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Evaluating the sustainability of e-commerce deliveries strategies: A simulation-based approach

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Resumo

O rápido crescimento do *e-commerce* tem afetado os sistemas de transporte urbano e as condições de vida nas cidades, tornando necessário o desenvolvimento de estratégias de entrega eficientes que atendam à crescente procura, ao mesmo tempo que se minimizam os impactos ambientais.

Este estudo teve como objetivo avaliar diferentes estratégias de entrega do *e-commerce* em zonas residenciais urbanas, considerando diferentes tipos de características do território. Para isso, foram definidos três cenários de inclinação do solo (*baseline*, plano e com declive alto) e quatro estratégias de entrega de encomendas, designadamente usando diferentes tipos de veículos: veículos com motores de combustão interna (ICE), carrinhas elétricas e bicicletas de carga elétricas grandes e pequenas. No caso dos veículos ICE, estes foram avaliados não só quando o motor era desligado nos momentos da entrega, mas também quando o motor não era desligado.

A análise foi realizada utilizando o pacote *Simulation of Urban Mobility* (SUMO), uma poderosa ferramenta de simulação de tráfego de código aberto. Os resultados foram avaliados em termos de desempenho operacional (duração, distância, e tempo de espera), consumo de energia (combustível ou eletricidade) e emissões (CO_2, CO, HC, PM_x e NO_x).

Os resultados das simulações indicam que os veículos de entregas de encomendas ICE e as carrinhas elétricas tiveram um desempenho similar em termos do tempo total da rota de entrega para todos os cenários de inclinação. No entanto, o uso de veículos ICE em cenários com inclinações mais acentuadas resultou num aumento considerável de emissões, especialmente CO_2 (17,9%). Quando o motor permanece ativo durante as paragens para entrega das encomendas, esse impacto é ainda maior. Neste caso, regista-se um aumento médio de 47% nas emissões de CO_2, em comparação com os cenários em que o motor é desligado.

As bicicletas de carga tiveram um bom desempenho em cenários com inclinações suaves. Verificou-se que esses veículos consomem menos energia do que as carrinhas elétricas. No entanto, a sua menor capacidade exige que eles regressem ao armazém para reabastecer de carga, aumentando assim o comprimento da rota e o tempo total das entregas de encomendas.

Nas regiões mais inclinadas, a bicicleta de menor carga demonstrou melhor desempenho devido ao seu design mais leve do que as bicicletas maiores. No entanto, em cenários com menor inclinação, a bicicleta maior, dado que tem maior capacidade de carga, apresenta-se como uma solução mais vantajosa.

Ao promover a adoção de veículos elétricos e implementar medidas como desligar o motor durante as paragens, as empresas podem melhorar a eficiência das entregas, ao mesmo tempo que mitigam as consequências ambientais. Esse conhecimento permite desenhar melhores estratégias de entrega, contribuindo assim para a implementação de serviços de mobilidade urbana otimizados e mais sustentáveis de *e-commerce*.

Palavras-chave: Simulação de tráfego, Estratégias de entrega do comércio eletrónico, Cenários de inclinação, Eficiência operacional, Impactos ambientais, Veículos elétricos, Bicicletas de carga.

Abstract

The rapid growth of e-commerce has affected urban transportation systems and living conditions in cities, making it necessary to develop efficient delivery strategies to meet the increasing demand while minimizing environmental impacts.

This study aims to evaluate different e-commerce delivery strategies in urban residential areas, considering different types of terrain characteristics. For this purpose, three terrain slope scenarios (baseline, flat, and steep) and four delivery strategies were defined using different types of vehicles: vehicles with internal combustion engines (ICE), electric vans, and large and small electric cargo bikes. In the case of ICE vehicles, they were evaluated not only when the engine was turned off during delivery stops but also when the engine was not turned off.

The analysis was conducted using the Simulation of Urban Mobility (SUMO) package, a powerful open-source traffic simulation tool. The results were evaluated in terms of operational performance (duration, distance, waiting time), energy consumption (fuel or electricity), and emissions (CO_2, CO, HC, PM_x, and NO_x).

The ICE delivery vehicles and electric vans performed similarly in terms of total delivery route time across all slope scenarios. However, the use of ICE vehicles in steeper slope scenarios resulted in a considerable increase in emissions, especially CO_2, with a 17.9% increase. When the engine remained active during delivery stops, this impact was even greater. In this case, there was an average increase of 47% in CO_2 emissions compared to scenarios where the engine was turned off.

The cargo bikes performed well in scenarios with gentle slopes (baseline). It was found that these vehicles consume less energy than electric vans. However, their lower capacity requires them to return to the warehouse to replenish the cargo, thereby increasing the route length and total delivery time.

In steeper regions, the smaller cargo bike demonstrated better performance due to its lighter design compared to larger cargo bikes. However, in scenarios with lower slopes, the larger bike, due to its greater cargo capacity, proves to be a more advantageous solution.

By promoting the adoption of electric vehicles and implementing measures such as engine shutdown during stops, companies can improve delivery efficiency while mitigating environmental consequences. This knowledge allows for the design of better delivery strategies, thereby contributing to the implementation of optimized and more sustainable urban mobility services for e-commerce.

Keywords: Traffic simulation, E-commerce delivery strategies, Slope scenarios, Operational efficiency, Environmental impacts, Electric vehicles, Cargo bikes.

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Kristen Vidal

"Feliz aquele que transfere o que sabe
e aprende o que ensina."

Cora Coralina

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Abbreviations and Symbols

B2C	Business-to-consumer
CBL	Large Cargo Bike
CBS	Small Cargo Bike
CO_2	Carbon Dioxide
DSS	Decision Support System
ELV	Electric Van
EU	European Union
GHG	Greenhouse gases
HC	Hydrocarbons
ICE	Internal Combustion Engine
NO_x	Nitrogen Oxides
OSM	Open Street Map
PM	Particulate Matter
SLR	Systematic Literature Review
SUMO	Simulation of Urban Mobility
UB	Unloading bay
UCC	Urban Consolidation Center
UZ	Unloading zone
VKT	Vehicle Kilometers Traveled
ZEZ	Zero Emission Zone

Chapter 1

Introduction

This chapter is structured into four sections. First, it is explored the significant impact of e-commerce industry on transportation and its associated environmental challenges (Section 1.1). By addressing the growing concerns related to pollution and traffic resulting from online retail, this section establishes a foundation for investigating environmentally friendly and sustainable delivery logistics methods.

Building upon the preceding section, Section 1.2 delves into the importance and motivation behind the research conducted in this work. It highlights the need for practical solutions to mitigate the environmental impact of e-commerce transportation, considering the pressing global concerns of sustainability and resource conservation.

To provide a clear framework for the research, Section 1.3 outlines the objectives and scope of this work. It articulates the specific goals and intentions of the research, emphasizing the areas of focus and the intended outcomes.

Finally, Section 1.4 offers an overview of the document's organization and subsequent chapters. It highlights the contributions of each chapter to the overall research.

1.1 Context

The rise of e-commerce in Europe has been remarkable, with a significant number of consumers turning to online shopping in recent years. According to research from E-commerce News, in 2020 alone, approximately 297 million European consumers engaged in online shopping, contributing to the substantial growth of e-commerce revenue, which reached 718 billion euros in 2021, marking a 13% increase [2]. This surge in e-commerce activity has fueled the demand for efficient supply chain management practices that can keep pace with customer expectations.

Just-in-time (JIT), a concept widely used in supply chain management, focuses on minimizing inventory and optimizing production and delivery processes by ensuring that goods arrive precisely when needed. This approach, which includes crucial last-mile delivery, has proven instrumental in facilitating the growth of e-commerce by enabling businesses to streamline their operations and provide timely delivery to customers. The last-mile refers to the final stage of the delivery process, from a distribution center or a local hub to the end recipient. It is often the most complex and costly part of the delivery chain, requiring efficient route planning, coordination, and execution. The convenience of just-in-time and next-day home deliveries, including the efficient completion of the last-mile, has become increasingly attractive to consumers, enhancing their online shopping experience and driving the preference for this mode of retail.

In the current climate crisis context, it is crucial for companies to conscientiously evaluate the environmental implications of their services. Notably, the e-commerce industry has experienced substantial growth, especially during the COVID-19 pandemic [3]. However, it is important to acknowledge that this growth has come with a significant environmental cost, positioning the e-commerce sector as a noteworthy contributor to environmental degradation.

Moreover, a significant portion of the challenges associated with the growth of e-commerce can be attributed to the increasing demand for transportation. The rise in e-commerce has led to a surge in freight transport requirements, thereby exacerbating environmental concerns. According to a report by the European Environment Agency (EEA) [4], between 2000 and 2019, there was a substantial 22% increase in freight transport demand in Europe. This rise in transport demand has significant consequences, particularly in terms of carbon dioxide (CO_2) emissions. Heavy-duty vehicles operating within the European Union alone account for approximately 25% of CO_2 emissions from road transport [5]. Despite continuous efforts to reduce greenhouse gas emissions in the EU, CO_2 emissions from heavy-duty vehicles have persistently increased since 2014 [6].

