a stop sign |
| Event 4 | Left-turn without priority |
| Event 5 | Left-turn after a stop sign |
| Event 6 | Left-turn after a traffic light |
| Event 7 | Right-turn after a traffic light |
| Event 8 | Left-turn without priority |
| Event 9 | Right-turn after a stop sign |
| Event 10 | Right-turn with priority |
| Event 11 | Left-turn after a stop sign |
| Event 12 | Left-turn after a stop sign |
| Event 13 | Give way |
| Event 14 | Right-turn with priority |

Table 4.8: Highway trip

| | |
|---|---|
| Event 1 | Entering highway |
| Event 2 | Moving forward |
| Event 3 | Moving forward |
| Event 4 | Exiting highway |
| Event 5 | Entering highway |
| Event 6 | Moving forward |
| Event 7 | Moving forward |
| Event 8 | Exiting highway |

After using *Google Earth* to find the coordinates of each event, it was possible to assign and identify each event according to its geographic location spreadsheet. To correctly estimate the distances previously indicated in Table 4.1 the method outlined in Section 4.2 was, again, implemented. The data from the urban travel event "Right-turn with priority," gathered using this method, is shown in Figure 4.6.



| Time | Longitude | Latitude | Horizontal Dilution of Precision | Altitude | Bearing | Acceleration Sensor (g) | Engine Load(%) | Engine RPM | Fuel flow (l/hr) | Speed (GPS)(km/h) | Speed (OBD)(km/h) | Torque(Nm) | Travelled Distance | Event |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 294 | -8,650317 | 40,62906 | 9,648000717 | 73,79578 | 83,8 | 0,03 | 13,73 | 2297 | 0,81 | 36,04 | 34 | 9,66 | 12601,77945 | Turn right with priority |
| 295 | -8,650308 | 40,62898 | 9,648000717 | 74,42023 | 83,9 | 0,05 | 0,39 | 2306,75 | 0,84 | 34,81 | 32 | - | 12610,6789 | Turn right with priority |
| 296 | -8,650307 | 40,62892 | 9,648000717 | 73,23431 | 81,7 | 0 | 0 | 1790,75 | 0,4 | 30,89 | 26 | - | 12618,91779 | Turn right with priority |
| 297 | -8,650301 | 40,62888 | 9,648000717 | 72,54712 | 81 | -0,01 | 0 | 1302,5 | 0,31 | 26,21 | 19 | - | 12625,15001 | Turn right with priority |
| 298 | -8,650302 | 40,62883 | 9,648000717 | 71,5293 | 83,7 | 0,03 | 9,02 | 1272,25 | 0,38 | 19,08 | 15 | - | 12629,79279 | Turn right with priority |
| 299 | -8,650327 | 40,62879 | 9,648000717 | 71,40942 | 102,1 | -0,02 | 2,35 | 1391 | 0,62 | 14,51 | 10 | - | 12633,75945 | Turn right with priority |
| 300 | -8,650368 | 40,6288 | 10,72000027 | 69,45673 | 119,7 | 0,01 | 27,06 | 1776,5 | 1,08 | 13,07 | 8 | - | 12636,03223 | Turn right with priority |
| 301 | -8,650419 | 40,62879 | 10,72000027 | 69,61267 | 141 | 0,05 | 30,2 | 2234 | 1,53 | 9,43 | 5 | - | 12637,74445 | Turn right with priority |
| 302 | -8,650477 | 40,62878 | 10,72000027 | 69,57062 | 154,4 | 0,04 | 32,16 | 2888 | 2,19 | 5,76 | 5 | - | 12638,94834 | Turn right with priority |
| 303 | -8,650519 | 40,62877 | 10,72000027 | 69,58594 | 163,2 | -0,01 | 31,76 | 3347,25 | 2,38 | 4,43 | 5 | - | 12640,35723 | Turn right with priority |
| 304 | -8,650593 | 40,62877 | 10,72000027 | 69,28796 | 168,1 | -0,06 | 17,25 | 3608 | 1,57 | 4,57 | 14 | 19,31 | 12642,36112 | Turn right with priority |
| 305 | -8,650664 | 40,62879 | 10,72000027 | 69,9585 | 174,8 | 0,03 | 15,69 | 3603,25 | 1,23 | 9 | 14 | 19,31 | 12646,70001 | Turn right with priority |
| 306 | -8,650702 | 40,62881 | 10,72000027 | 68,4129 | 179,4 | -0,01 | 2,35 | 3362 | 0,63 | 12,24 | 18 | 32,77 | 12650,8739 | Turn right with priority |
| 307 | -8,650761 | 40,62882 | 10,72000027 | 67,62201 | 185 | 0,01 | 0 | 3362 | 0,59 | 14,29 | 21 | 19,19 | 12655,9789 | Turn right with priority |
| 308 | -8,650855 | 40,62881 | 10,72000027 | 68,31012 | 188,6 | 0,03 | 0 | 3038,5 | 0,59 | 15,05 | 23 | 19,19 | 12662,29223 | Turn right with priority |

Figure 4.6: Empirical *Excel* sheet data from the urban trip event "Turn right with priority".

# Chapter 5

# Presentation and Discussion of Results

This chapter presents the results obtained through the experiments conducted using the driving simulator and the on-road vehicle.

This chapter is organised as follows:

The examination of each driver's speed, acceleration, and deceleration is shown in Section 5.1, where drivers driving behaviour is compared during the simulated and empirical tests. The following sections, Sections 5.2 and Section 5.3, illustrate urban and highway events by carefully examining each driver's average frequency of VSP mode, VSP mode distribution, speed, acceleration, and deceleration on the simulator and real-road tests, respectively. An analysis of the average emissions generated in both virtual and real tests will also be presented. Finally, the last section describes in detail the validation analysis conducted in this research to explore how reliable driving simulator data can be in reproducing vehicle dynamics from a microscopic point of view. Finally, this data is validated in Section 5.4, where the VSP mode averages and the distance error for all events are analysed, and the K-S test for the average frequency of VSP mode distributions is executed.

All the data and information collected earlier are organised in this Section into tables and graphs, allowing for better visualization, and making it easier to comprehend and proceed with a comparative evaluation of the results. In addition, the empirical testing will be displayed in blue column label and the simulated testing in orange.

## 5.1 Participants Driving Behaviour

In the first part of the presentation of the results, a brief descriptive analysis of some key variables associated with driver behaviour both in real driving tests and in the simulator is provided.

The results concerning speed, acceleration, and deceleration obtained for each event considering both drivers and all runs are reported in Tables 5.1 and 5.2. These tables present the minimum value (min), lower quartile (Q1), median (Q2), upper quartile (Q3), maximum value (max) and average value for each variable.

It is important to note that the speed data takes into account every second the car was in a halted position while travelling these events (speed = 0 km/h), as this is a crucial component of the trip that affects the emission of pollutants. Since points with no speed imply that the acceleration is also zero, only cases where the speed is constant and the vehicle is in motion are considered so as not to bias the results.

Table 5.1: Speed, acceleration and deceleration data from Driver 1.

| | Speed (km/h) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Simulated | | | | | | Empirical | | | | | |
| | Min | Q1 | Q2 | Q3 | Max | Average | Min | Q1 | Q2 | Q3 | Max | Average |
| Right-turn with priority | 15,2 | 20,2 | 23,7 | 29,8 | 46,0 | 25,38 | 0,0 | 13,5 | 19,0 | 25,0 | 38,0 | 19,5 |
| Left-turn without priority | 0,0 | 0,4 | 10,8 | 25,6 | 43,0 | 13,61 | 0,0 | 11,0 | 17,1 | 26,1 | 38,3 | 17,4 |
| Right-turn after a traffic light | 0,0 | 0,0 | 9,6 | 24,4 | 46,1 | 13,65 | 0,0 | 0,0 | 14,5 | 21,0 | 34,0 | 13,0 |
| Left-turn after a traffic light | 0,0 | 0,0 | 5,6 | 26,4 | 43,5 | 12,29 | 0,0 | 0,0 | 0,0 | 18,0 | 39,1 | 9,3 |
| Right-turn after a stop sign | 0,0 | 1,8 | 14,1 | 24,5 | 42,9 | 14,59 | 2,9 | 8,7 | 18,0 | 25,0 | 41,0 | 17,9 |
| Left-turn after a stop sign | 0,0 | 7,0 | 16,8 | 25,5 | 39,7 | 16,45 | 0,0 | 3,0 | 12,7 | 21,0 | 38,4 | 12,7 |
| Give way | 0,0 | 2,7 | 14,9 | 26,8 | 51,7 | 15,66 | 0,0 | 6,0 | 16,0 | 23,0 | 35,0 | 15,0 |
| Entering highway | 64,7 | 83,4 | 88,4 | 94,2 | 102,1 | 87,60 | 18,7 | 45,2 | 57,5 | 69,6 | 86,4 | 57,7 |
| Exiting highway | 69,8 | 84,2 | 89,2 | 96,4 | 112,8 | 90,80 | 44,4 | 66,1 | 73,7 | 80,2 | 86,6 | 71,6 |
| Moving forward | 75,1 | 86,9 | 95,6 | 106,3 | 117,2 | 96,44 | 66,3 | 81,8 | 88,3 | 92,0 | 101,8 | 85,9 |
| | Accelaration (m/s$^2$) | | | | | | | | | | | |
| | Simulated | | | | | | Empirical | | | | | |
| | Min | Q1 | Q2 | Q3 | Max | Average | Min | Q1 | Q2 | Q3 | Max | Average |
| Right-turn with priority | 0,2 | 0,6 | 1,1 | 1,3 | 1,5 | 0,96 | 0,1 | 0,5 | 0,8 | 1,4 | 2,5 | 0,9 |
| Left-turn without priority | 0,01 | 0,70 | 1,28 | 1,48 | 1,60 | 1,08 | 0,0 | 0,4 | 0,8 | 1,7 | 3,3 | 1,1 |
| Right-turn after a traffic light | 0,0 | 0,3 | 0,8 | 1,2 | 1,6 | 0,79 | 0,0 | 0,2 | 0,5 | 0,8 | 3,4 | 0,7 |
| Left-turn after a traffic light | 0,0 | 0,3 | 0,8 | 1,2 | 1,6 | 0,70 | 0,0 | 0,4 | 0,7 | 1,1 | 3,2 | 0,9 |
| Right-turn after a stop sign | 0,0 | 0,6 | 1,3 | 1,5 | 1,6 | 1,08 | 0,2 | 0,6 | 0,9 | 1,1 | 1,7 | 0,9 |
| Left-turn after a stop sign | 0,0 | 0,7 | 1,2 | 1,5 | 1,6 | 1,05 | 0,0 | 0,5 | 0,8 | 1,4 | 3,5 | 1,0 |
| Give way | 0,0 | 0,5 | 1,2 | 1,5 | 1,5 | 1,02 | 0,0 | 0,6 | 1,1 | 1,4 | 2,2 | 1,1 |
| Entering highway | 0,0 | 0,4 | 0,6 | 0,7 | 1,2 | 0,59 | 0,0 | 0,4 | 0,8 | 1,1 | 2,0 | 0,8 |
| Exiting highway | 0,0 | 0,1 | 0,3 | 0,4 | 0,9 | 0,32 | 0,0 | 0,1 | 0,2 | 0,3 | 0,5 | 0,2 |
| Moving forward | 0,0 | 0,1 | 0,2 | 0,3 | 0,3 | 0,20 | 0,0 | 0,1 | 0,4 | 0,6 | 0,9 | 0,4 |
| | Decelaration (m/s$^2$) | | | | | | | | | | | |
| | Simulated | | | | | | Empirical | | | | | |
| | Min | Q1 | Q2 | Q3 | Max | Average | Min | Q1 | Q2 | Q3 | Max | Average |
| Right-turn with priority | -3,3 | -1,8 | -1,0 | -0,6 | -0,2 | -1,27 | -4,1 | -1,6 | -1,1 | -0,6 | -0,0 | -1,2 |
| Left-turn without priority | -6,1 | -2,9 | -1,3 | -0,6 | 0,0 | -1,74 | -3,5 | -1,7 | -0,8 | -0,3 | -0,0 | -1,0 |
| Right-turn after a traffic light | -5,4 | -1,5 | -0,8 | -0,4 | -0,6 | -1,11 | -3,1 | -1,3 | -0,6 | -0,2 | -0,0 | -0,8 |
| Left-turn after a traffic light | -3,7 | -1,2 | -0,7 | -0,4 | 0,0 | -0,99 | -3,4 | -1,4 | -0,8 | -0,4 | -0,0 | -1,0 |
| Right-turn after a stop sign | -4,7 | -3,0 | -1,6 | -0,8 | -0,1 | -1,83 | -2,8 | -1,8 | -1,3 | -0,8 | -0,3 | -1,3 |
| Left-turn after a stop sign | -3,9 | -1,9 | -1,1 | -0,7 | -0,1 | -1,39 | -3,9 | -1,5 | -1,0 | -0,5 | -0,0 | -1,1 |
| Give way | -5,3 | -3,1 | -1,3 | -0,7 | 0,0 | -1,86 | -3,1 | -1,9 | -1,1 | -0,7 | -0,2 | -1,2 |
| Entering highway | -0,6 | -0,5 | -0,4 | -0,1 | -0,0 | -0,32 | -3,9 | -0,9 | -0,5 | -0,2 | -0,0 | -0,7 |
| Exiting highway | -3,2 | -0,9 | -0,4 | -0,1 | -0,0 | -0,63 | -2,9 | -0,9 | -0,5 | -0,3 | -0,0 | -0,6 |
| Moving forward | -1,2 | -0,8 | -0,6 | -0,3 | -0,0 | -0,60 | -0,7 | -0,3 | -0,2 | -0,1 | -0,0 | -0,2 |

Table 5.2: Speed, acceleration and deceleration data from Driver 2.