Furthermore, freight vehicles have a significant impact on total transport emissions at the urban level, accounting for an estimated 6-18% of total urban transport and contributing to 21-55% of total transport emissions [7]. These statistics highlight the substantial environmental consequences of freight transport, including the release of harmful pollutants and noise pollution, particularly in densely populated urban areas.

Emissions from freight vehicles consist of various pollutants that have different effects on the environment and human health. Carbon dioxide (CO_2) is a greenhouse gas that contributes to climate change and global warming by trapping heat in the atmosphere. Carbon monoxide (CO) is a toxic gas that, when inhaled, can impair oxygen delivery in the body. Hydrocarbons (HC) are a group of pollutants that can react with other compounds in the atmosphere, forming harmful ozone and contributing to smog formation. Particulate matter (PM) consists of tiny particles suspended in the air, which can penetrate deep into the respiratory system and have adverse health effects, particularly on the lungs and cardiovascular system. Nitrogen oxides (NO_x) are a group of gases that contribute to the formation of smog and acid rain, and they can also irritate the respiratory system. Furthermore, the continuous movement and operation of freight vehicles generate excessive levels of noise, leading to disturbances in residential areas and impacting the overall well-being of urban residents [8].

Despite the efforts made to implement environmentally friendly measures, global emissions continue to rise due to the increased demand for e-commerce services [6]. Therefore, further measures and innovations are needed to effectively address the environmental impact of the e-commerce industry and ensure a sustainable future.

1.2 Motivation

In an effort to responsibly address the challenges posed by this industry and contribute to the European Union's goals of reducing CO_2 emissions by 55% by 2030 [9], it is imperative to have a better understanding of parcel delivery processes in urban centers and their impacts.

As the digital market continues to rapidly expand to meet consumer demands, it approaches a critical juncture with significant economic, social, and environmental implications. This phenomenon can have multifaceted impacts on the quality of life in urban cities, including increased traffic congestion, elevated noise levels, and heightened pollution. Addressing these negative impacts is essential to prevent further deterioration of urban environments.

To mitigate the environmental and urban consequences of e-commerce deliveries, it is crucial to implement tools and techniques that assist companies in optimizing their parcel delivery operations. Through route simulations and the evaluation of different strategies in different scenarios, companies can reduce mileage, fuel consumption, carbon emissions, and costs. Additionally, the adoption of electric and low-emission vehicles plays a vital role in reducing both noise and greenhouse gas emissions in the e-commerce sector.

1.3 Objectives

This study seeks to enhance our understanding of how terrain slopes impact both operational efficiency and environmental consequences associated with various e-commerce delivery methods. By incorporating the influence of terrain slopes on traffic patterns, this research aims to investigate the effects of different scenarios on delivery strategies within a typical urban residential area. The main objectives are summarized as followed:

- To examine the influence of terrain characteristics on different parcel delivery strategies;
- To evaluate the operational efficiency of the parcel delivery strategies considered;
- To assess the environmental impacts of the parcel delivery strategies considered.

To achieve these objectives, a traffic simulation tool was employed to evaluate different delivery strategies in different terrains. Factors such as route length, vehicle cargo capacity, and population density were considered in the analysis. Through simulations, this research seeks to provide actionable insights for making informed decisions in urban logistics and e-commerce operations.

1.4 Document structure

This document is organized into five interconnected chapters, each serving a specific purpose to ensure a comprehensive study. Chapter 1, "Introduction", sets the tone by providing a contextual foundation for the study. It not only goes into the subject but also elucidates the motivations that drove its development, establishing a clear understanding of the research objectives that will be explored in subsequent chapters.

Building upon the foundation built in the introduction, Chapter 2 conducts a literature review. This review serves as an exploration of existing research on the chosen theme, synthesizing and analyzing prior work conducted in the field.

In Chapter 3, the methodology behind this work is meticulously described. This chapter serves as a guide, providing a clear understanding of the approach and techniques employed in the work. By offering this detailed insight into the simulation methodology, readers can analyze it punctually, fostering transparency and facilitating the reproducibility of the results obtained. This chapter will describe various aspects, including the case study itself, the parameterization of vehicles, and the estimation of demand.

Chapter 4 presents the simulations data, offering a detailed examination and discussion of the obtained results. Finally, Chapter 5 serves as the conclusion of the study, synthesizing the entire research. In this chapter, the key findings and results from Chapter 4 are summarized, providing a cohesive understanding of the outcomes. It also addresses the limitations of the study, acknowledging areas for improvement and potential future research opportunities.

Chapter 2

Literature review

In recent years, there has been a growing focus on addressing the environmental impact associated with traffic across different domains. However, the vast amount of research available in this field can make it challenging to comprehend the current state of knowledge. Consequently, numerous studies have been conducted exploring various aspects and perspectives of the subject matter. This literature review aims to offer a comprehensive and systematic analysis of the existing research, focusing on a specific area of investigation. By synthesizing the available literature, this review seeks to provide valuable insights and a deeper understanding of the chosen research domain.

2.1 Literature review methodology

A systematic literature review (SLR) is a method of systematically and rigorously examining the existing research on a specific topic. It is designed to provide a thorough and objective analysis of the current state of the field. Unlike a traditional narrative review, an SLR follows strict guidelines and utilizes a replicable, scientific, and transparent process [10]. The SLR conducted for this project followed the five-stage guideline proposed by Denyer and Tranfield [11]. Figure 2.1 illustrates the process that was followed.

The first step in the systematic literature review process is to formulate the review question. The main goal of this phase is to clearly define the scope of the review and understand the current state of research in the relevant fields. The review question for this SLR is:

- **RQ1** — How is the impact of parcel delivery operation strategies being studied to assess their sustainability and efficiency?

The second stage of the systematic literature review process called the identification stage, involves collecting a large number of references related to the research theme. The Web of Science (WoS) platform was chosen for this purpose because it offers a comprehensive database of publications on the topic. A search query was created based on specific keywords and their synonyms to identify relevant publications. The final search query used in the WoS was:

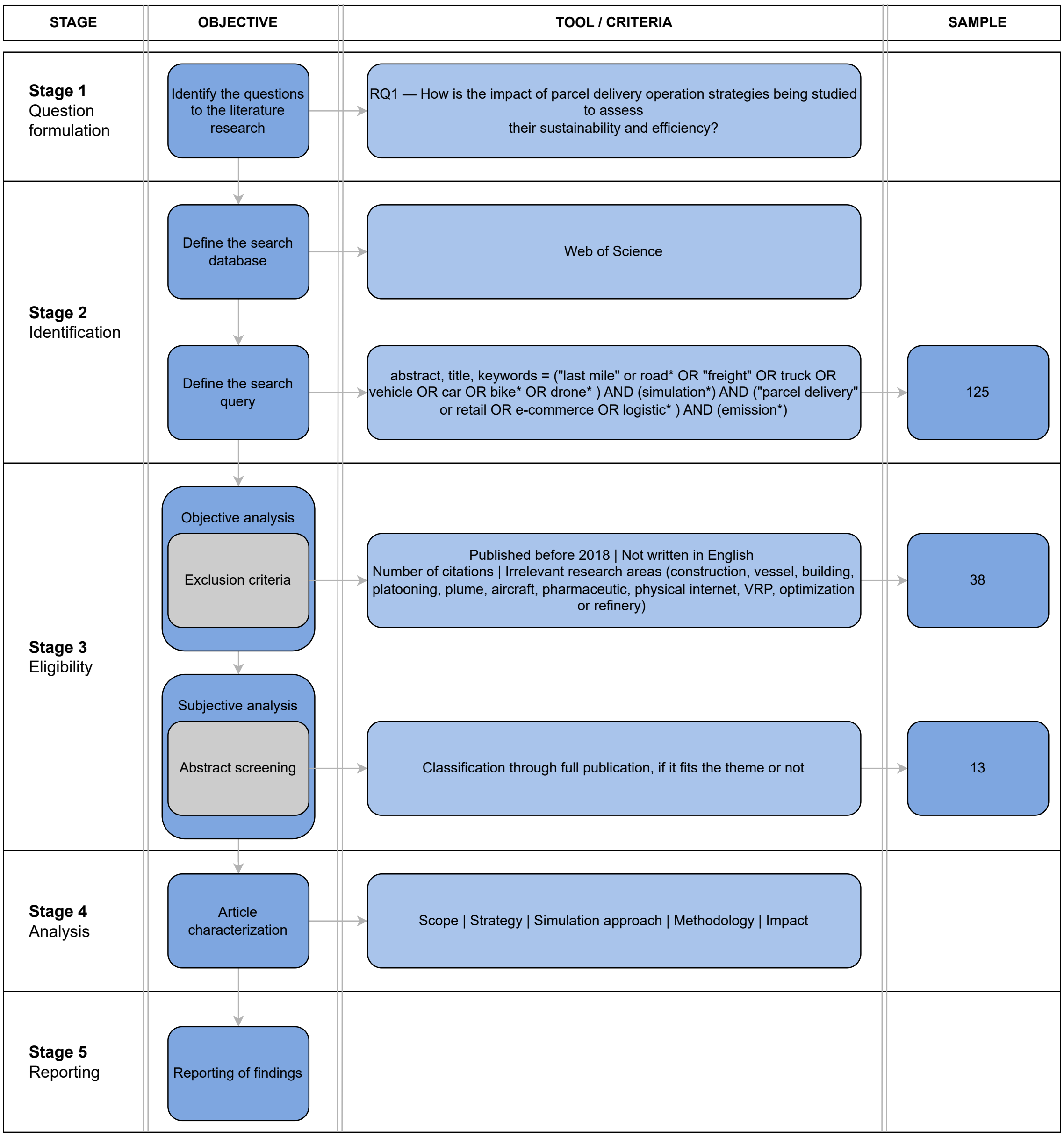


Figure 2.1: SLR methodology.

- ("last mile" OR road* OR "freight" OR truck OR vehicle OR car OR bike* OR drone*) AND (simulation*) AND ("parcel delivery" OR retail OR e-commerce OR logistic*) AND (emission*)

The identification stage involved applying the search query to the titles, abstracts, and keywords of publications in the Web of Science database. This search was conducted between December 2022 and January 2023, resulting in an initial sample of 125 publications.

The eligibility stage, which is the third stage of the systematic literature review process, plays a crucial role in refining the initial sample. During this stage, scientifically and thematically relevant studies were carefully selected using objective and subjective analysis.

To ensure the rigor and transparency of the systematic literature review process, a Microsoft Excel spreadsheet was used to further filter the sample. The exclusion criteria for the objective analysis included the following: (i) publications published before 2018, (ii) publications not written in English, (iii) number of citations, and (iv) publications classified with irrelevant research areas (identified by having keywords such as construction, vessel, building, platooning, plume, aircraft, pharmaceutical, physical internet, VRP (vehicle routing problem), optimization, or refinery in the abstract).

In the second screening, a subjective analysis was conducted by evaluating the compatibility of each study with the objectives of this work based on the content of the full paper. The initial sample of 125 articles was reduced to 38 after applying the exclusion criteria and finally narrowed down to 13 results after the subjective analysis.

Both screenings were designed to select scientifically and thematically relevant studies that aligned with the research questions. This process ensures that the final sample of studies is representative and relevant to the research theme. This systematic approach helps maintain the integrity and validity of the literature review, providing a comprehensive and meaningful synthesis of the available scientific evidence.

2.2 Overview of simulation-based research on delivery systems

The table presented below, labeled as Table 2.1, provides a comprehensive overview of the publications gathered through the literature research. It encompasses vital details about each publication, including their respective location, date of publication, simulation approaches employed, the scope of the study, delivery strategies tested, simulated scenarios, and the aspect of last-mile delivery examined.

In this collection, the majority of articles focus on freight transport, with only three exceptions. Specifically, both the studies conducted by Zissis et al. [12, 13] center around grocery deliveries. On the other hand, Sullet and Dossou [14] explore a comprehensive strategy implemented in the Paris region focusing on logistics and the mobility aspect.

In the analysis of the 13 simulation articles, a clear trend emerged, indicating that the majority of the studies (8 out of 13) were carried out in various European cities. The remaining articles covered diverse geographical regions, including one conducted in South America, specifically in Brazil [15], another in North America focusing on Mexico [16], and a third study conducted in Asia, with a particular emphasis on India [17]. Furthermore, it is worth noting that one of the studies simulated hypothetical locations [18], suggesting that the scenarios were meticulously crafted for fictional regions.

The majority of the studies in this literature review focused on simulations conducted in small areas of cities, such as neighborhoods or even specific streets. These simulations specifically targeted commercial and urban regions [12, 13, 19, 15, 20, 17, 21]. On the other hand, another portion of the studies aimed at macrosimulations, encompassing entire cities or even regions within countries [18, 22, 14, 23, 16, 24].

2.2.1 Simulation approaches

When it comes to the studies' simulation approaches, researchers predominantly relied on PTV Vissim as their primary traffic simulation software of choice. This preference can be attributed to the software's extensive range of input parameters, making it a versatile tool in the field. PTV Vissim stands out for its ability to create detailed and accurate models that simulate various traffic scenarios [25].

One such alternative approach is the utilization of statistical analysis, like Monte Carlo simulations, which employ probabilistic methods to analyze and predict traffic behavior. By considering factors such as traffic flow, congestion, and travel times, researchers can gain valuable insights into the stochastic nature of traffic. Monte Carlo simulations enable the assessment of uncertainties' impact on the system.

Another alternative approach is the use of agent-based models, such as MASS-GT (Multi-Agent Simulation System for Goods Transport). These models simulate the behavior and interactions of individual agents, such as vehicles or travelers, within a spatial environment.

Researchers have also explored other traffic simulation technologies. Discrete-event simulation focuses on modeling and analyzing the events that occur in a system over time, enabling researchers to study the dynamic behavior of traffic systems. Flexsim is an example of software based on discrete-event simulations, providing a comprehensive platform for simulating complex traffic systems, offering features such as 3D visualization and analysis tools.

In addition, hybrid simulation frameworks integrate multiple simulation techniques, combining the strengths of different approaches to model and analyze traffic dynamics more effectively.

By embracing a combination of traffic simulation software, statistical models, and agent-based models, researchers can employ diverse modeling methods that are suited to their specific research objectives and scenarios. This multidimensional approach enhances their ability to gain comprehensive insights into traffic dynamics and improve their understanding of complex transportation systems.

2.2.2 Scope and strategies

Different strategies of last-mile deliveries were identified in the literature, in particular, the use of cargo bikes [19, 17, 24], smart lockers [15, 23], collaboration [12, 13, 18, 22, 14] and alternative solutions [20, 21, 16].

Three publications specifically address the strategy of delivery through cargo bikes: Vasiutina et al. [19], Ben Rajesh and Rajan [17], and Arnold et al. [24].

The study conducted by Vasiutina et al. [19] investigated the impact of utilizing cargo bikes for last-mile deliveries on carbon dioxide (CO_2) transport emissions in various urban districts, including Vitoria-Gasteiz and San Sebastian in Spain, Dubrovnik in Croatia, and Mechelen in Belgium.

By analyzing the total distance covered by vehicles and employing the COPERT methodology, the researchers estimated CO_2 emissions for different scenarios. The results clearly demonstrated that incorporating cargo bikes as auxiliary means of transport led to a significant reduction in total CO_2 emissions from freight vehicles in the case study area.

On average, the implementation of cargo bikes resulted in a noteworthy 59.4% decrease in total CO_2 freight emissions in the central district of Vitoria-Gasteiz and a 60.5% reduction in the central district of San Sebastian, when compared to baseline scenario where no cargo bikes were used in the freight fleet. Similarly, the Old Town of Dubrovnik and the central part of Mechelen experienced a consistent 61.0% reduction in CO_2 emissions when cargo bikes were used for goods deliveries.

These findings highlight the potential environmental benefits of integrating cargo bikes into last-mile delivery systems, showcasing their effectiveness in reducing CO_2 emissions.

Taking a different approach, Arnold et al. [24] examined the cost structure of various scenarios for urban business-to-consumer (B2C) distribution in Antwerp, Belgium. By analyzing real-world data and calculating delivery routes, the researchers found that external costs associated with transportation via delivery vans accounted for 18%–28% of operational costs. The study explored the impact of self-pick-up and bike delivery systems on costs, revealing that neither approach alone was beneficial for all stakeholders. However, a combination of self-pick-up and bike deliveries, along with the implementation of additional delivery points, demonstrated improved quality of life in Antwerp while appealing to small logistics service providers. The study emphasized the importance of adopting a global perspective when considering urban B2C distribution, recognizing the diverse goals and strategies of stakeholders. However, it should be noted that these findings are specific to these distinct urban areas and may not directly generalize to other cities.

Two other works address the strategy of delivery using smart lockers, namely Alves et al. [15] and Kiousis et al. [23].

In Alves et al. [15], the usefulness of an agent-based simulation model for modeling urban freight transport, particularly in the context of e-commerce deliveries, was demonstrated. The model simulated the interactions and actions of agents in various situations. The scenario resembling the current situation, where multiple delivery attempts were made, yielded the poorest results. However, the implementation of smart lockers improved this scenario by reducing redeliveries and truck travel distances.

When comparing the introduction of smart lockers to a traditional method of delivery, significant benefits were observed. The use of smart lockers resulted in notable reductions in fuel consumption (up to 30%), time-related costs (up to 30%), and external costs (up to 19%). Additionally, the simulation revealed that smart lockers not only reduced kilometers traveled but also decreased the number of trucks in urban areas (between 17% and 33%), leading to economic benefits and contributing to the overall quality and livability of the urban environment by reducing accidents and congestion.