| | Speed (km/h) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Simulated | | | | | | Empirical | | | | | |
| | Min | Q1 | Q2 | Q3 | Max | Average | Min | Q1 | Q2 | Q3 | Max | Average |
| Right-turn with priority | 0,0 | 19,6 | 22,8 | 28,0 | 41,8 | 22,00 | 4,0 | 12,0 | 15,0 | 22,0 | 33,0 | 16,8 |
| Left-turn without priority | 0,0 | 0,5 | 11,0 | 22,4 | 48,2 | 13,47 | 0,0 | 6,0 | 19,0 | 24,0 | 33,0 | 16,9 |
| Right-turn after a traffic light | 0,0 | 0,0 | 8,2 | 28,4 | 51,4 | 14,73 | 0,0 | 0,0 | 11,0 | 19,0 | 29,0 | 10,6 |
| Left-turn after a traffic light | 0,0 | 0,0 | 5,9 | 25,7 | 37,1 | 12,04 | 0,0 | 0,0 | 7,0 | 20,0 | 31,0 | 10,4 |
| Right-turn after a stop sign | 0,0 | 11,6 | 19,5 | 26,7 | 45,1 | 18,82 | 2,0 | 9,0 | 15,0 | 20,0 | 34,0 | 15,7 |
| Left-turn after a stop sign | 0,0 | 2,4 | 14,5 | 24,4 | 35,5 | 14,35 | 0,0 | 4,0 | 10,0 | 18,0 | 29,0 | 11,2 |
| Give way | 0,0 | 1,2 | 14,4 | 24,9 | 40,7 | 14,43 | 0,0 | 5,0 | 19,0 | 25,0 | 28,0 | 15,5 |
| Entering highway | 56,3 | 75,1 | 78,0 | 82,9 | 93,7 | 78,84 | 27,7 | 48,3 | 61,2 | 70,3 | 83,2 | 59,0 |
| Exiting highway | 61,3 | 69,7 | 73,4 | 81,0 | 87,0 | 74,76 | 48,9 | 70,7 | 76,7 | 81,7 | 88,4 | 75,7 |
| Moving forward | 49,6 | 66,0 | 79,1 | 89,7 | 109,1 | 77,87 | 10,2 | 33,7 | 64,9 | 33,7 | 92,8 | 60,0 |
| | Accelaration (m/s$^2$) | | | | | | | | | | | |
| | Simulated | | | | | | Empirical | | | | | |
| | Min | Q1 | Q2 | Q3 | Max | Average | Min | Q1 | Q2 | Q3 | Max | Average |
| Right-turn with priority | 0,0 | 0,4 | 0,7 | 0,9 | 1,5 | 0,69 | 0,3 | 0,3 | 0,8 | 1,1 | 1,7 | 0,8 |
| Left-turn without priority | 0,0 | 0,7 | 1,0 | 1,1 | 1,6 | 0,88 | 0,3 | 0,3 | 0,6 | 0,8 | 1,1 | 0,6 |
| Right-turn after a traffic light | 0,0 | 0,3 | 0,6 | 1,1 | 1,5 | 0,68 | 0,3 | 0,3 | 0,6 | 0,9 | 1,7 | 0,7 |
| Left-turn after a traffic light | 0,0 | 0,2 | 0,4 | 0,8 | 1,3 | 0,52 | 0,3 | 0,4 | 0,6 | 0,8 | 2,5 | 0,8 |
| Right-turn after a stop sign | 0,1 | 0,6 | 0,9 | 1,1 | 1,5 | 0,85 | 0,3 | 0,6 | 0,7 | 1,1 | 1,9 | 0,8 |
| Left-turn after a stop sign | 0,0 | 0,7 | 1,2 | 1,5 | 1,5 | 1,08 | 0,3 | 0,3 | 0,6 | 1,1 | 1,7 | 0,7 |
| Give way | 0,0 | 0,6 | 1,2 | 1,5 | 1,5 | 1,05 | 0,3 | 0,3 | 0,7 | 0,8 | 0,8 | 0,7 |
| Entering highway | 0,0 | 0,1 | 0,3 | 0,4 | 0,8 | 0,28 | 0,0 | 0,2 | 0,4 | 0,6 | 2,3 | 0,5 |
| Exiting highway | 0,0 | 0,2 | 0,3 | 0,4 | 0,6 | 0,29 | 0,0 | 0,1 | 0,2 | 0,4 | 0,9 | 0,3 |
| Moving forward | 0,0 | 0,2 | 0,3 | 0,5 | 1,0 | 0,34 | 0,0 | 0,1 | 0,2 | 0,4 | 0,9 | 0,3 |
| | Decelaration (m/s$^2$) | | | | | | | | | | | |
| | Simulated | | | | | | Empirical | | | | | |
| | Min | Q1 | Q2 | Q3 | Max | Average | Min | Q1 | Q2 | Q3 | Max | Average |
| Right-turn with priority | -4,3 | -1,7 | -1,1 | -0,7 | -0,3 | -1,37 | -3,9 | -1,7 | -1,1 | -0,5 | -0,3 | -1,3 |
| Left-turn without priority | -4,2 | -2,3 | -1,2 | -0,4 | 0,0 | -1,47 | -1,9 | -1,3 | -0,8 | -0,3 | -0,3 | -0,9 |
| Right-turn after a traffic light | -4,1 | -2,2 | -0,6 | -0,2 | 0,0 | -1,20 | -2,2 | -1,4 | -0,8 | -0,5 | -0,3 | -1,0 |
| Left-turn after a traffic light | -3,1 | -1,0 | -0,5 | -0,2 | -0,0 | -0,79 | -2,8 | -1,9 | -1,4 | -0,6 | -0,3 | -1,3 |
| Right-turn after a stop sign | -4,0 | -2,5 | -1,1 | -0,6 | -0,0 | -1,53 | -2,2 | -1,7 | -0,8 | -0,6 | -0,3 | -1,1 |
| Left-turn after a stop sign | -4,1 | -1,9 | -0,6 | -0,4 | -0,0 | -1,15 | -3,1 | -1,8 | -1,1 | -0,5 | -0,3 | -1,3 |
| Give way | -4,5 | -1,8 | -0,9 | -0,5 | 0,0 | -1,34 | -1,9 | -1,2 | -0,6 | -0,3 | -0,3 | -0,8 |
| Entering highway | -1,4 | -0,8 | -0,4 | -0,2 | -0,0 | -0,49 | -1,6 | -0,4 | -0,2 | -0,1 | -0,0 | -0,3 |
| Exiting highway | -0,6 | -0,2 | -0,1 | -0,1 | -0,0 | -0,15 | -2,4 | -0,9 | -0,4 | -0,2 | -0,0 | -0,6 |
| Moving forward | -1,2 | -0,5 | -0,3 | -0,2 | -0,0 | -0,35 | -1,3 | -0,5 | -0,3 | -0,2 | -0,0 | -0,4 |

These results suggest that drivers 1 and 2 exhibit higher maximum and average speeds in the simulated than in the on-road experiments, which is aligned with the findings reported by Zöller et al. [2019] and Hallvig et al. [2013]. A possible reason that may explain this finding is that it is likely that drivers are less hesitant to speed up in virtual environments than in real-world conditions since they are not at risk [Yu et al., 2016].

When comparing the drivers' interquartile speed range (from Q1 to Q3) in both simulated and empirical tests, it is noticeable that the speeds were similar, proving that both participants have the same speeding trend when undergoing the same kind of experiment. This is also evident during the deceleration phases, where the deceleration patterns of both drivers in each type of event showed the same trends. However, regarding the variable acceleration, the results turned out to be different. Driver 1 frequently accelerated harder than Driver 2, especially in the real environment, possibly due to a higher level of familiarity with the traffic context.

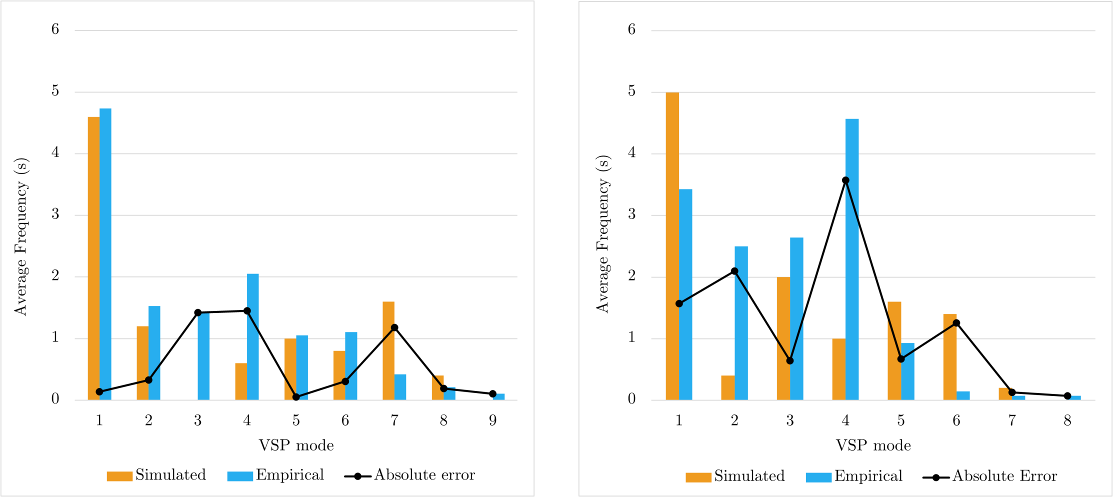
When comparing each driver's empirical results with the simulated ones, it becomes clear that Driver 1 typically breaks harder in the simulator than on the real road. This may be attributed to the driving style and the simulator's brake pedal, which is more sensitive than an in-vehicle pedal. Under a real-world experiment, this would mean that the speed fluctuation would be excessive if the driver applied the same amount of pressure on the pedal to regulate the brake, as explained by Yu et al. [2016]. Another possible explanation is that in static driving simulators, like the one used in this study, there are no movement stimuli, which can be a drawback since the sense of motion vanishes, and it is thought to be connected to some decisions about when to brake the vehicle [Siegler et al., 2001].

Driver 2's acceleration and deceleration fluctuated according to the circumstances and did not follow a particular pattern, resulting in some noticeable gaps between the two experiments. These gaps will be analysed in the following Sections when each event is thoroughly examined.

## 5.2 Urban Events

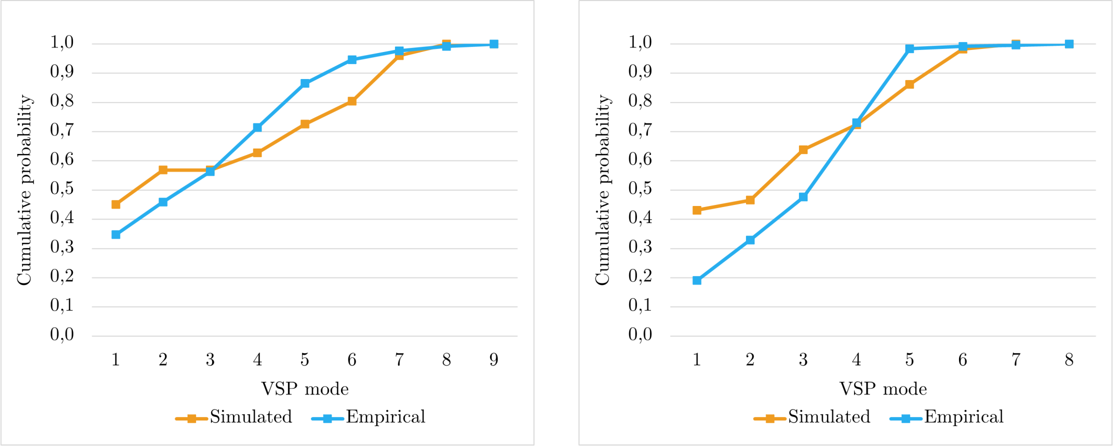
### 5.2.1 Right-turn with priority

This event occurs when the driver changes the direction of the road to the right without deferring to another vehicle. It is being examined along 60 m, 30 m before, and 30 m after the beginning of the curve. These critical distances were chosen since each of them involves differences in driving behaviour between these approaching and exiting areas.



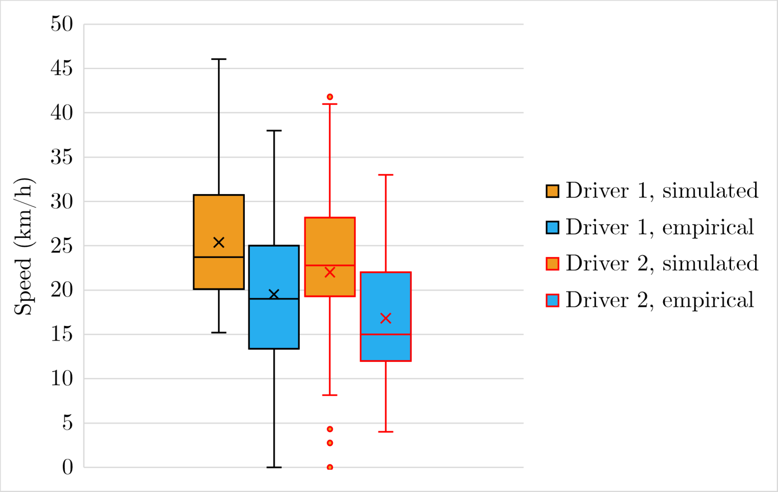
(a) Driver 1 (b) Driver 2

Figure 5.1: Average of time spent in each VSP mode during the event "right-turn with priority" and absolute error between simulated and empirical values.

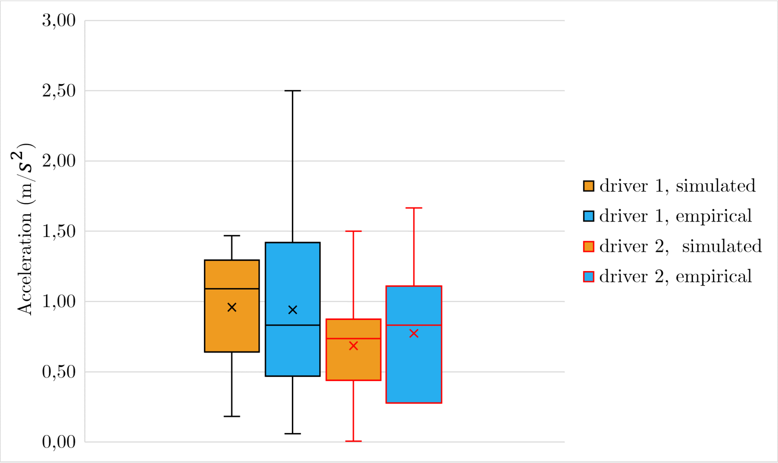


(a) Driver 1 (b) Driver 2

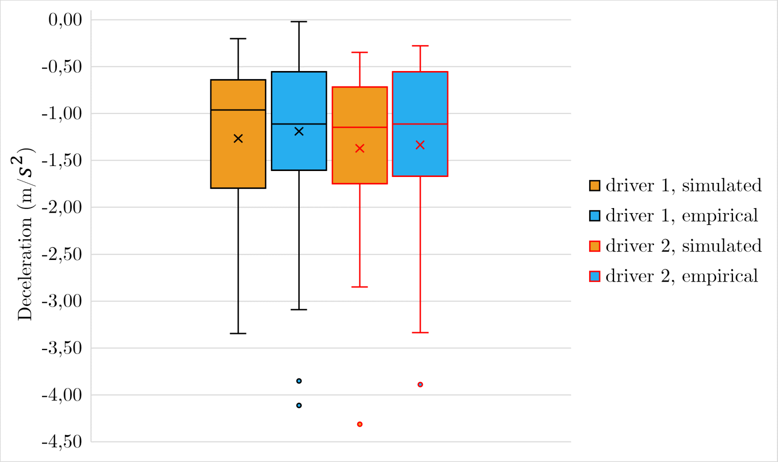
Figure 5.2: Cumulative distributions of simulated and empirical VSP modes for the "right-turn with priority" event.



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.3: Box plot for speed, acceleration and deceleration for the "right-turn with priority" event.

Results suggest that usually, even at intersections where the driver has priority, there is a deceleration when approaching the turn. It can be observed that VSP modes 1 and 2 are commonly generated in this event, reflecting significant and gradual decelerations, respectively.

Figure 5.1 shows a significant difference in the average frequency of mode 4, especially for Driver 2 (Figure 5.1b). This may be because, in this event, the driver travelled at lower speeds during the on-road trips (average of $\approx$ 17 km/h) compared to the simulated trips (average of $\approx$ 22 km/h), as shown in Figure 5.3a. Figure 5.2b further supports this, showing that nearly 100% of the VSP modes were less or equal to 5.

Driver 1's most significant difference in VSP average frequency is in modes 3, 4 and 7. In this case, the difference in the average frequency of modal bin 3 can be attributed to the car moving at a constant low speed during the empirical trials and not during the simulated ones. Figure 5.3a illustrates how the average frequency of modal bins 4 and 7 differs, demonstrating that the driver travelled faster in the simulated environment than in the empirical one (generating more modes 4 on the road and 7 in the simulator).

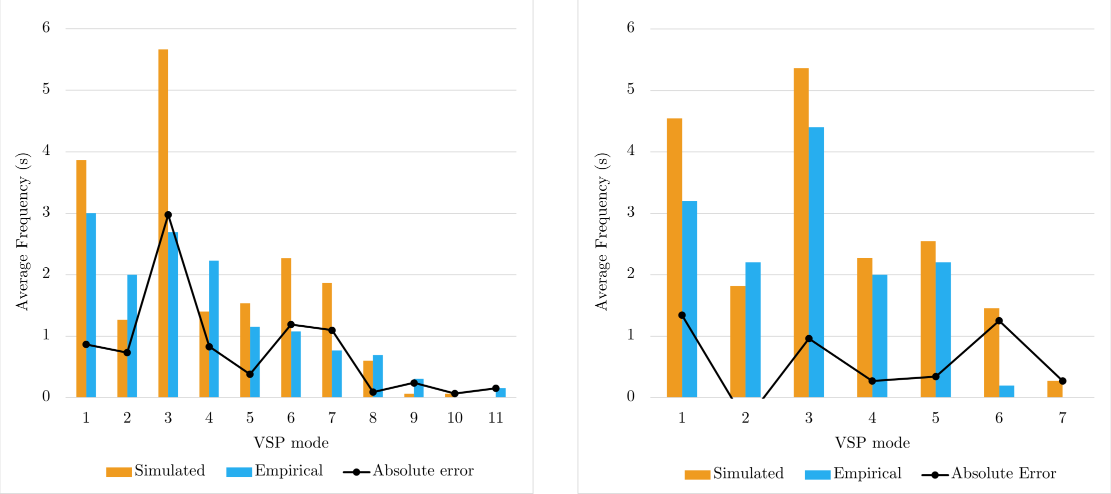
It is also possible to see from Figure 5.1 that, for Driver 2, the difference between the simulated averages of VSP modes 1 and 2 is significantly larger than the empirical difference between these modes. Depending on the current speed and acceleration, VSP mode values can change considerably. Therefore, this does not necessarily imply that the driver deceleration values are higher in the simulator than on the real road. These values are similar, as shown in Figure 5.3c.