Similarly, in Kiousis et al. [23], a methodology was proposed to assess the impacts of smart lockers as a city logistics measure. Traffic simulation was employed to evaluate the situation before and after the implementation of smart lockers. The results demonstrated significant benefits for both the operator and the municipality.

The average travel time for freight vehicles was reduced by 82.4%, accompanied by a similar reduction in traffic delays. Furthermore, the total vehicle kilometers decreased by 90.9%, rendering almost 80.0% of the vehicle fleet unnecessary.

From an environmental perspective, there were improvements in overall emissions and traffic delays, indicating that the advantages derived from avoiding home delivery trips outweighed the negative impacts of additional pickup trips made by motorized vehicles.

Overall, the establishment of smart lockers in both studies showcased numerous benefits, including improved efficiency, reduced costs, environmental advantages, enhanced quality standards, increased flexibility, and decreased reliance on traditional delivery methods.

While this dissertation primarily focuses on various last-mile delivery strategies, it is crucial to acknowledge that collaboration strategies have a broader scope within the realm of freight transport systems.

Horizontal collaboration, in the context of freight transport systems, refers to the coordinated efforts and partnerships among multiple stakeholders involved in the supply chain. It involves sharing resources, information, and infrastructure to optimize logistics operations and enhance overall efficiency. Collaboration strategies aim to address challenges such as empty backhauls, inefficient route planning, and underutilization of resources by promoting cooperation and synergy among different actors within the transport network.

The findings from the studies conducted by Zissis et al. [12, 13] shed light on the significant benefits of collaboration through micro hubs in the last-mile delivery of groceries. By operating shared vehicles within residential areas with a 2-kilometer service radius, collaboration led to substantial reductions in both distance and route. On average, distance reductions of 17% (with a standard deviation of 28%) for 10 orders per route and 37% for 15 orders per route were observed. Similarly, route reductions averaged at 22% and 26% (with standard deviations of 17% and 21%) for vehicle capacities of 10 and 15 orders per route, respectively. These findings demonstrate the potential for improved efficiency in the last mile, especially when collaborating retailers face higher demand. Retail managers can benefit from the concept of micro hubs operated collaboratively in residential areas, as it offers a practical solution to reduce distances traveled and enhance overall delivery performance.

Another example of horizontal collaboration is the Urban Consolidation Centers (UCCs). UCCs are centralized hubs strategically located within urban areas. These centers serve as consolidation points where goods from multiple suppliers are aggregated before being distributed to their final destinations. UCCs play a crucial role in reducing congestion, mitigating environmental impacts, and optimizing last-mile deliveries in urban settings.

The study conducted by de Bok et al. [22] found that implementing a Zero Emission Zone (ZEZ) in Rotterdam unexpectedly increased vehicle kilometers traveled (VKT) due to additional transportation legs. However, logistical efficiency improvements, such as consolidating shipments at UCCs, offset the VKT increase. Although emissions decreased within the ZEZ, logistical efficiency gains compensated for the higher VKT outside the zone. The results emphasize the significance of UCCs and the need for careful UCC location planning.

In addition to horizontal collaboration, vertical collaboration is another form of collaboration within freight transport systems. Vertical collaboration refers to the collaboration between organizations operating at different levels of the supply chain, such as suppliers, manufacturers, wholesalers, and retailers. This type of collaboration aims to improve coordination, communication, and overall supply chain performance by aligning activities and sharing information among different stages of production and distribution.

The key conclusion of the study conducted by Jerbi et al. [18] is that supply chain pooling strategies, characterized by collaboration among stakeholders, lead to a significant reduction in CO_2 emissions compared to non-pooled strategies. The evaluation of five strategies in the study consistently demonstrated a decrease in CO_2 levels. The implementation of the most effective supply chain pooling strategies can result in emission reductions of up to 13%. This research provides valuable insights into the importance of collaboration in promoting low-carbon supply chains.

Crowdsourced delivery services, another form of collaboration in freight transport systems, involve leveraging a network of independent drivers who use their own vehicles to make deliveries on behalf of a company or platform. This collaborative model connects the demand for delivery services with available drivers through a mobile app or online platform. By collaborating with individual drivers, crowdsourced delivery services enable companies to optimize last-mile deliveries by efficiently utilizing the resources and capacity of a decentralized network of drivers.

The study conducted by Simoni et al. [21] investigated the potential impacts of alternative crowdshipping practices on traffic and pollution through simulation. The findings demonstrate that crowdshipping can have varying effects on emissions and traffic congestion depending on the chosen transportation mode. Car-based crowdshipping shows higher negative externalities compared to traditional deliveries, highlighting the need for optimization strategies such as off-peak hours and parking availability. Understanding the balance between car-based and environmentally friendly crowdshipping services can inform policy solutions aimed at optimizing crowdshippers' trips.

Finally, Voegl et al. [20] examined the effects of different unloading infrastructure configurations on emissions and lead times of delivery vehicles in a busy retail street in Vienna, Austria. Factors such as the ratio of unloading zones (UZs) to unloading bays (UBs), the number of staff assisting with unloading, and parking behavior of passenger cars were analyzed. A discrete-event simulation model was developed to assess these factors' impact on emissions and lead times. The results indicate that simply increasing the number of UBs may not always be the most effective approach, especially without UBs available at all unloading areas. Providing additional staff consistently improved delivery vehicle lead times and emissions. However, changes in lead times did not always correspond directly with changes in emissions.

Table 2.1: Literature review - studies on delivery strategies.

Reference	Local	Date	Simulation approach	Scope	Strategy	Last-mile
Zissis, Aktas & Bourlakis [12]	United Kingdom	2020	Monte Carlo simulation	Grocery deliveries	Collaboration	Y
Zissis, Aktas & Bourlakis [13]	United Kingdom	2018	Monte Carlo simulation	Grocery deliveries	Collaboration	Y
Vasiutina, Naumov, Szarata & Rybicki [19]	Vitoria-Gasteiz, San Sebastian, Dubrovnik, and Mechelen	2022	Python-based simulation code	Freight transport	Cargo bikes	Y
Alves, Lima, de Sena, de Pinho & Holguin-Veras [15]	Belo Horizonte, Brazil	2019	Agent-based simulation model	Freight transport	Smart lockers	Y
Jerbi, Jribi, Aljuaid, Hachicha & Masmoudi [18]	Hypothetical location	2022	Discrete-event simulation	Freight transport	Horizontal and vertical collaboration	N
de Bok, Tavasszy & Thoen [22]	The Netherlands	2022	MASS-GT	Freight transport	UCC	N
Voegl, Fikar, Hirsch & Gronalt [20]	Vienna, Austria	2019	Discrete-event simulation	Freight transport	Unloading operations	Y
Sullet & Dossou [14]	Grand Paris Sud	2018	Flexsim and PTV Vissim	Urban logistics and mobility	Collaboration	Y
Kiousis, Nathanail & Karakikes [23]	Athens, Greece	2019	PTV Vissim	Freight transport	Smart lockers	Y
Ben Rajesh & Rajan [17]	Bangalore, India	2020	PTV Vissim	Freight transport	Cargo bikes	Y
Simoni, Marcucci, Gatta & Claudel [21]	Rome, Italy	2020	Hybrid simulation framework	Freight transport	Crowdsourced delivery services	Y
Munoz-Villamizar, Velazquez-Martinez, Haro, Ferrer & Marino [16]	Mexico	2021	Discrete-event simulation	Freight transport	Evaluation of logistics operations	N
Arnold, Cardenas, Sorensen & Dewulf [24]	Antwerp, Belgium	2018	Statistical analysis simulation	Freight transport	Cargo bikes and delivery Points	Y

Chapter 3

Methodology

In recent years, traffic simulation technologies have emerged as crucial tools in assessing and enhancing the efficiency and safety of transportation systems. These technologies create virtual models of real-world traffic environments, enabling the analysis of various transportation-related scenarios.

This chapter defines the procedures implemented to achieve the defined objectives, explicitly focusing on the simulation methodology employed. It is organized into four main sections, each addressing a specific aspect of the methodology. First, it outlined the chosen technologies and methods used for conducting the simulations. It is explained the approach adopted in this study, highlighting the tools and frameworks utilized. Then, it provides an in-depth exploration of the chosen study area.

This second section offers a comprehensive overview, emphasizing its significance and suitability as a representative sample. The rationale for selecting this area is discussed, considering its alignment with the research objectives and its relevance within the broader transportation context.

The configuration and adjustment of various parameters within the simulation model and the definition of scenarios are outlined in sections three and four, respectively. First, it is presented the specific parameters that were modified and fine-tuned to ensure the simulation accurately represents real-world conditions. Then, the scenarios evaluated in the simulations are presented, highlighting the particular factors and variables manipulated to create these scenarios. The chapter overview is illustrated in Figure 3.1.

3.1 Simulation approach

Traffic simulation is a crucial aspect of transportation analysis, with a wide range of tools available to public agencies, research institutions, and private organizations. These tools aim to replicate the intricate dynamics of traffic behavior within a transportation network, providing insights into system performance over time and space. This section aims to showcase the technologies utilized in this work.

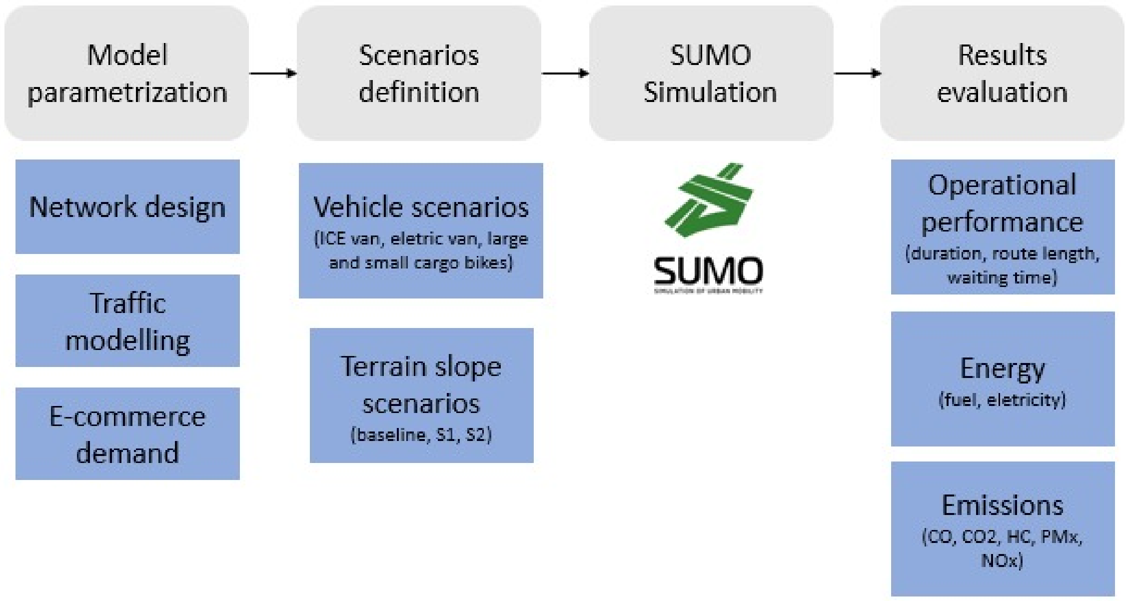


Figure 3.1: Methodology overview.

3.1.1 Simulation models

Simulation models, a significant category of traffic analysis tools, are specifically designed to emulate real-world traffic patterns, enabling the experimentation and evaluation of various scenarios. Researchers and practitioners can effectively assess transportation systems' efficiency, safety, and overall performance by utilizing these simulation models [26]. These tools can be grouped into the following categories, also shown in Figure 3.2:

- **Macroscopic level**: Based on the deterministic relationships of the flow, speed, and density of the traffic stream. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles [26];
- **Mesoscopic level**: Combines the properties of both microscopic (discussed below) and macroscopic simulation models. As such, mesoscopic models provide less fidelity than microsimulation tools but are superior to the typical planning analysis techniques [26];
- **Microscopic level**: The modeling of individual vehicle movements on a second or subsecond basis for the purpose of assessing the traffic performance of highway and street systems, transit, and pedestrians, allowing users to have more control of the scenario they are creating [26].

On a microscopic level, the traffic simulator offers the highest level of detail, as it is able to simulate individual vehicles and pedestrians. This modeling approach was selected for the development of the present work as it allows a great detail of the design of the traffic lanes, as well as the extension and the number of lanes it allows intersecting.

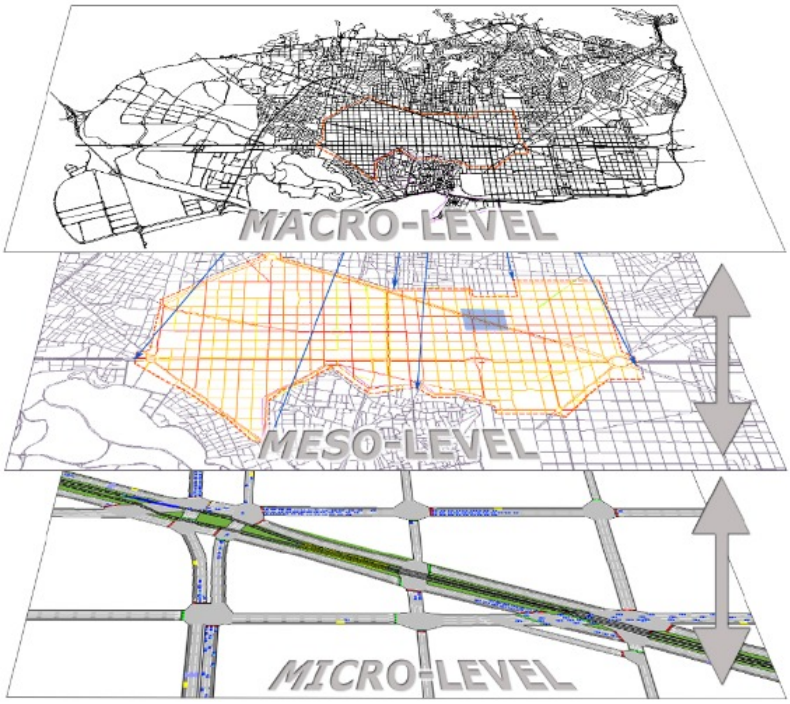


Figure 3.2: Simulation models [1].

This model is well-suited for accurately simulating the movement of individual vehicles within a network [27], making it an ideal tool for simulating parcel deliveries.

3.1.2 SUMO

The open-source microscopic traffic simulation package, Simulation of Urban Mobility (SUMO), was utilized to quantify the impacts of last-mile operations [28]. This tool, developed by the German Aerospace Center and a community of users, provides a solid and reliable choice for simulating and analyzing traffic in transportation and urban mobility research. SUMO users have the advantage of being able to experiment with new approaches by making changes to the program source code through the open-source license. This transparency, adaptability, helpful documentation, and regular software updates contribute to SUMO's effectiveness as a simulation tool [28].

SUMO offers flexibility, allowing customization to fit specific research needs, such as configuring a wide range of vehicle types, including vans, trucks, cargo bikes, and people, enabling the assessment of the sustainability of different delivery methods. The simulator also has advanced features like a fast graphical user interface, modeling public transportation, simulating pedestrian behavior, and providing the capability to display vehicle emission outputs (such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM)), making it suitable for complex studies.

Working with SUMO offers numerous advantages, primarily due to its extensive range of tools and continuous updates driven by an active community. One noteworthy tool provided by SUMO is the Open Street Map (OSM) Web Wizard. This tool offers a user-friendly solution for initiating simulations within SUMO.

The OSM Web Wizard goes beyond network creation by allowing the configuration of randomized traffic demand. Moreover, it provides flexibility in selecting the simulation time, importing public transport data, and choosing specific connections from the map area of interest to import. This capability enables the simulation of diverse traffic scenarios, offering valuable insights into different traffic patterns and congestion levels. The simulation results can be conveniently visualized and analyzed using SUMO's intuitive graphic user interface, facilitating a comprehensive understanding of the simulated scenarios.

One notable advantage of utilizing the OSM Web Wizard within SUMO is its seamless integration with the continuously evolving Open Street Map data. This integration ensures access to up-to-date map information, reflecting real-world changes in road layouts, traffic regulations, and infrastructure developments. Such up-to-date data enhances the accuracy and realism of simulations, enabling researchers to make informed decisions based on current and relevant information.

3.2 Case study

A region spanning 1 km^2 located in the central area of the city of Porto, Portugal, was selected as the study area. This area's layout of streets and avenues was chosen due to its representative nature of a typical residential urban area, making it easier to relate findings to similar blocks located in other medium European-sized cities.

The selected study area has a population of approximately 15.5 thousand inhabitants [29] and comprises various essential services, including schools, sports pavilions, gas stations, supermarkets, pharmacies, and public transportation. In addition to these services, this area is a popular gateway to the city center, which imply an increased influx of people and goods. This further enhances the area's suitability as a case study. The case study area is presented in Figure 3.3, adapted from OSM Web Wizard.

Five major streets intersect the selected study area in Porto: Rua da Constituição (from East to West), Rua de Egas Moniz (from West to East), Rua de Serpa Pinto (North/South), Rua de Antero de Quental (North/South), and Rua de São Dinis (West/East). The first two operate as one-way streets, with Rua da Constituição being the only one which features a dedicated bike lane. On the other hand, Rua de Serpa Pinto, Rua de São Dinis, and Rua de Antero de Quental are two-way streets.