Simulated cumulative probability curves for Drivers 1 and 2 diverge significantly from empirical ones. This demonstrates different driving actions when comparing the two environments.

In this event, the acceleration box plot (Figure 5.3b) is shorter for both drivers in the simulation. This can be explained by the fact that the traffic and environmental circumstances in the simulator were constant and that it is likely that the driver would already be expecting and ready to act in a particular situation after a few tests. While in the real road, the driver runs across some traffic variations, which would support this higher unpredictability in acceleration.

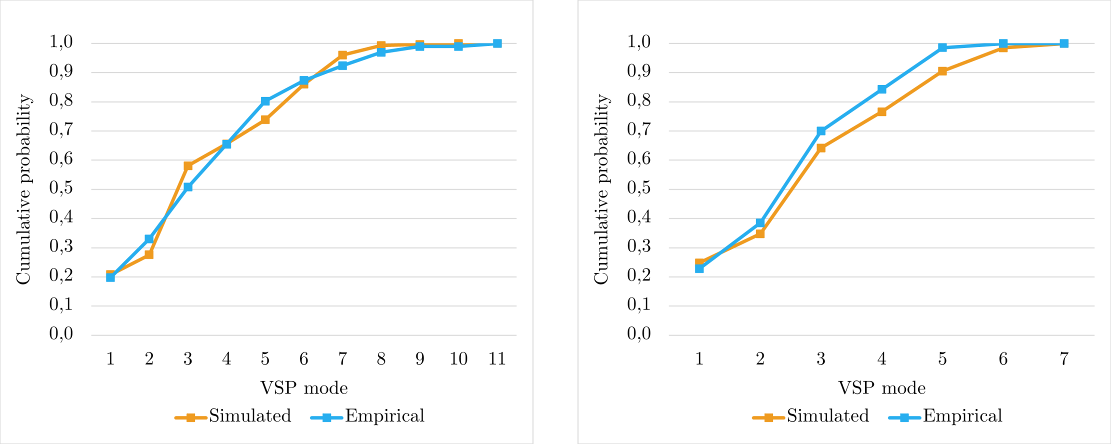
### 5.2.2 Left-turn without priority

The following analysis focused on an event that occurs when the driver changes the direction of the road to the left without priority (because of a yield sign or just because of the driving rules), meaning that depending on the traffic at the moment, the car may need to slow down or even come to a stop to give way to another vehicle. The analysis section related to this event corresponds to 30 m before and 30 m after the curve's start.



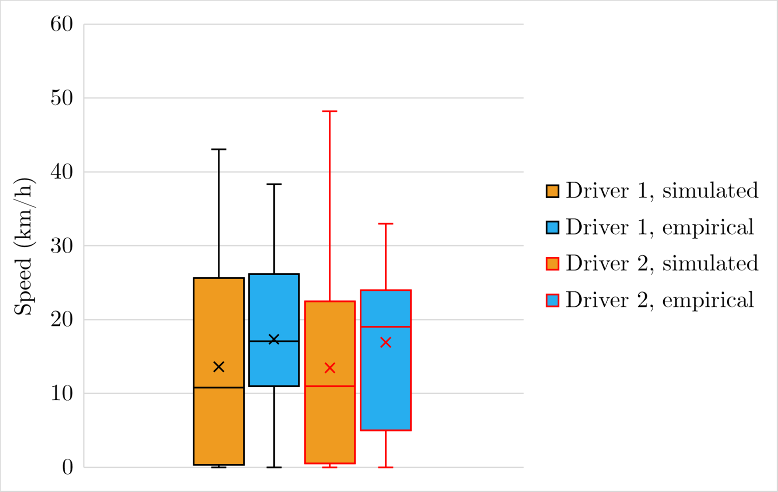
(a) Driver 1 (b) Driver 2

Figure 5.4: Average of time spent in each VSP mode during the event "left-turn without priority" and absolute error between simulated and empirical values.

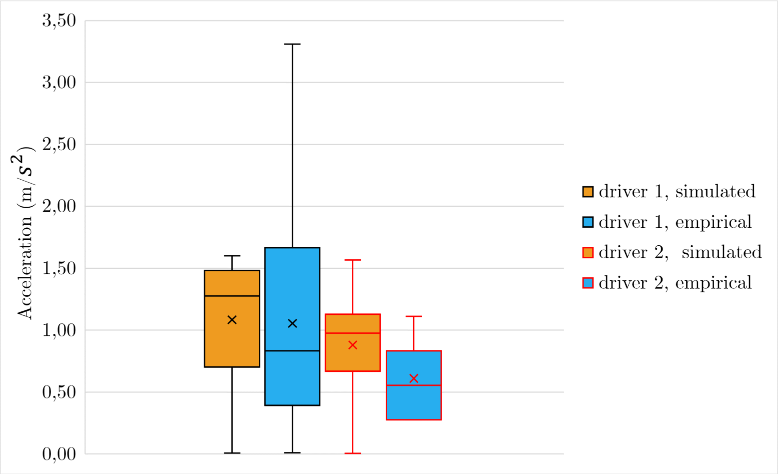


(a) Driver 1 (b) Driver 2

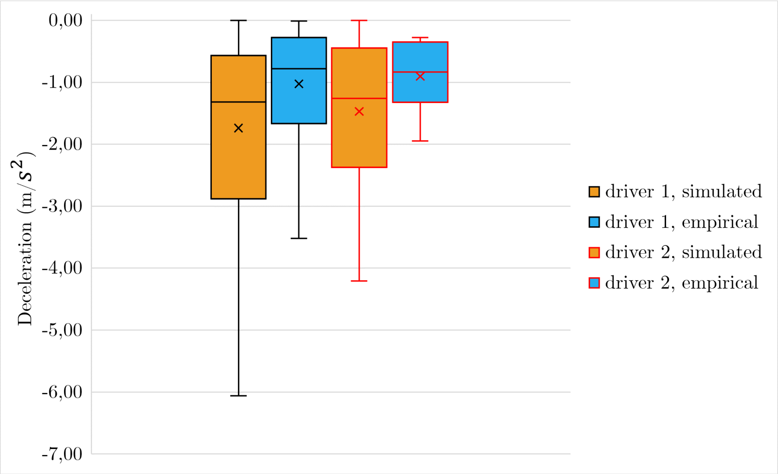
Figure 5.5: Cumulative distributions of simulated and empirical VSP modes for the "left-turn without priority" event.



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.6: Box plot for speed, acceleration and deceleration for the event "left-turn without priority".

Based on the obtained results, it can be observed that overall outcomes are similar when comparing simulated and empirical test results from this occurrence. The more obvious distinction may be noticed in Driver 1's VSP mode (Figure 5.4a), where it is evident that the average frequency of modal bin 3 is bigger in simulated trials than it is in the empirical ones. This mode primarily describes the vehicle in stop-and-go situations as described in Section 3.7, therefore, the discrepancy does not reflect a difference in how the car was being driven at the time rather than the traffic flow.

The empirical VSP values of Driver 1 reach mode 11, while those of Driver 2 only reach mode 6. The same happens for the simulated findings as Driver 1's reaches VSP mode 10 and Driver 2's only mode 7. After examining the graphs in Figure 5.6a, it is compelling to see that Driver 1 speeds are not exactly greater than Driver 2, raising the question of why Driver 1 achieved higher VSP modes. This may be the case because Driver 2 reached higher speeds when decelerating, meaning instead of producing high VSP modes, produced modal bins 1 and 2. This is demonstrated by Figure 5.5, which shows that while modes 1 and 2 accounted for about 30% of the results for Driver 1, they accounted for about 40% of the results for Driver 2.

Figure 5.5b demonstrates how Driver 2's actions in the driving simulator and on the road are identical. Figure 5.5a illustrates how Driver 1 behaved differently in the two tests while having relatively few faults. For this exploratory validation analysis, this information is quite useful.

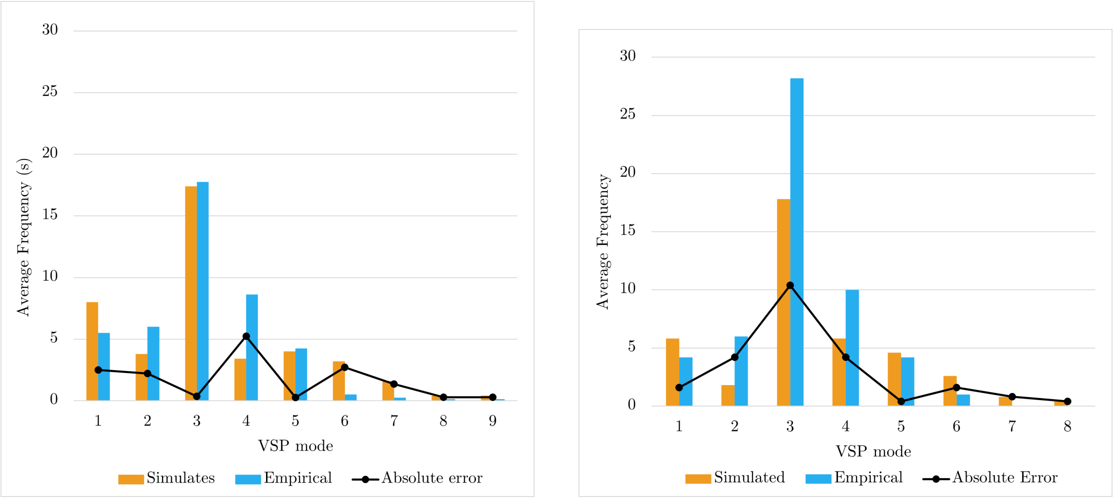
Driver 1 generates stronger deceleration in the simulator and higher acceleration on the real road, according to the graphs in Figure 5.6. Driver 1's acceleration pattern was different here (the driver typically produces higher acceleration values in the simulator), demonstrating how participants' behaviour might change in response to an event and the present circumstances. The higher acceleration levels can be explained by the need to accelerate quickly at the intersection to ensure a safety gap concerning vehicles travelling on the road with priority.

From Figure 5.6c, a clear trend between the simulation and on-road environments can be observed, in which the deceleration variability is much smaller in the empirical tests, also associated with a higher median for both drivers. This may be due to better anticipation of the driving scene and the more sensible pedal.

### 5.2.3 Traffic light: Right-turn

These two subsections are devoted to understanding drivers' behaviour when approaching traffic light intersections.

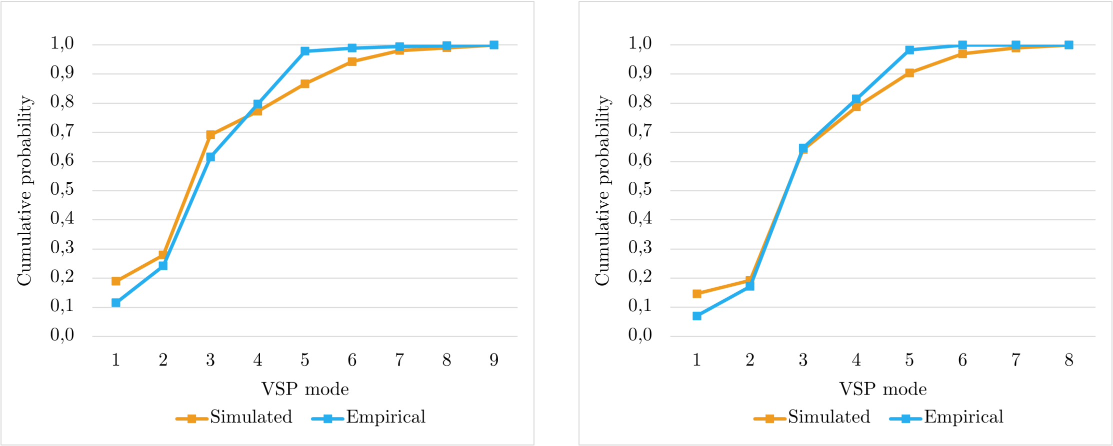
This subsection will be focused on an event that occurs when the vehicles need to stop at a traffic light and then turns right. This event was selected to be examined for 150 m: 100 m for the approaching and 50 m after the traffic light. These distances were selected based on the difference in speeds obtained from the collected data, ensuring no conflict with other types of critical events areas.



(a) Driver 1

(b) Driver 2

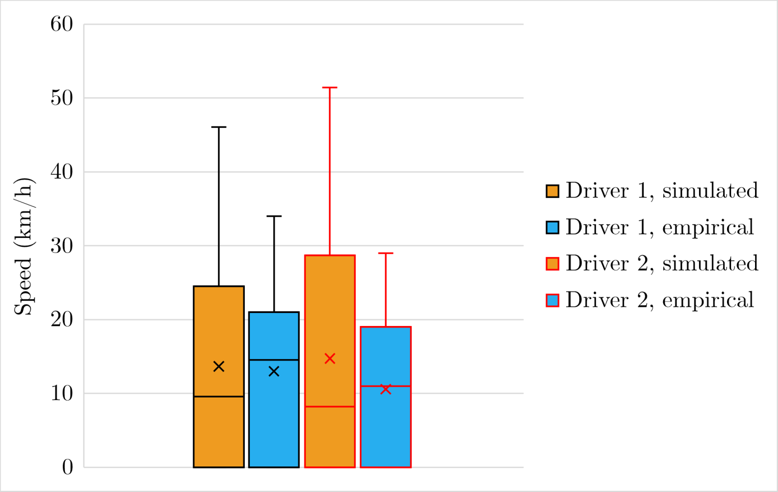
Figure 5.7: Average of time spent in each VSP mode during the event "right-turn after a traffic light" and absolute error between simulated and empirical values.



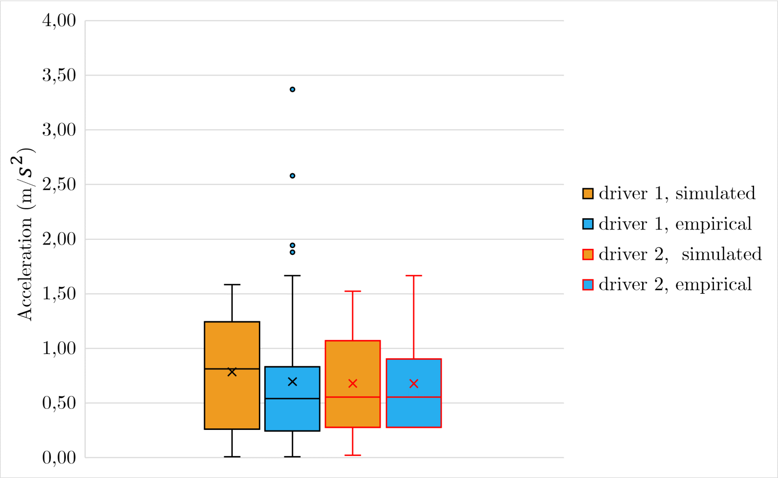
(a) Driver 1

(b) Driver 2

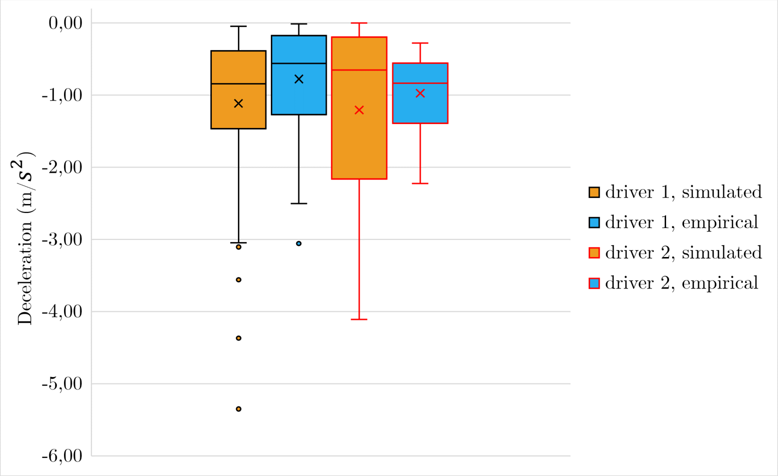
Figure 5.8: Cumulative distributions of simulated and empirical VSP modes for the "right-turn after a traffic light" event.



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.9: Box plot for speed, acceleration and deceleration for the "right-turn after a traffic light" event.

During this event's runs, the red traffic light was on and required stopping the vehicle. The location where the vehicle may stop depends on the traffic volume; differently than in the simulation occurrences, where the driver would always stop about 10 meters before the traffic light, under the on-road tests, the driver could stop 2 - 60 m before the traffic light. This may impact the VSP modes because acceleration is typically studied when the car stops far from the light, and deceleration generally is studied when the car stops close to the light.

Figure 5.7 shows the predominance of VSP mode 1 over mode 2 is more noticeable in the simulated environment for both drivers. This can be explained by the higher sensitivity of the brake pedal in the simulated environment, which leads to sharper braking.

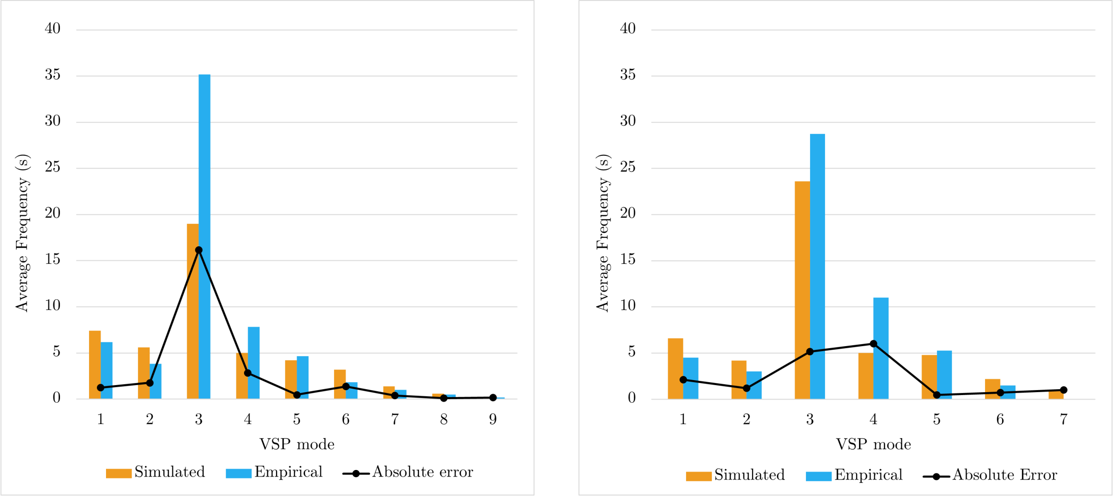
In this case, it is interesting to note that the differences between empirical and simulated outcomes are much larger than between individuals' actions. This is because both drivers' behaviour in this scenario were remarkably identical (as proven by Figure 5.8), with the exception of Driver 2's VSP mode 3, which, as previously explained, depends on traffic context.

In the simulated scenario, the two participants reached higher speed values, as seen in Figure 5.9a, however, the speed median is higher in the empirical tests. This can be due to less volume of traffic in the simulated test, which allows the driver's speed to fluctuate more. Figure 5.8 also shows this, since the empirical cumulative probability for the two subjects nearly 100% of the time was spent on VSP modes lower than or equal to mode 5, and simulated values go up to modes 8 or 9.

Results show that when the drivers were aware of the red light, deceleration values were higher in the simulator, probably due to the fact that in the simulated environment, there was no traffic in this particular event, therefor the drivers were circulating at higher speeds right before the traffic light. This also explains the higher variability in the simulated acceleration and deceleration for both drivers.

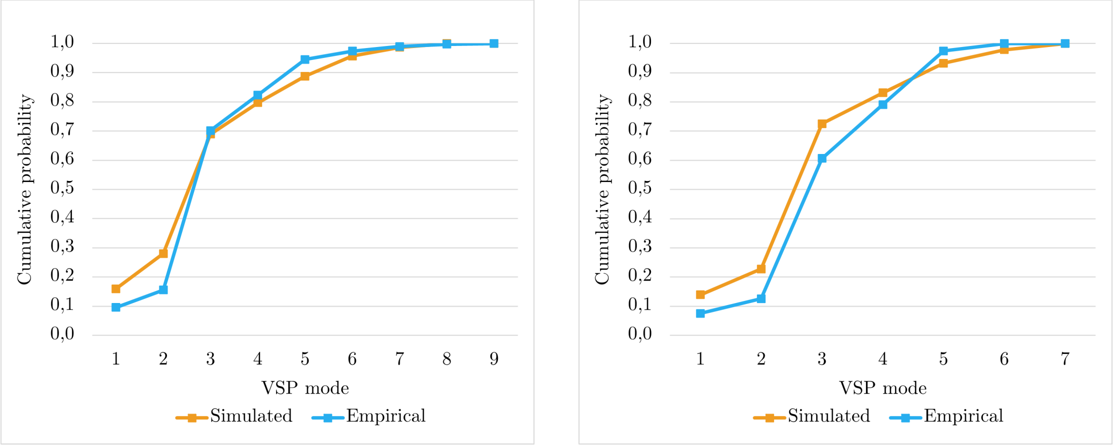
### 5.2.4 Traffic light: Left-turn

This traffic event is characterised by a left turn after stopping at a traffic light. As in the previous case, the same critical distances were selected for the analysis.



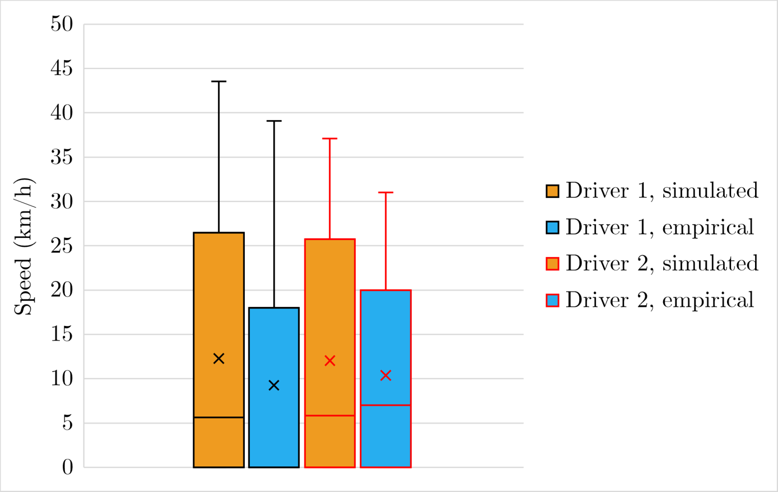
(a) Driver 1 (b) Driver 2

Figure 5.10: Average of time spent in each VSP mode during the event "left-turn after a traffic light" and absolute error between simulated and empirical values.

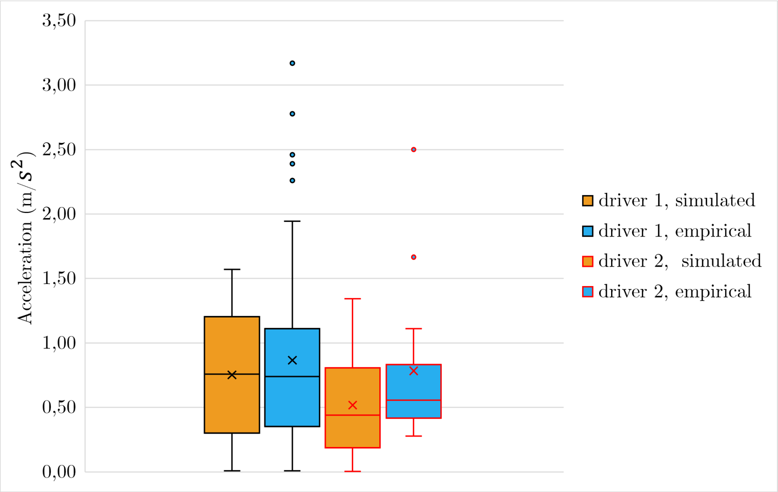


(a) Driver 1 (b) Driver 2

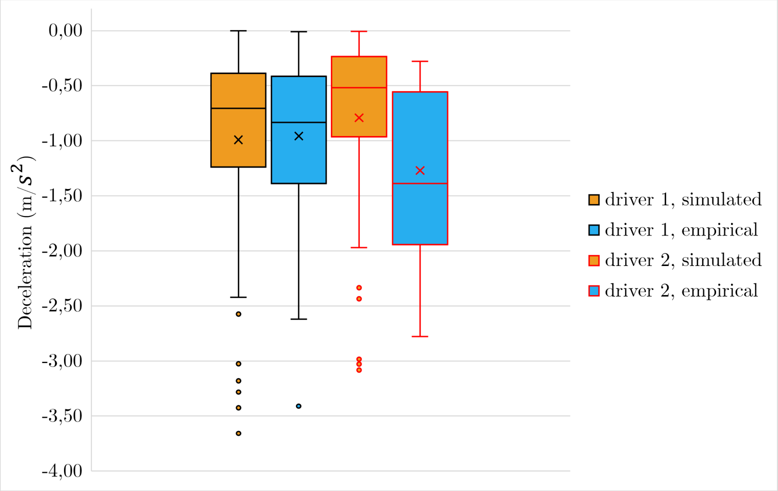
Figure 5.11: Cumulative distributions of simulated and empirical VSP modes for the "left-turn after a traffic light" event.



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.12: Box plot for speed, acceleration and deceleration for the event "left-turn after a traffic light".

Given how similar the two events are, it makes sense that the data from this one would exhibit similar patterns as the previous one. During this event's runs, the traffic light was red when the drivers reached it.

It should be noted that Driver 1 achieved higher VSP mode values (up to mode 9) than Driver 2 (up to mode 7) due to driving faster throughout both simulated and real testing, as shown in Figure 5.12a.

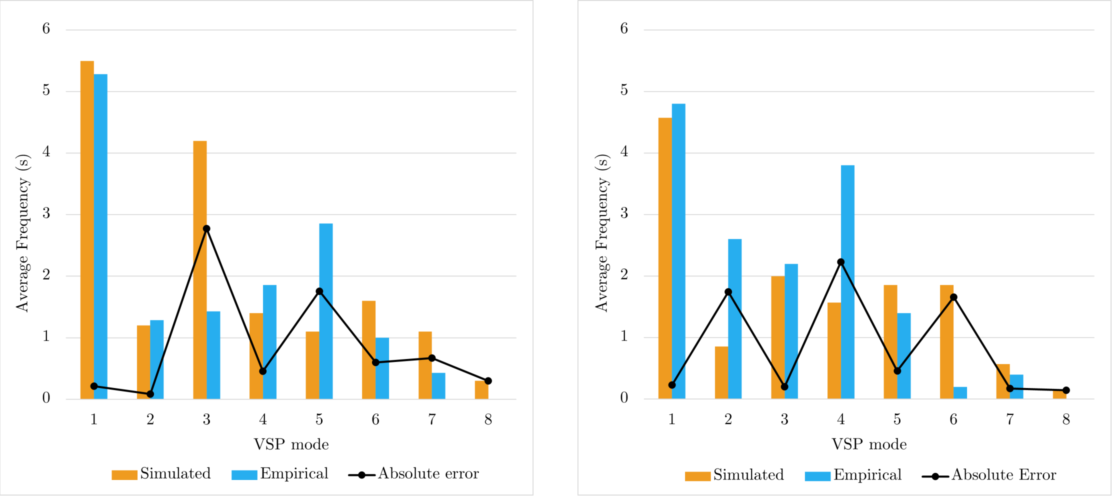
On-road tests revealed smaller speed variability when compared with the simulation. Regarding acceleration and deceleration (Figures 5.12b and 5.12c), Driver 1 showed more consistent variability when compared to both tests, while Driver 2 presents smoother decelerations and less variability in the simulator than in the on-road experiments. Additionally, comparing both drivers' performance in terms of deceleration in the on-road tests, it can be observed higher variability and lower median for Driver 2.

In the simulation tests, both drivers moved faster (Figure 5.12a) and achieved comparable acceleration levels (Figure 5.12b). Overall, simulated speeds were higher than empirical, and this may be linked to Section 5.1's findings, where it is suggested that drivers travel faster in simulation environments, but it may also be due to real-world road infrastructure, such as a roundabout immediately after the left turn on the traffic light, which forced drivers to move slower.

### 5.2.5 Stop Sign: Right-turn

Although in the presence of a stop sign, drivers must stop and yield appropriately, the truth is that in the real world, this does not always happen as some drivers slow down the car to an almost halted position, which may take different periods halted since it depends on the amount of traffic. In this study, we will focus on two situations: a) where the vehicle proceeds with a right turn and b) where it proceeds with a left turn.

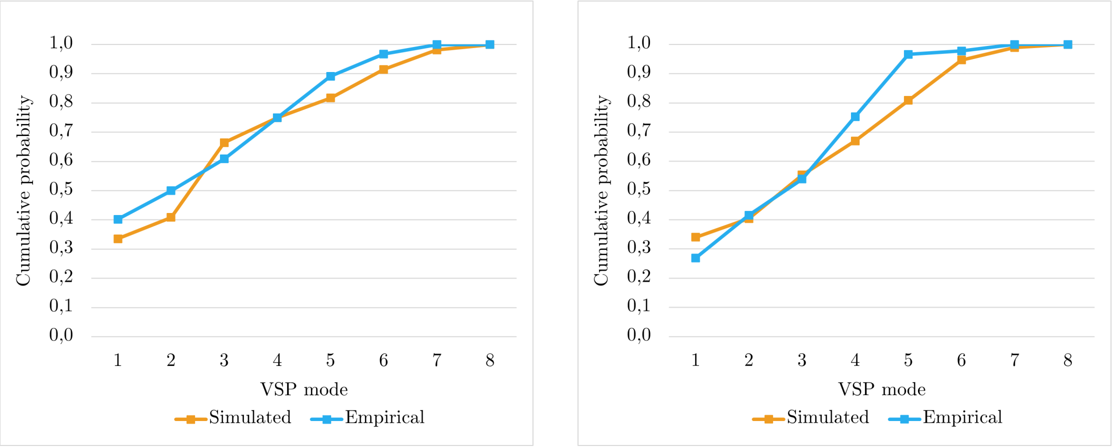
In this section, an analysis is conducted to try to understand the driver's behaviour in an event characterized by the car stopping at a stop sign and then turning to the right. The critical area to be considered comprises 60 m: 30 m for the approaching area and 30 m after the stop sign.



(a) Driver 1

(b) Driver 2

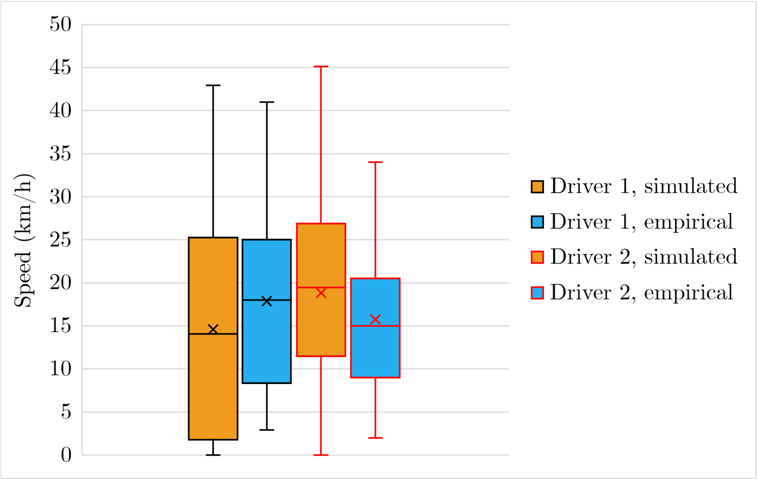
Figure 5.13: Average of time spent in each VSP mode during the event "right-turn after a stop sign" and absolute error between simulated and empirical values.