These streets serve as vital connections between key city locations, including Aliados, Marquês, and Boavista. Aliados is renowned as a tourist hub; Boavista is an important commercial center; and Marquês represents a residential area with a network of bus lines serving its residents. The study area also encompasses a variety of residential structures, ranging from multi-story buildings to individual houses.

Figure 3.3: Case study area.

3.3 Model parameterization

This section provides an overview of network definition and configuration, highlighting its essential role in simulating realistic traffic scenarios. It covers the key parameters to achieve the simulation objectives of the study.

Detailed explanations are provided regarding selecting and adjusting key parameters that influence traffic flow and network performance in general, such as vehicle routes, traffic volumes, stops, and vehicle types. By delving into these aspects, this section seeks to offer a detailed account of the methodology adopted to create a robust and representative network model for the subsequent simulations.

The network model, which will be described in detail in this section, can be visualized in Figure 3.4.

Figure 3.4: Case study area network.

3.3.1 Network design

By selecting a specific area of interest from an OSM map, it is possible to generate a network based on the chosen region, as illustrated in Figure 3.5.

While OSM provides valuable functionalities, it's important to note that occasional inaccuracies or inconsistencies may arise. Due to the collaborative and voluntary nature of Open Street Map and the diverse sources of contributed data, there can be instances where the information may not always be completely accurate or up to date.

Therefore, the imported OSM network data was thoroughly reviewed and modified as needed to ensure an accurate representation of the study area's network. These adjustments were crucial in capturing the realistic traffic flow within the study area.

Specific enhancements were made to improve the representation of pedestrian and cycling

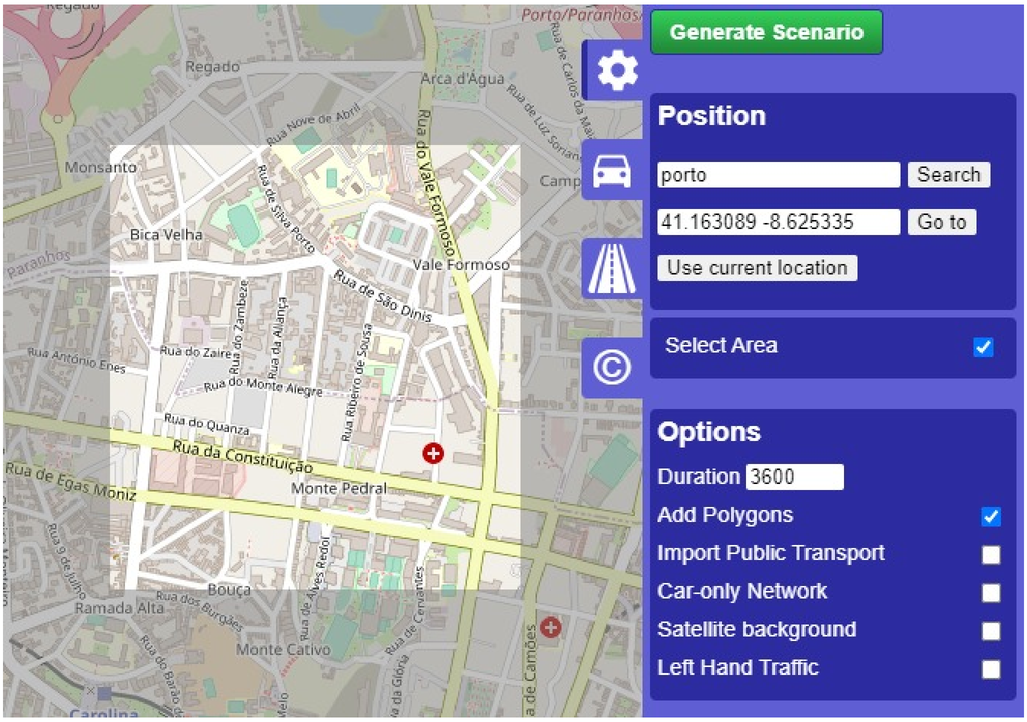


Figure 3.5: OSM Interface.

infrastructure. As instance, sidewalks and crosswalks were manually created on all streets and avenues to facilitate pedestrian flow, and a dedicated bicycle lane was incorporated on the main street (Rua da Constituição). Return connections (U-turns) that do not exist in real life were corrected to ensure accurate network connectivity. Particularly, the maximum velocities assigned in the streets were established at 50 km/h for normal streets and 10 km/h for residential streets.

3.3.2 Traffic modeling

Randomized trips were generated for various modes of transportation. Accordingly, random trips of cars, trucks, vans, motorcycles, bicycles, and pedestrians were generated for the study's network.

The random routes were generated using the in-built tool randomTrips.py from SUMO. This tool offers a range of customizable parameters that enable the user to achieve the desired traffic patterns in the simulation. To illustrate it, consider the following code snippet that demonstrates the generation of random trips specifically for trucks (Figure 3.6):

A parameter worth mentioning is the "–insertion-density", which specifies the density of a certain type of vehicle to be inserted in the network [30]. When extracting trips from OSM, a default number of vehicle insertions is provided based on the network size and typology. However, it was noticed that the resulting distribution of vehicle types did not accurately reflect the real-world scenario, as some vehicles are higher than the observed (e.g. buses and trucks) and others are not considered at all (e.g. vans).

```
python "%SUMO_HOME%\tools\randomTrips.py" -n osm.netbaseline.xml.gz --fringe-factor max
                                            --insertion-density 2 -r osm.truck.rou.xml -b 0 -e 39600
                                            --trip-attributes "departLane=\"best\""
                                            --fringe-start-attributes "departSpeed=\"max\""
                                            --validate --remove-loops --vehicle-class truck --vclass truck
                                            --prefix truck --min-distance 600 --min-distance.fringe 10
```

Figure 3.6: randomTrips.py usage example.

To address this issue, vehicle counts were conducted by category. The counts were performed during random 5-minute intervals on weekdays on one of the main entry and exit roads within the study domain. The obtained values closely align with those published in [31].

The distribution of vehicle types was revised based on the collected data. The revision process involved a proportional calculation to determine the appropriate distribution for each vehicle category, excluding buses, which were manually added to ensure accuracy. The adjusted insertion results can be found in Table 3.1.

Table 3.1: Traffic density distribution.

Vehicle type	**% of observation**	**Traffic density used in SUMO**
Bicycles	1	1
Bus	3	1
Motorcycles	4	2
Passenger vehicles	53	23
Pedestrians	26	11
Trucks	4	2
Vans	9	4
Total	100	44

Another important parameter is the '–fringe-factor'. This parameter plays a crucial role in defining how trips are generated and distributed within the network. It influences the placement of vehicles' origins and destinations, ensuring that they are evenly distributed across the map.

In this study, the value of the '–fringe-factor' parameter was modified specifically for trucks and vans, which are known to primarily pass through the study area. By setting the 'max' value for the '–fringe-factor', the generation algorithm ensures that the trips of vans and trucks begin and end at the map's boundary, simulating their movement through the study area without making internal stops.

For bicycle, motorcycle, passenger, and pedestrian trips, the maximum fringe value was set to 2, 2, 5, and 1, respectively. This means that these trips are more likely to begin and end closer to the center of the map, reflecting their typical movement patterns within the study area.

By customizing the value of the '–fringe-factor' parameter for each vehicle type, a more realistic simulation is achieved, enabling a comprehensive assessment of traffic patterns and dynamics.

Public transport routes were manually created. This process involved gathering information from the local bus company responsible for operating in Porto (STCP) [32]. A total of 8 bus lines were included in the simulation, covering major streets such as Rua da Constituição (lines 203, 303, and 402), Rua de Egas Moniz (lines 203 and 402), Rua de Antero de Quental (lines 304 and 600), and Rua de São Diniz (lines 204, 206 and 803), shown in Figure 3.4. During working hours, the buses operated with an average frequency of 15 minutes, ensuring regular service along these busy routes.

To further enhance the realism of the simulation, additional measures were taken to replicate peak traffic hours. Based on data from the TomTom Traffic Index [33], it was determined that rush hour intervals in Porto typically occur from 8:00 a.m. to 9:00 a.m. and from 5:00 p.m. to 7:00 p.m. during the weekdays.

To simulate these peak hours, additional trips were specifically generated for passenger vehicles, purposefully inserted onto Rua da Constituição and Rua de Egas Moniz — two key streets experiencing significant traffic volumes. The purpose of focusing on these specific locations was to capture the peak hour conditions and accurately represent the congestion experienced during periods of high demand.

To conclude, modifying the "carfollowmodel" parameter was necessary for each vehicle type in the simulation. This parameter controls the car-following behavior of vehicles in SUMO. By default, SUMO employs the Krauss model, assuming flat road surfaces and disregarding slopes. However, to accurately assess the impact of inclinations, the carfollowmodel parameter was changed from Krauss to KraussPS for all vehicles in the network.