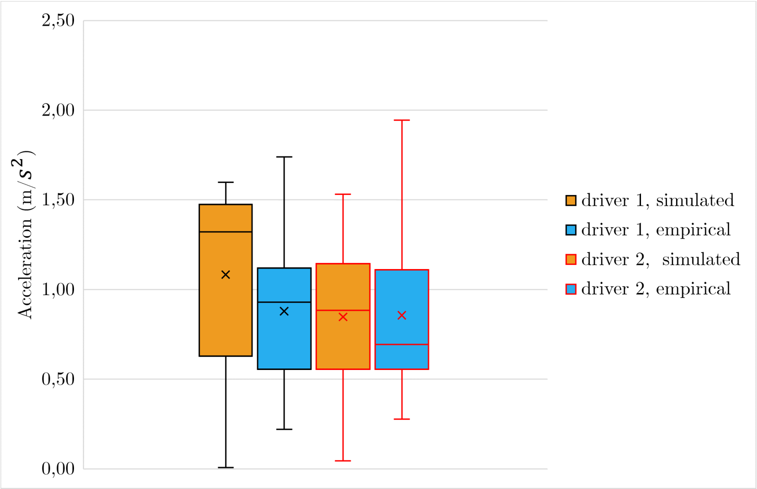
(a) Driver 1

(b) Driver 2

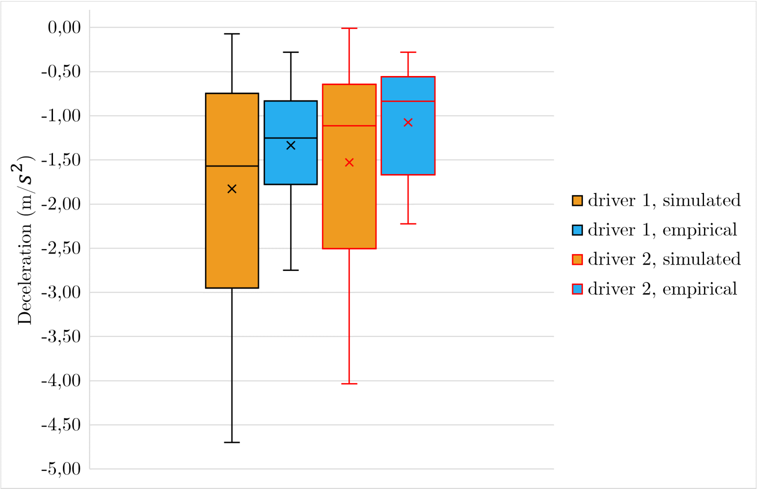
Figure 5.14: Cumulative distributions of simulated and empirical VSP modes for the "right-turn after a stop sign" event.



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.15: Box plot for speed, acceleration and deceleration for the event "right-turn after a stop sign".

Foremost, when comparing the data of the two drivers, it is evident that there is a significant amount of VSP modal bin 1, particularly for Driver 1 (Figure 5.13). This is because this situation requires deceleration when approaching the stop sign. Driver 1 stayed longer in the halted position during the simulated tests, proven by a large average frequency of mode 3 and by the speed values in Figure 5.15a.

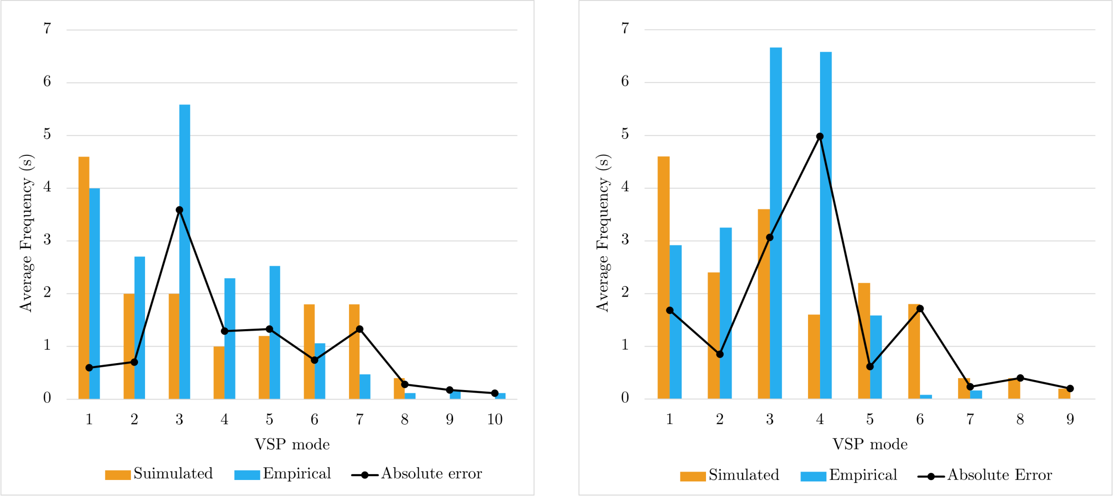
From the cumulative probability curves (Figure 5.14), it is clear that both participants achieved greater VSP modes on the virtual road, indicating that they once again drove faster in this setting; this is especially noted in Driver 2's graph (Figure 5.14b), showing nearly 100% of the empirical VSP modes are less or equal than 5, and there is a high predominance of VSP mode 4, this can be attributed to the volume of traffic in the real road preventing the driver from speeding. This can also explain the speed results that show lower variability in the empirical tests.

Acceleration values (Figure 5.15b) are quite different between the drivers. Driver 1 noticeably accelerated harder in the simulator, and Driver 2 presented a lower variability in the two tests; this can perhaps be explained by a more cautious behaviour, from this driver, in the application of force on the gas pedal in both tests.

For both participants, deceleration values in the simulated setting were higher than in the real world (Figure 5.15c), reinforcing the assertions made in Section 5.1 that the simulator's higher deceleration is caused by a more sensitive brake pedal and a lack of motion feeling.

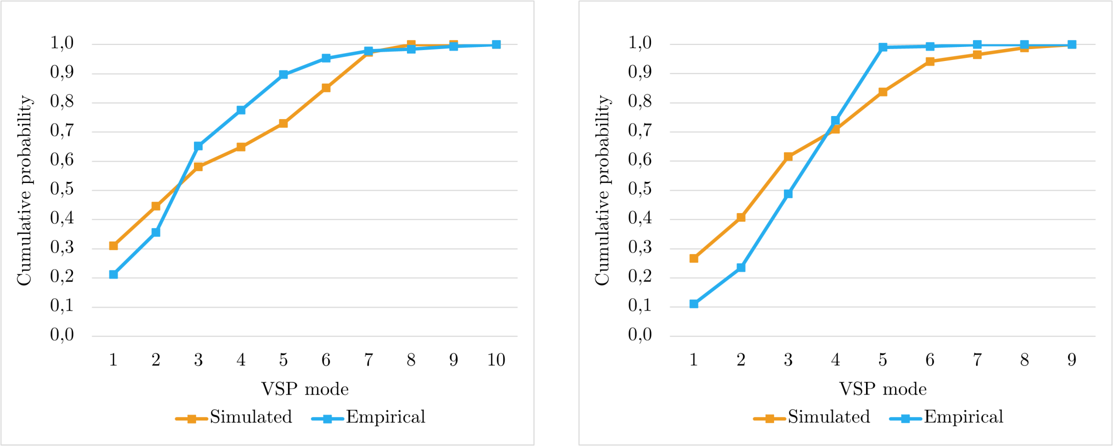
### 5.2.6 Stop sign: Left-turn

This event is fairly similar to the previous one, but in this case, the driver needs to proceed with a left turn after the stop sign, so the same critical areas were considered.



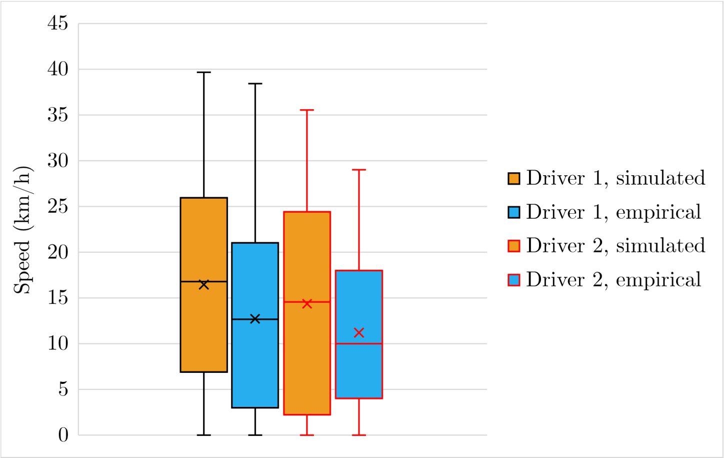
(a) Driver 1 (b) Driver 2

Figure 5.16: Average of time spent in each VSP mode during the event "left-turn after a stop sign" and absolute error between simulated and empirical values.

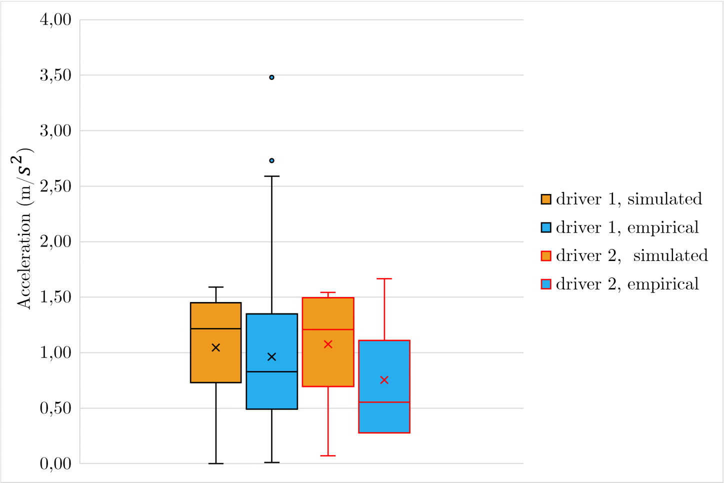


(a) Driver 1 (b) Driver 2

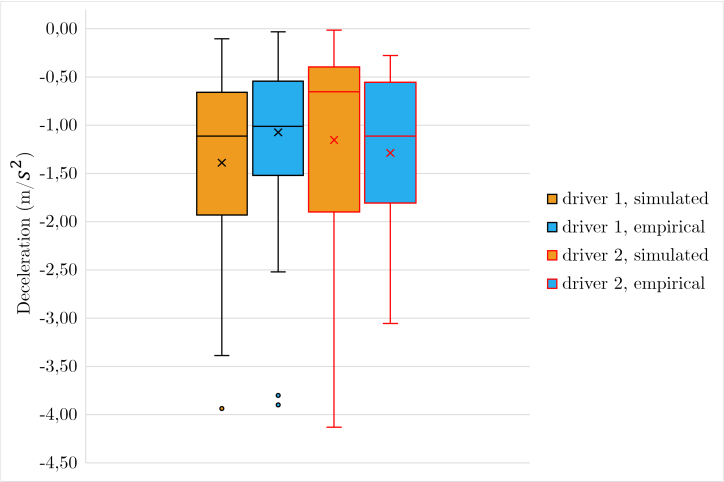
Figure 5.17: Cumulative distributions of simulated and empirical VSP modes for the "left-turn after a stop sign" event.



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.18: Box plot for speed, acceleration and deceleration for the event "left-turn after a stop sign".

From the VSP mode frequency plots (Figure 5.16), it is once again clear that the drivers decelerate harder in the simulator since, in this environment, there is a more predominance of VSP mode 1. This is also proven in Figure 5.18c, where is it seen that the empirical and simulated deceleration box plots are quite different.

The average frequency of VSP mode 3 for the two drivers is higher during the empirical tests (Figure 5.16), which may be linked to the fact that those types of trips had more traffic.

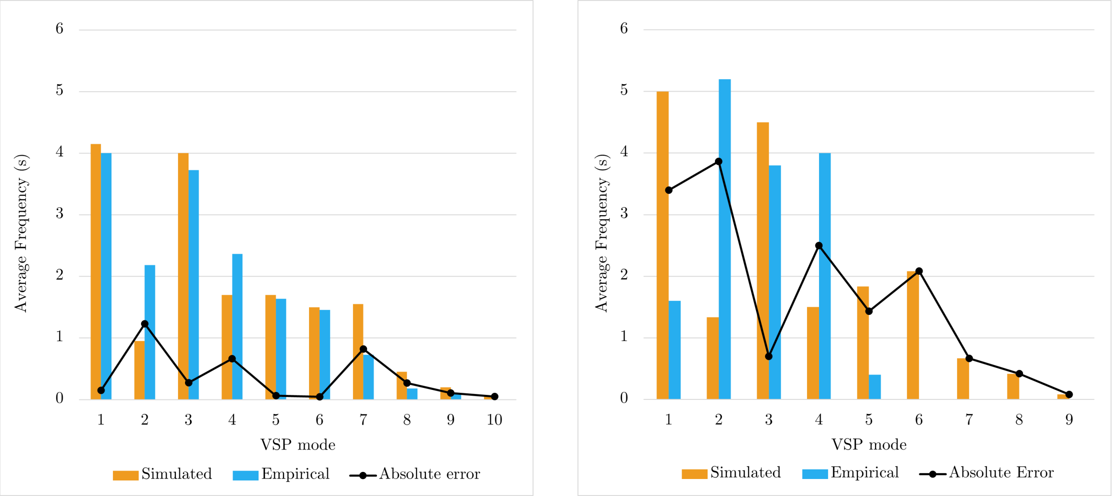
Another difference is that Driver 2's average frequency of VSP modal bin 4 is much higher on real-world trips; this might be because Driver 2 did not speed up or accelerate as much during this test as in the simulation tests, as shown in Figure 5.18. This caused the simulation tests to present higher values of VSP modes like modal bins 6, 7, 8 and 9, as shown in Figure 5.17b. Supporting the conclusion from Section 5.1 that the driver was uncomfortable operating a vehicle in the city of Aveiro.

Overall speed was higher on the simulator for this event for the two drivers (Figure 5.18a), and Driver 2 presented less variability in speed values during the tests on the road, proving, once again, that the driver was more cautious in this environment. Regarding acceleration (Figure 5.18b), overall results have low variability, but it is noticeable that the empirical acceleration reaches higher values.

Globally, in this event, the drivers' performance in the simulation and real settings was not as similar to each other as in previous events.

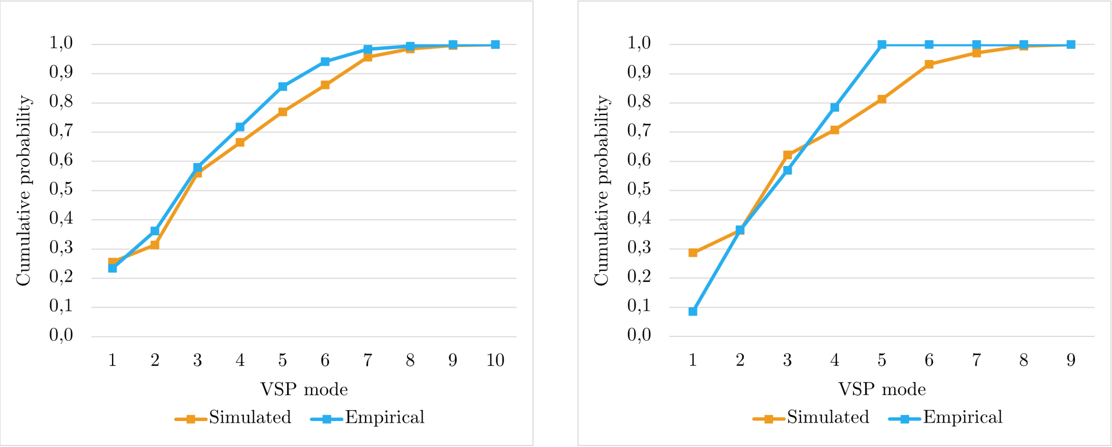
### 5.2.7 Give way

This event is unique from the others since there is no need to proceed with any left or right turns. Instead, the vehicle should move forward but has to halt or slow down due to a yield sign or because it is on a roadway with no priority. Likewise, in previous analyses, this event is examined considering a critical distance involving 60 m: 30 m are set to the approaching area and 30 m after the yield sign.



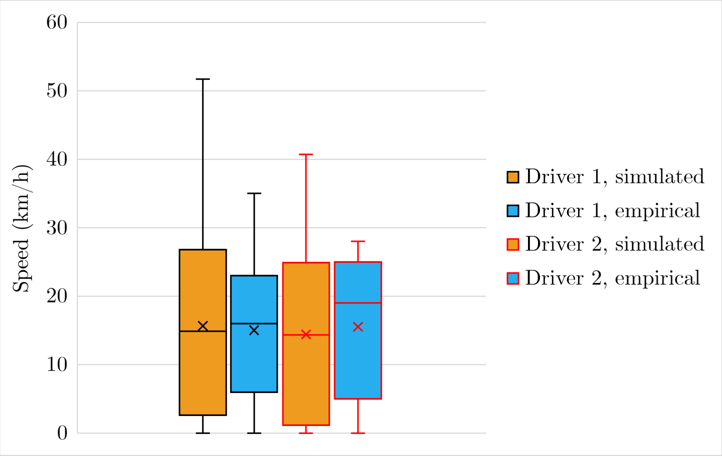
(a) Driver 1 (b) Driver 2

Figure 5.19: Average of time spent in each VSP mode during the event "give way" and absolute error between simulated and empirical values.

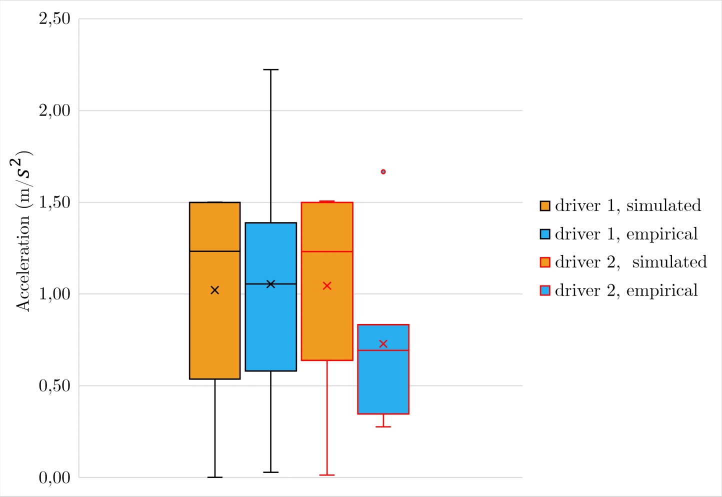


(a) Driver 1 (b) Driver 2

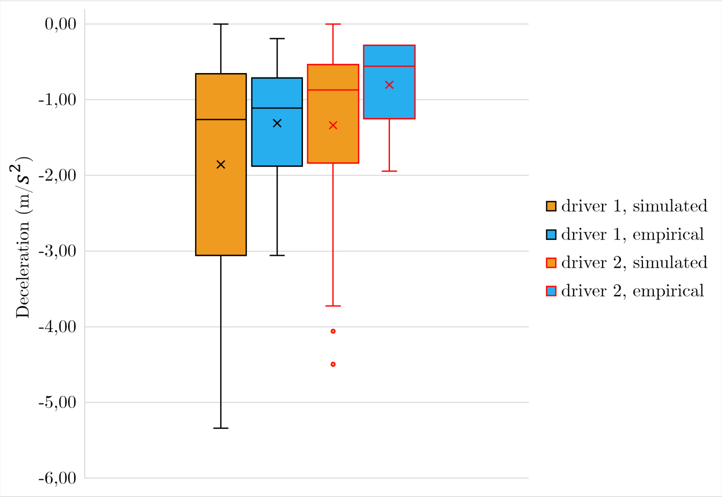
Figure 5.20: Cumulative distributions of simulated and empirical VSP modes for the event "give way".



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.21: Box plot for speed, acceleration and deceleration for the event "give way".

Figure 5.19 shows that, in contrast to Driver 1, Driver 2 behaved differently while operating a vehicle in the two environments, with a significant difference in almost all VSP mode frequencies. The high discrepancy values of Driver 2 can be explained by the fact that this event depends a lot on the flow of traffic and the type of sign that is encountered. The driver sometimes had to completely stop the car (more frequency of VSP mode 1), while other times only needed to slow down (more frequency of VSP mode 2).

The findings of Section 5.1—that, in virtual trips, drivers decelerate more intensely and speed more than on the empirical trips—are again supported by Driver 1's empirical and simulated test findings (Figure 5.21). Aside from these findings, Driver 1's global results in this event were very similar.

The outcomes of Driver 2, however, were not as favourable. The driver reached higher speeds in the virtual testing (Figure 5.21a); as a consequence, higher VSP modes that were not reached in the real road tests were generated; this can be understood by analysing the cumulative probability curve in Figure 5.20b. 50% of Driver 2's simulated acceleration values are between 0.6 and 1.5 $m/s^2$, while in road tests, 50% of the data is between 0.3 and 0.8 $m/s^2$; showing clearly different medians, and overall deceleration for both drivers is less variable in the empirical tests. This difference in acceleration and deceleration behaviour can be due to the different volumes of traffic in both environments, as explained above.

### 5.2.8 Overall Urban Emissions

This section is sought to present emission estimates for all the events considered in this study. These estimates are computed based on the VSP methodology presented earlier. The following table (Table 5.3) shows the average $CO_2$ and $NO_x$ emission results for each driver and event in both simulated and real tests conducted in an urban environment. The drivers' emission quotient is also calculated; the closer this number is to 1, the more equivalent Drivers 1 and 2's emissions were during that particular type of trip and event. Additionally, the relative error between simulated and empirical emissions is also calculated. This way, it is possible to understand the difference between drivers' emissions and between empirical and simulated emissions.

Table 5.3: Average event emissions for each type of test, event and driver, together with the related relative error and ratio between drivers.

| Right-turn with priority | | | | | | |
|---|---|---|---|---|---|---|
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 23,48 | 23,95 | 0,98 | 0,26 | 0,27 | 0,96 |
| Empirical | 26,5 | 27,52 | 0,96 | 0,3 | 0,31 | 0,97 |
| Relative error | -11% | -13% | | -13% | -13% | |
| Left-turn without priority | | | | | | |
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 39,95 | 35,94 | 1,11 | 0,45 | 0,4 | 1,13 |
| Empirical | 30,85 | 26,95 | 1,14 | 0,35 | 0,3 | 1,17 |
| Relative error | 29% | 33% | | 29% | 33% | |
| Right-turn after traffic light | | | | | | |
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 83,65 | 75,87 | 1,10 | 0,94 | 0,85 | 1,11 |
| Empirical | 80,09 | 96,59 | 0,83 | 0,9 | 1,09 | 0,83 |
| Relative error | 4% | -21% | | 4% | -22% | |
| Left-turn after traffic light | | | | | | |
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 90,17 | 88,76 | 1,02 | 1,01 | 0,99 | 1,02 |
| Empirical | 112,75 | 97,78 | 1,15 | 1,26 | 1,1 | 1,15 |
| Relative error | -20% | -9% | | -20% | -10% | |
| Right-turn after a stop sign | | | | | | |
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 34,17 | 28,34 | 1,21 | 0,38 | 0,32 | 1,19 |
| Empirical | 29,17 | 30,31 | 0,96 | 0,33 | 0,34 | 0,97 |
| Relative error | 17% | -6% | | 15% | -6% | |
| Left-turn after a stop sign | | | | | | |
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 32,66 | 35,85 | 0,91 | 0,37 | 0,4 | 0,93 |
| Empirical | 38,19 | 39,5 | 0,97 | 0,43 | 0,45 | 0,96 |
| Relative error | -14% | -9% | | -14% | -11% | |
| Give Way | | | | | | |
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 35,12 | 36,29 | 0,97 | 0,4 | 0,41 | 0,98 |
| Empirical | 33,49 | 27,72 | 1,21 | 0,38 | 0,32 | 1,19 |
| Relative error | 5% | 31% | | 5% | 28% | |

It is interesting to note that events like "left-turn without priority", "right-turn after a traffic light", and "left-turn after a traffic light" had simulated and empirical VSP modes with very identical cumulative distribution (Figures 5.5, 5.8 and 5.11), were not the events that showed lower relative errors between empirical and virtual emissions. This is because a few differences between VSP mode frequencies do not exactly translate into a few differences in emissions. Each VSP mode is associated with a different amount of vehicle emissions, and, for example, a small difference between frequency in VSP mode 14 may result in higher $CO_2$ emissions than a big difference in VSP mode 3.

That said, the events with lower errors between empirical and virtual emissions, according to the analysis of the table, were "right-turn with priority", "right-turn after a stop sign", and "left-turn after a stop sign". In these events, the biggest differences between VSP mode are in modes 2 to 6. The event with the highest errors between empirical and virtual emissions is "left-turn without priority" this could be because this event is one of the most unpredictable because, depending on the flow of traffic, you could either slow down, stop, or maintain speed. In the simulated trips, drivers almost always stopped the car, whereas, in the empirical trips, drivers only slowed down. These two methods of carrying out this event clearly produce different emissions.

Comparing drivers' emissions, it is noticeable they were the most similar in the events "right-turn with priority" and "left-turn after a stop sign" in these events, the drivers' actions were similar both in the simulator and on the road. These are both very predictable events, therefor this is expected.

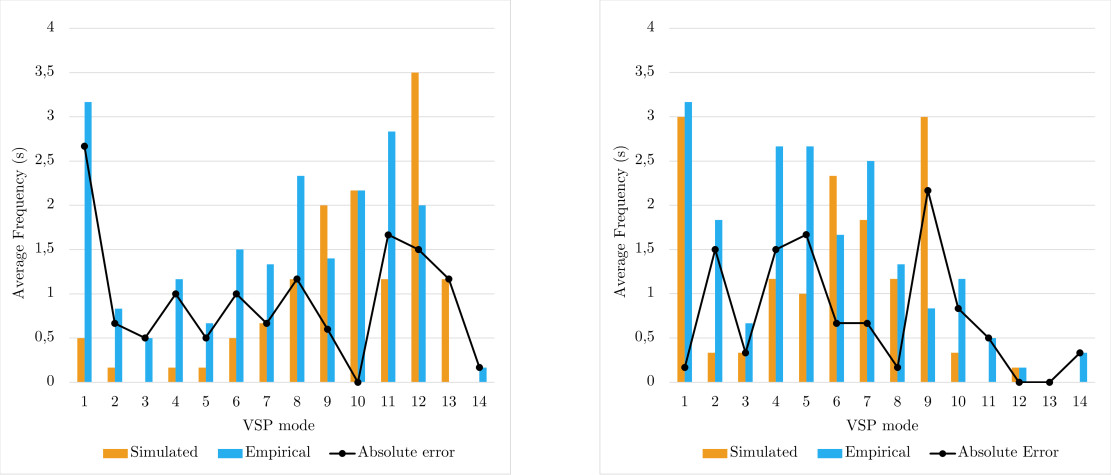
A closer look at the relative error associated with the emissions found that the results obtained for Driver 1 presented, in general, smaller error values. This may be due to various factors, such as Driver 2's lack of experience driving the type of car used in this study, his unfamiliarity with the on-road routes, and variations in traffic volume between the empirical and simulated tests.

It is also noteworthy that the overall emissions outcomes on the empirical tests are slightly higher, and this may be justified by the fact that drivers took longer times to complete the same tasks on the empirical trips, and it may also be due to drivers tend to drive with less speed variability in simulation environments.

## 5.3 Highway Events

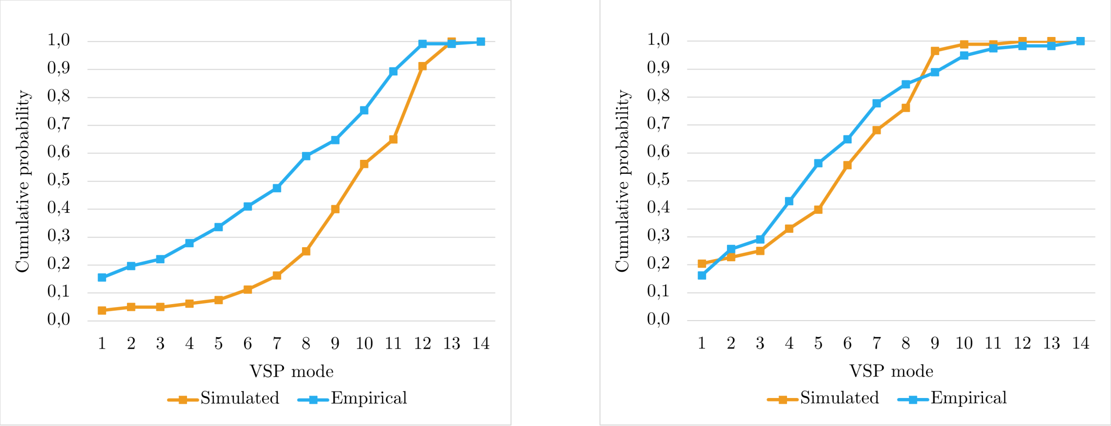
### 5.3.1 Entering Highway

The event begins 150 m before the highway entrance, which can be described as when the car's route joins the highway. After the entry, it continues for another 150 m. It is important to note that, even though this event is a freeway entrance, which usually means accelerating, if there is no room to enter the highway due to heavy traffic, the driver has to slow down or even stop the car until space opens to enter without causing an accident. A high volume of traffic when trying to enter the highway happened in both simulated and empirical environments, causing the drivers to decelerate.



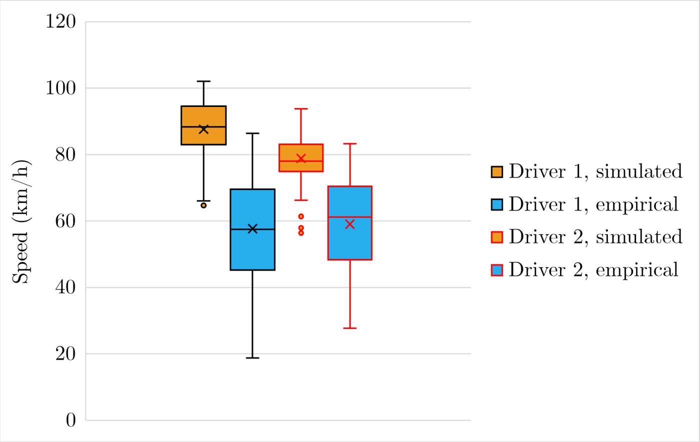
(a) Driver 1 (b) Driver 2

Figure 5.22: Average of time spent in each VSP mode during the event "entering highway" and absolute error between simulated and empirical values.