3.3.3 E-commerce demand

To estimate the daily volume of deliveries in the domain, real data from official reports provided by CTT, a prominent Iberian logistics player with a 48% market share in Portugal [34], were utilized. According to the reports, CTT delivered 33.1 million parcels in Portugal during 2022 [35]. Furthermore, CTT stated that 20% of all Portuguese e-buyers in 2022 resided in the Porto metropolitan area [36]. Based on the available information, an estimated 6,620,000 parcels were delivered in the study region, which has a population of 1,737,395 inhabitants according to the latest census [29].

Considering that the studied area comprises a population of 15,584 inhabitants [29], it becomes essential to estimate the volume of parcels delivered within this region. By applying straightforward mathematical calculations, it is possible to derive a plausible estimate: approximately 59,380 parcels were delivered in the studied area during 2022, averaging around 163 parcels per day. Employing the same calculation approach, these parcels can be distributed among the subsections of the studied area based on the respective number of inhabitants in each subsection.

To account for the diversity in weights and volumes among parcels, a categorization system was devised. The result was the establishment of five distinct parcel types, with specific weight and volume parameters adhering to CTT's delivery package specifications [37]. The frequency distribution for each parcel type was derived from CTT's e-commerce Report 2022 [36] in conjunction with supplementary insights obtained from a Statista report [38]. A summarized overview of these parcel specifications is provided in Table 3.2.

Table 3.2: Types of parcels.

Category	Type	Weight (kg)	Volume (L)	Frequency
Small (Blue ●)	XS	< 0.5	0.63	45%
Large (Cyan ▲)	S	$0.6 - 1$	2.01	25%
	M	$1.1 - 2$	5.55	17%
	L	$2.1 - 5$	10.05	9%
	XL	> 5	26.40	4%

By making use of QGIS, an allocation of the daily parcels was accomplished by distributing them randomly across different subsections of the study zone proportionate to the population of each area. To ensure efficient delivery, a total of 100 stops (depicted as pink rectangles in Figure 3.4), a value in line with surveys based in Porto [39], was established. These stops were strategically placed in areas that maximize accessibility and minimize travel distances, optimizing the overall delivery process.

Out of the 100 stops, ten were intentionally located on roads to simulate scenarios where vans encounter difficulty in finding suitable parking spaces and therefore resort to illegal parking practices. This aspect was included to reflect real-world challenges faced by delivery vehicles and to assess the impact of parking constraints on the delivery process. It is important to note that these parking-related scenarios only affect the van delivery simulations and do not impact other types of vehicles.

The delivery time for each parcel was carefully determined by considering various factors, including the size and weight of the packages. Following industry insights and available statistics [36, 38], a distinction was made between two categories: small and large parcels.

For the category of small parcels, comprising 74 items (depicted in blue circles in Figure 3.4), a standard delivery time of 2 minutes was allocated, regardless of the quantity delivered. This time frame accounts for the convenience of placing these small parcels directly in the delivery box, eliminating the need for additional handling.

In contrast, the remaining 89 parcels (shown in cyan triangles in Figure 3.4), classified as large parcels, require a slightly longer delivery time. For delivering one large parcel was estimated that 4 minutes are necessary to locate the parcel and deliver it in person. For delivering more than one large parcel per stop, an additional 2 minutes per parcel within this category, equivalent to 50% of the base time, was assigned. These time allocations are consistent with reported data from Porto [39] and ensure realistic simulation results.

When a delivery location involves the simultaneous delivery of both small and large parcels, the delivery time for the small parcel was not considered separately. It was taken into account that while waiting for the recipient to retrieve the larger parcel, the delivery personnel could conveniently place the small parcel in the delivery box, optimizing time and operational efficiency.

3.4 Scenarios

This section provides a comprehensive overview of the scenarios defined to analyze and evaluate different parcel delivery strategies. These scenarios have been derived from a baseline case.

This work encompasses the evaluation of different slope scenarios to identify and compare the impacts of different road slopes and distinct vehicle types to assess the feasibility of implementing various delivery strategies.

3.4.1 Delivery vehicles scenarios

Four distinct delivery vehicles were employed in the simulations, including an Internal Combustion Engine (ICE) van, an electric van (ELV), and two electric cargo bikes with varying payloads: 125 kg (CBL) and 50 kg (CBS) (shown in Figure 3.7). To ensure the fidelity of the simulation, these vehicles were meticulously parameterized to match the actual specifications, such as battery capacity and vehicle mass, of the vehicles utilized by CTT in Portugal. Table 3.3 shows the values used in the simulations.

Table 3.3: Vehicle specifications per scenario.

Vehicle	**Max load (kg/L)**	**Dimensions (L x W x H) (m)**	**Emission Class (SUMO)**	**Acceleration (m/s^2)**	**Max speed (m/s)**	**Ref.**
ICE: ICE van	1000/3900	4.75 x 2.1 x 1.85	LCV_diesel_N1-III_Euro-6d	2.1	47.78	[40]
ELV: Electric van	1000/5300	4.96 x 2.2 x 1.89	Energy	2.12	36.11	[41]
CBL: Electric cargo bike L	125/350	2.74 x 0.7 x 1.10	Energy	1	6.94	[42]
CBS: Electric cargo bike S	50/150	2.03 x 0.7 x 1.10	Energy	1.5	6.94	[43]

Large cargo bike [42]

Small cargo bike [43]

Figure 3.7: Large and small cargo bikes.

The ICE scenario represent the current conventional approach to last-mile delivery, utilizing ICE-powered vehicles. In contrast, the other scenarios explore alternative power solutions for last-mile delivery.

To assess the influence of driving behavior, the ICE scenario was simulated under two distinct conditions. Firstly, the default ICE condition was implemented, where the vehicle promptly shuts off when stopped. Secondly, the ICEv2 condition was employed, wherein the vehicle only shuts off immediately if the planned stop exceeds 300 seconds (which aligns with the default behavior of SUMO). Throughout this study, the term 'shutoff-stop duration' denotes the period in which a vehicle's engine remains turned off during planned delivery stops. On the other hand, all remaining delivery vehicle scenarios are configured to consistently shut off during delivery stops.

In the context of the network, the parcels under consideration have a total weight of 269.4 kg and a volume of 604.38 L (Table 3.2). By taking into account the load capacity limits per vehicle (Table 3.3) and utilizing 70% of the load capacity in this study, it is observed that both the ICE van and the electric van can comfortably accommodate all the parcels in a single trip. However, the large cargo bike would necessitate 3 trips, while the small cargo bike would need to make 8 trips in order to deliver all the parcels within the designated area.

The route planning for the deliveries did not involve an optimal routing algorithm. Instead, a manual process was employed to replicate the actual decision-making process of the delivery personnel. This approach aimed to capture their preferences, such as choosing to cross the street on foot rather than searching for a street to make a U-turn.

To ensure a realistic simulation, the base delivery time for each type of parcel (small and large) was adjusted by reducing it by 30 seconds for deliveries made with cargo bikes. This adjustment takes into account the ease of parking, locating, and retrieving parcels with cargo bikes. Furthermore, cargo bikes provide the advantage of accessing areas that are typically inaccessible to vans, resulting in improved efficiency in terms of accessibility.

Furthermore, due to the requirement of multiple trips to deliver all the parcels, the cargo bikes would return to the warehouse (shown in Figure 3.4) after each load and allocate 10 minutes for the reloading process. This estimated time encompasses various tasks, including collecting the parcels for replenishment, loading them onto the cargo bike, re-planning the route, and subsequently resuming the delivery process. It is worth noting that no charging stations were included in the route as the chosen vehicles have sufficient autonomy to complete the delivery route when starting with a full charge. However, if necessary, the energy recharge could be done during the reload of the parcels.

To summarize, the required delivery times for each type of vehicle at a stop are provided in Table 3.4. It is important to note that when a delivery includes both small and large parcels, the delivery time for the small parcel is not accounted for.

3.4.2 Slope scenarios

Three scenarios were established to evaluate the influence of terrains with varying ground inclinations on parcel delivery operations. The first scenario, referred to as the baseline (SB), encompasses the existing study area. The second scenario, a flat terrain scenario devoid of any inclines, was introduced as a hypothetical area (S1). Lastly, the third scenario, inspired by the inclinations found in the historic center of Porto, specifically captures its distinct slopes (S2).

Table 3.4: Parcel delivery required time.

	Delivery time (s)	
Number of parcels	**Vans**	**Cargo bikes**
1+ small	120	90
1 large	240	210
1+ large	240 + 120 * n of additional parcels	210 + 105 * n of additional parcels
Reload time	x	600

The locations from which the elevation data for the different scenarios were obtained are depicted in Figure 3.8, with blue representing the case study area and red representing the historic center area. This figure provides a visual reference for the specific areas used to create terrains with varying inclinations. These scenarios enable a comprehensive analysis of the effects of varying terrain on logistics activities, enhancing the understanding of its impact on the simulation outcomes.