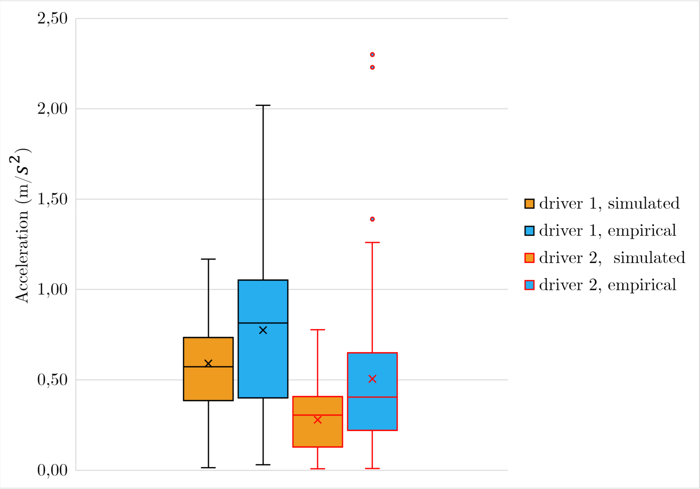


(a) Driver 1 (b) Driver 2

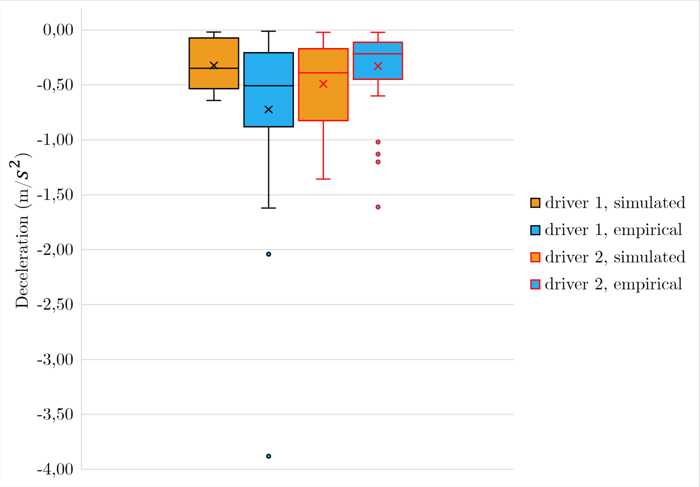
Figure 5.23: Cumulative distributions of simulated and empirical VSP modes for the event "entering highway".



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.24: Box plot for speed, acceleration and deceleration for the event "entering highway".

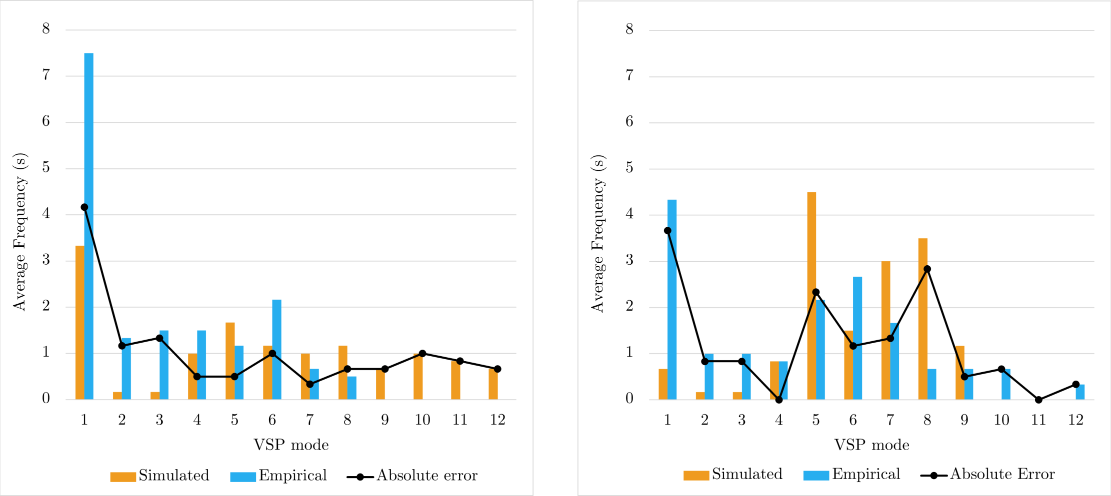
The absolute difference between the empirical and simulated average frequencies of modal bin 1 is visible when analysing the graph in Figure 5.22a. This difference can be easily explained by the occurrence of higher traffic levels in the empirical tests. Driver 1 experienced heavy traffic when entering the freeway on some trips. This has caused sharp decelerations due to the impossibility of acquiring the necessary speed to follow the main traffic flow speed on the motorway.

It's also interesting to look at the graph in Figure 5.23a. This illustrates a significant difference in Driver 1's behaviour on these two tests, with the cumulative probability of the VSP mode being 6 or less for the simulated trials at 10% and the empirical trials at 40%. This is also displayed in Figure 5.22a since practically all modal bin average frequencies deviate slightly. The same occurred with driver 2. Even though the cumulative probability curves do not show a significant absolute difference, it is still evident from the VSP mode chart (Figure 5.22b) that driver 2 behaved rather differently in the two types of tests. The speed values in Figure 5.24a can be used to explain this. In the driving simulator tests, both participants' overall speeds were significantly greater and more stable than in the empirical tests, indicating that there was less traffic than on the real road, enabling an easier entry to the motorway and leading to significantly higher VSP modes in the virtual road.

Overall speed and acceleration values show less variability in the simulated environment; this can be due to this environment being less complex in terms of traffic volume, making the trip unvarying.

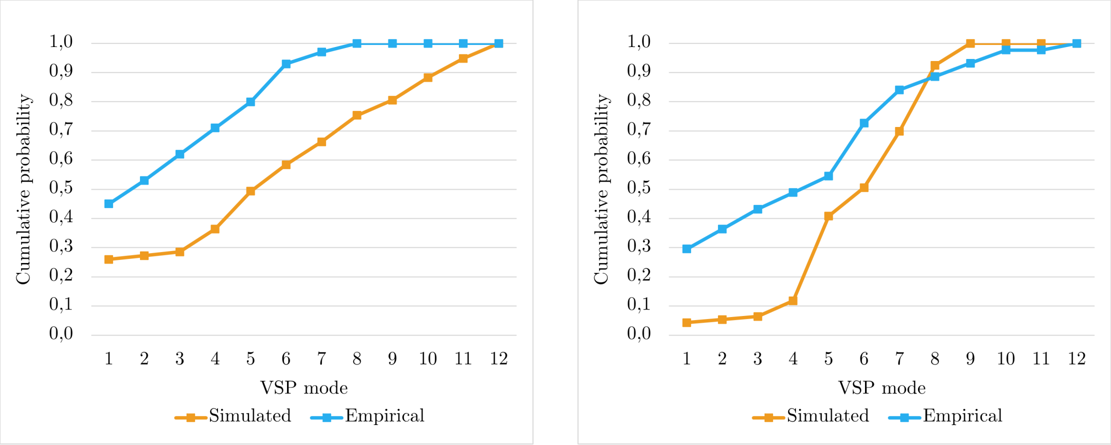
### 5.3.2 Exiting Highway

The event starts 150 m before the highway exit or when the road the car is travelling on begins to diverge from the main road. It continues for another 150 m after the exit.



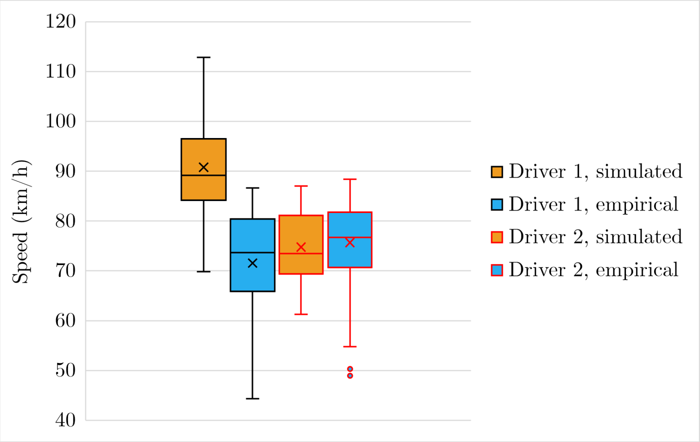
(a) Driver 1 (b) Driver 2

Figure 5.25: Average of time spent in each VSP mode during the event "exiting highway" and absolute error between simulated and empirical values.

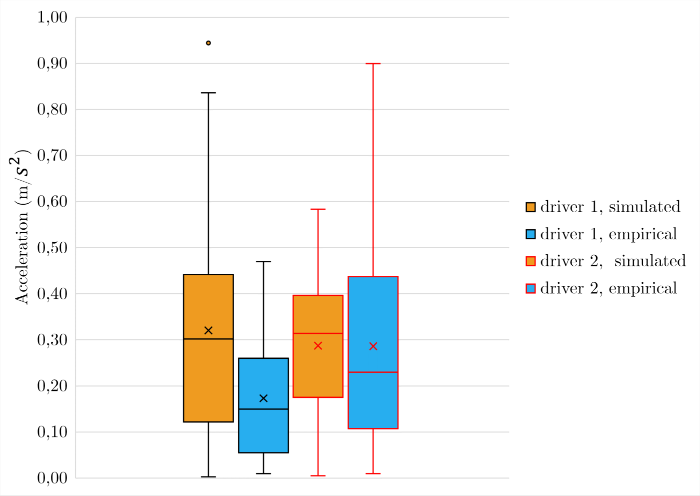


(a) Driver 1 (b) Driver 2

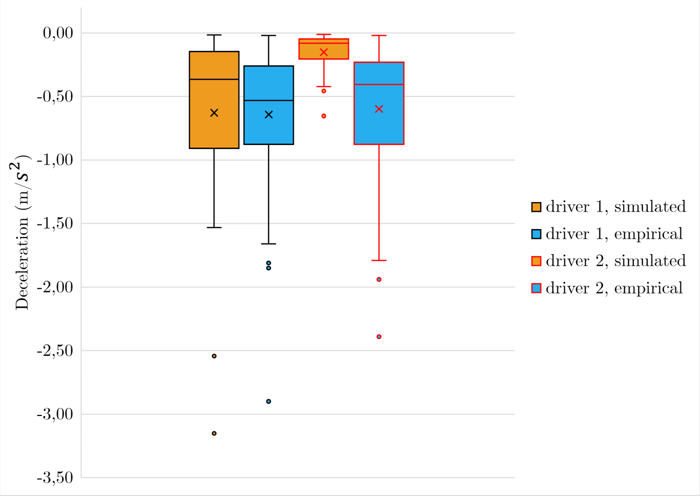
Figure 5.26: Cumulative distributions of simulated and empirical VSP modes for the "exiting highway" event.



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.27: Box plot for speed, acceleration and deceleration for the event "exiting highway".

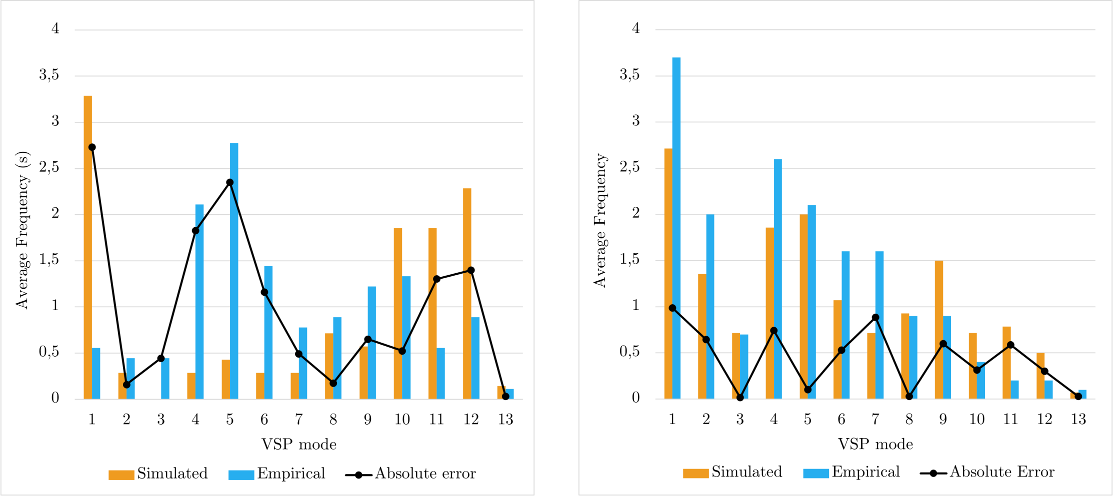
When exiting the highway, it is common to decelerate or circulate during some periods at a lower speed, producing modal bins 3, 4 and 5, according to the VSP mode analysis graph (Figure 3.7). As shown in the graphs in Figure 5.25 an odd number of modal bin 1 were produced by both drivers in the empirical setting; this is attributed to the real road infrastructure since there was a roundabout right after the exit, about 130 m after the highway exit, forcing the motorists to quickly slow down the vehicle before reaching it.

Figure 5.26a shows how the behaviour of Driver 1 varied between the two types of tests. For the simulated and empirical tests, the cumulative probability of the VSP mode being less than or equal to 6 was 58% and 93%. This wide discrepancy can be explained by the higher speeds of Driver 1 in the simulator, as shown in Figure 5.27a and, as a result, reached higher VSP modes on this setting (up to modal bin 12, as shown in Figure 5.25a).

Driver 2's VSP mode and cumulative distribution chart (Figures 5.25b and 5.26b) both illustrate different performances from this subject in the two types of tests. When examining the speed chart in Figure 5.27a it becomes clear that this is strange because the speed trend in both experiments is surprisingly similar. However, it is evident from looking at the acceleration and deceleration values in the Figures 5.27b and 5.27c that the participant behaved very differently in the simulated and empirical tests when leaving the highway, this can also be noticed in Driver 2's deceleration values in the simulator, which show very low variability. This can be attributed to various factors, including the road's infrastructure and the amount of traffic, proving that the simulated trip was less complex and predictable. This can also be attributed to the difference between the simulator's pedals and the real vehicle's pedals.

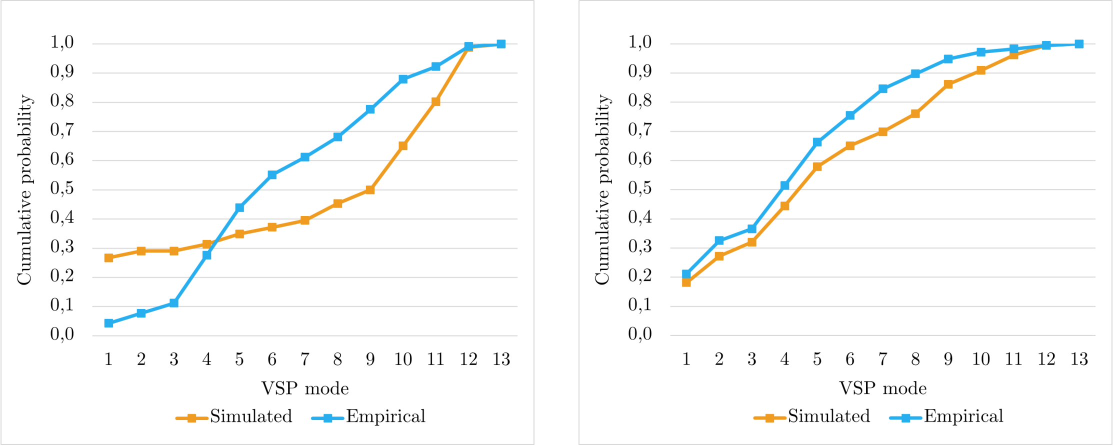
### 5.3.3 Moving Forward

This event takes place throughout 800 m, randomly selected from the section of the route between the highway entrance and exit.



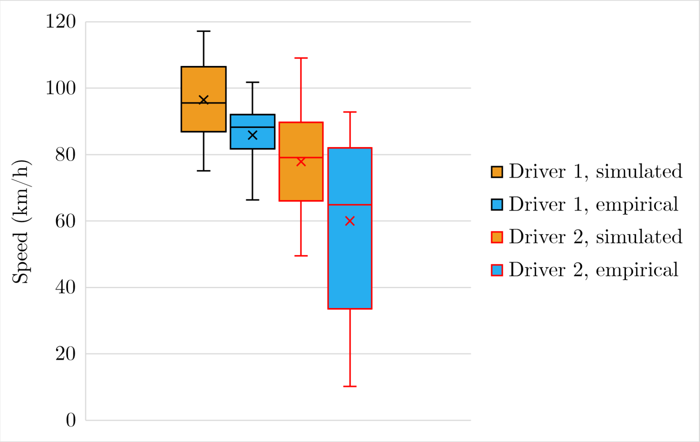
(a) Driver 1 (b) Driver 2

Figure 5.28: Average of time spent in each VSP mode during the event "moving forward" and absolute error between simulated and empirical values.

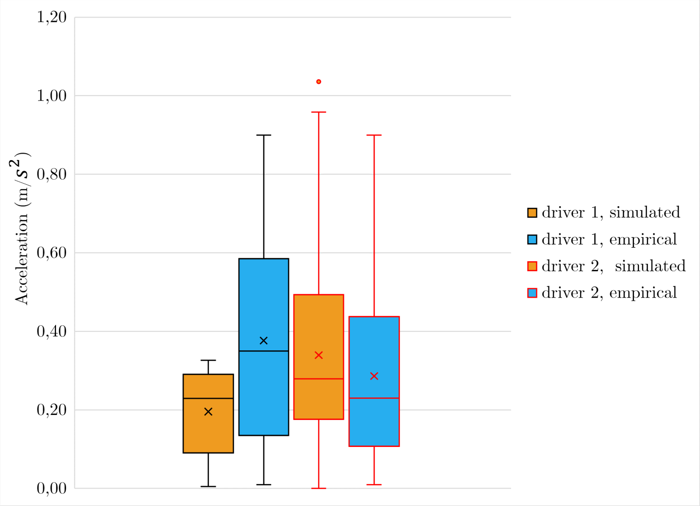


(a) Driver 1 (b) Driver 2

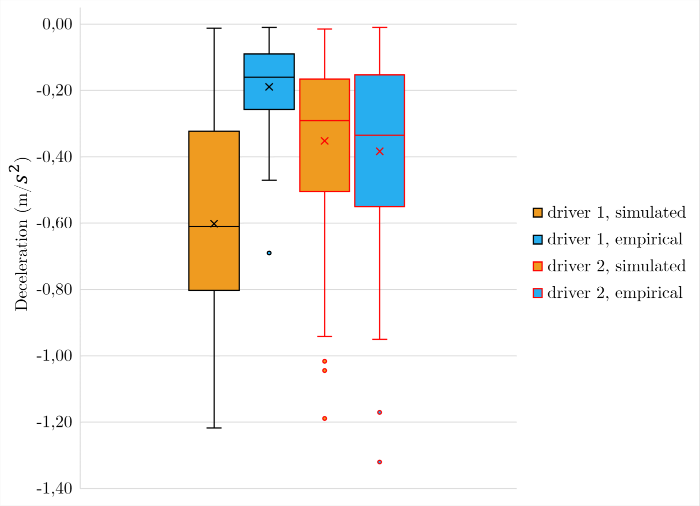
Figure 5.29: Cumulative distributions of simulated and empirical VSP modes for the "moving forward" event.



(a) Speed.



(b) Acceleration.



(c) Deceleration.

Figure 5.30: Box plot for speed, acceleration and deceleration for the event "moving forward".

As depicted in Figure 5.30 Driver 1 decelerated more sharply in the virtual tests and accelerated more intensely in the empirical ones; overall speed was constant for both tests but higher in the virtual environment. The high deceleration levels are believed to be due to traffic in the virtual trials, given that there was a brief period when the cars were stopped on the highway, requiring the driver to slow down abruptly. This would account for the experiments' high frequency of modal bin 1 (Figure 5.28a). The high acceleration values on the real highway can be credited to the motorist overtaking another vehicle; this would generate the high VSP modes such as 10, 11, 12 and 13 seen in the VSP chart.

Additionally, it is crucial to draw attention to the frequent occurrence of modal bins 4, 5, and 6 throughout Driver 1's empirical trials. After analysing the data sheets, it was determined that the frequency of this mode was caused by small decelerations made while travelling at high speed. This is relatively typical behaviour on the highway and is caused by the traffic ahead of the offending vehicle moving at a slower pace.

Compared to Driver 1, Driver 2 shows a similar pattern of accelerations and decelerations between the simulator environment and the empirical tests. Figures 5.30b and 5.24c show how equal the accelerations and decelerations are, but the speed was higher and more steady throughout the tests in the driving simulator. This would explain the minor variations in VSP modes shown in Figure 5.28b.

Altogether, speeds were higher during the virtual experiments in all highway events. Contrary to urban events, this situation does not have to be linked to participants' less fear of speeding in virtual environments but rather to the traffic volume on the real roadways that caused the participants to travel more cautiously.

### 5.3.4 Overall Highway Emissions

The average emission results from each driver and highway event and the accompanying relative error, as well as Driver 1 and 2 emissions quotient, are shown in the table below (Table 5.4).

Table 5.4: Average event emissions for each type of test, event and driver, together with the related relative error and ratio between drivers.

| Entering highway | | | | | | |
|---|---|---|---|---|---|---|
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 64,07 | 43,24 | 1,48 | 0,80 | 0,50 | 1,60 |
| Empirical | 73,66 | 54,05 | 1,36 | 0,86 | 0,62 | 1,39 |
| Relative error | -13% | -20% | | -8% | -19% | |
| **Exiting highway** | | | | | | |
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 39,55 | 43,49 | 0,91 | 0,46 | 0,49 | 0,93 |
| Empirical | 35,31 | 41,19 | 0,86 | 0,40 | 0,47 | 0,84 |
| Relative error | 12% | 6% | | 15% | 4% | |
| **Moving forward** | | | | | | |
| | CO2 (g) | | Driver1/Driver2 | NOx (g) | | Driver1/Driver2 |
| | Driver 1 | Driver 2 | | Driver 1 | Driver 2 | |
| Simulated | 49,65 | 43,22 | 1,15 | 0,59 | 0,50 | 1,19 |
| Empirical | 42,73 | 42,32 | 1,01 | 0,50 | 0,49 | 1,03 |
| Relative error | 16% | 2% | | 19% | 3% | |

When Table 5.4 is analyzed, it becomes evident that the simulated and empirical emissions from the event "entering highway" correspond to the largest relative error. It is also noteworthy that this was the event where the drivers' behaviour was the most dissimilar from one another. This can be attributed to the high differences in VSP mode frequency in modes from 9 to 13 since these modes correspond to the highest emissions.

The results from the highway trips always exhibit the same pattern, with greater or lesser error. Whenever one driver's emissions are higher than the other in the empirical results, they are also higher in the simulated results, and vice versa. In the urban scenario, this did not take place.

## 5.4 Validation: Microscopic Analysis

### 5.4.1 Distances Error

Since the trajectory of the vehicles is recorded on a timely basis and with a frequency of 1 second, as was indicated in previous sections, some inconsistencies may occur in the distance analyzed for the various events among the various tests. In the case of the "right-turn with priority" event, for example, it is stated that 60 meters of data will be taken, but the actual data collected is either 58 or 63 meters.

The error associated with the distances must be calculated, and taken into account when analysing these exploratory analysis outcomes. To do that, the distance relative error (Equation 5.1) of each event used in this research was calculated.

$$relative\ error\ (\%) = \frac{|measured\ distance - real\ distance|}{real\ distance} \cdot 100 \tag{5.1}$$

The findings of the errors are shown in Table 5.5.

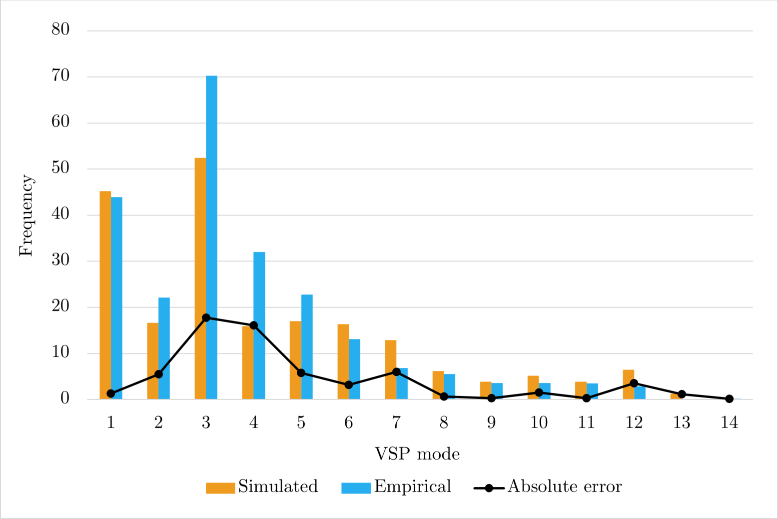
Table 5.5: Average simulated an empirical error for both drivers for highway and city events.

| simulated | | empirical | |
|---|---|---|---|
| highway | city | highway | city |
| 1,59% | 3,12% | 1,42% | 2,31% |

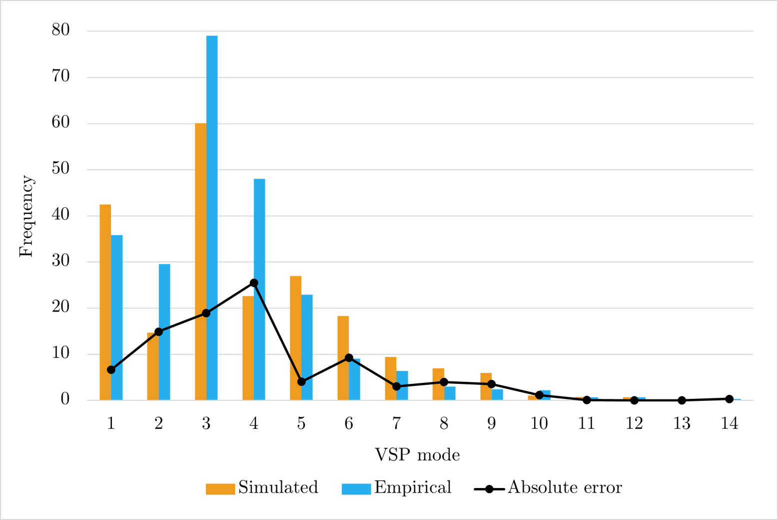
It was determined that the overall relative error of the distances is 2,11% after averaging the error. This inaccuracy is small and will not impact the outcomes of this exploratory analysis.

### 5.4.2 Results Overview

Based on data from all tests from both drivers, Figure 5.31 shows the average time spent in each VSP mode and the corresponding absolute differences.



(a) Driver 1



(b) Driver 2

Figure 5.31: Sum of the VSP mode averages across all events and absolute error between simulated and empirical values.

This graph's only purpose is to emphasise the points made in earlier sections and to aid in the overall data visualization. Similar to the emissions (Sections 5.2.8 and 5.3.4), driver 1 also exhibits a lower error in the average sum of VSP modes.

In VSP modes 3 and 4, there is the greatest variation. Mode 3 represents idling or stop-and-go situations, as previously explained, this can be related to traffic context fluctuations in the empirical tests.

The K-S test is the last step in the result analysis. Section 3.8 provided a step-by-step explanation of this test. The values of D-value and D-critical are displayed in the tables below for drivers 1 (Table 5.6) and 2 (Table 5.7). These values are related to the frequency of VSP modes distribution for each event.

Table 5.6: K-S test values for driver 1.

| Event | D-value | D-critical |
|---|---:|---:|
| Right-turn with priority | 0,14 | 0,21 |
| Left-turn without priority | 0,07 | 0,13 |
| Right-turn after a traffic light | 0,11 | 0,12 |
| Left-turn after a traffic light | 0,12 | 0,11 |
| Right-turn after a stop sign | 0,09 | 0,18 |
| Left-turn after a stop sign | 0,17 | 0,18 |
| Give way | 0,09 | 0,12 |
| Entering highway | 0,34 | 0,20 |
| Exiting highway | 0,35 | 0,21 |
| Moving forward | 0,28 | 0,19 |

Table 5.7: K-S test values for driver 2.

| Event | D-value | D-critical |
|---|---:|---:|
| Right-turn with priority | 0,24 | 0,20 |
| Left-turn without priority | 0,08 | 0,19 |
| Right-turn after a traffic light | 0,08 | 0,12 |
| Left-turn after a traffic light | 0,12 | 0,12 |
| Right-turn after a stop sign | 0,16 | 0,20 |
| Left-turn after a stop sign | 0,17 | 0,17 |
| Give way | 0,20 | 0,17 |
| Entering highway | 0,17 | 0,19 |
| Exiting highway | 0,37 | 0,20 |
| Moving forward | 0,15 | 0,14 |

The red cells denote results that reject the null hypothesis that the VSP modes' frequencies in the real-world and simulated tests are drawn from the same distributions. This occurred in four out of ten events for both drivers. The empirical and simulated frequencies of the VSP mode distribution differed noticeably, demonstrating that the drivers acted differently in the two types of tests. This can be further understood with the corresponding graphs from these distributions, which are presented in Figures 5.11a, 5.23a, 5.26a, 5.29a, 5.2b, 5.20b, 5.26b and 5.29b. The majority of the referred events are from the highway scenario; this reflects the fact that in these conditions, the degree of experience, driving style and risk perception of the driver assumes a greater preponderance than in urban events, which are characterised by the need to drive according to the traffic flow and infrastructure characteristics.

# Chapter 6

# Conclusions and Future Work

The final thoughts (Section 6.1), research limitations and research needs for related subjects that could be explored later (Section 6.2) are presented in this chapter.

## 6.1 Conclusions

This study conducted an experimental validation of VSP mode distributions from 10 different traffic events based on an in-depth analysis of over 18000 data points from around 24 driving experiments. The data were separated into two groups of driving activity, the real world and the driving simulator data, to ascertain whether the outputs obtained from the driving simulator can be relied upon to estimate vehicle emissions.

The average frequency of the two drivers' VSP mode distributions was found to have generally similar trends, and when shown by event, some occurrences had more errors than others. Total emissions were compared to support further the viability of using driving simulator data for vehicle emission estimations. Between simulated and empirical tests, there were small errors. After this exploratory validation analysis, and after speaking with both drivers to better understand how their behaviour varied between the two types of tests, several conclusions can be made:

1. The two drivers confirmed that they were less afraid of getting into an accident in the simulator, indicating that drivers tended to reach higher speeds in virtual environments because they did not have to worry about the consequences.

2. Drivers reached more negative decelerations in virtual environments because, as stated by them, they found it difficult to concentrate in the driving simulator after around 20 minutes of driving, therefore braking the car more abruptly; this indicates that this approach is better suited to brief car trips, with breaks between them. In addition, as was already mentioned, there are no motion stimuli, and the car's brake requires much less pressure to operate than a real car would.

3. The discrepancies in VSP mode frequencies between the driving simulator and the real road were noticeable in most events but not big enough to discern vehicle emissions differences. This is good news for those who intend to study operating mode distributions using the driving simulator.

4. The K-S test found that the driving simulator could replicate the driver's behaviour in the real environment for most of the events.

In general, there is variability between drivers' behaviour in the driving simulator and reality; however, the associated relative errors are not significant. The driving simulator was able to replicate the real emissions of the highway scenario with a relative error of 11% and of the urban scenario with a relative error of 15%.

## 6.2 Limitations and Recommendations for Future Work

The best way to conduct this study would have been to use a simulator to replicate the streets of the city of Aveiro; however, this step could not be completed because the researcher had to use the pre-set scenarios in the CarnetSoft Software. The path, traffic, and pedestrian inflow varied between the real and simulated scenarios despite having similar infrastructure and environments. The selected vehicle for this study was the Renault Clio 5p; since this vehicle has a lot of different versions, the emission factors are not the exact ones for this version. It is also important to remember that even though this study allows for a very interesting analysis of driving behaviour in the simulator and on the road, only two participants existed. Small samples lower the study's power and raise its margin of error.

It is advised that future studies utilising driving simulations to examine vehicle emissions should concentrate on the following issues:

1. To better understand the variables that affect testing outcomes in the driving simulator, a larger number of drivers of various ages, gender, and driving experience groups should participate in the research.
2. The exact architecture of the empirical journey should be created in the driving simulator for a more accurate study. This way, the entire trip may be compared rather than just different types of occurrences, greatly minimising inaccuracies.
3. Consider using the VT-Micro and CMEM emissions models as well; these models operate very differently from the VSP emissions model. Examining alternative possibilities will strengthen the research and make it more significant.
4. More tests should be conducted to further validate the driving simulator as a tool to study vehicle emissions.
5. Calculate the emission factors of the vehicle, and corresponding version, used on the on-road tests.

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