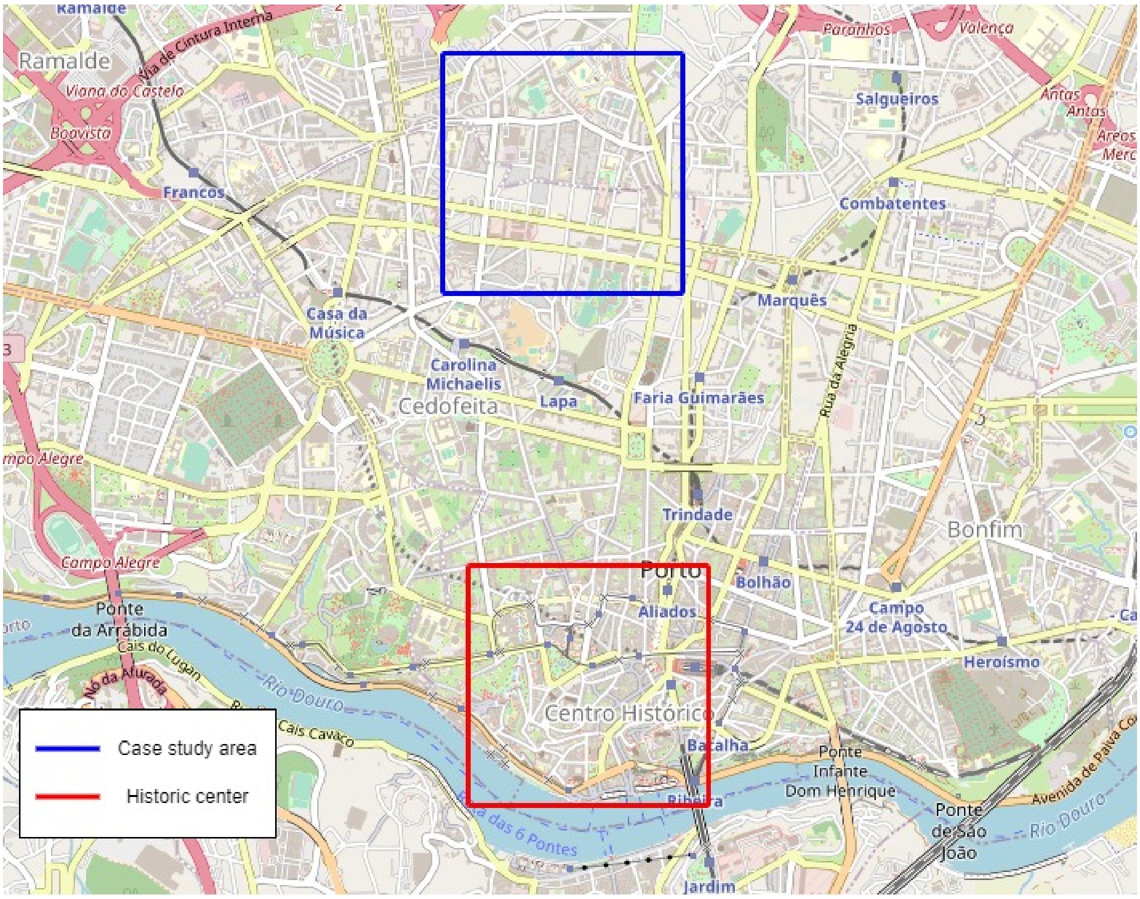
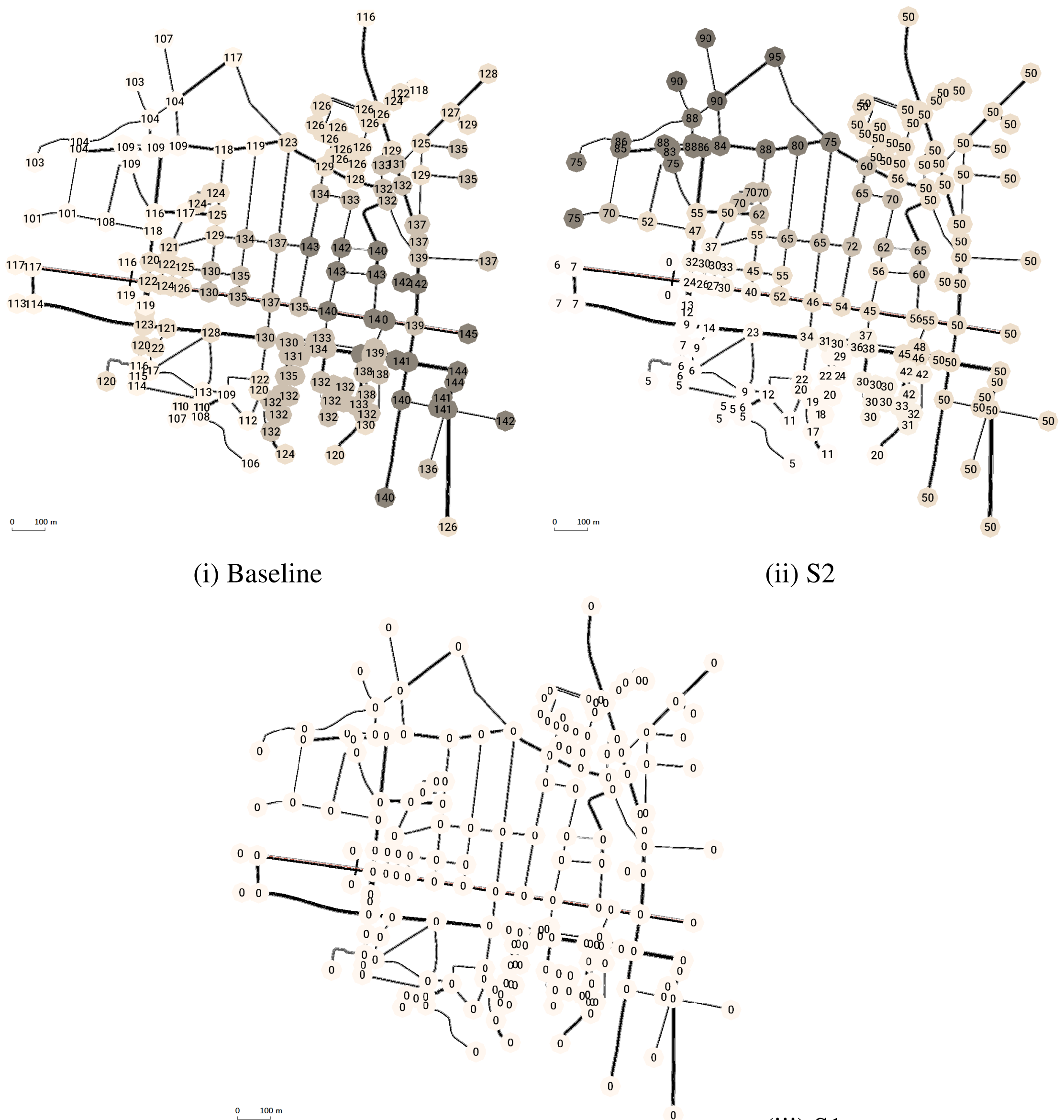


Figure 3.8: Slope scenarios locations.

Elevation data was retrieved via open-source software [44] and later organized into a grid using the QGIS software. The elevation points from the baseline, S1 and S2 scenarios are depicted in



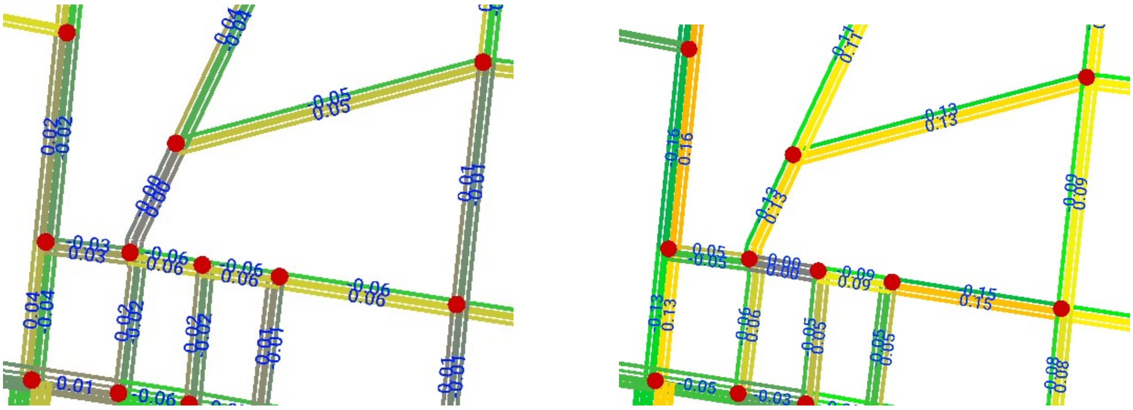
(i) Baseline (ii) S2 (iii) S1

Figure 3.9: Slope scenarios: (i) Baseline; (ii) S2; (iii) S1.

Figure 3.9.

In SUMO, the necessary modifications were carried out using netedit, a tool within the SUMO suite designed for network editing. Altitude values were assigned to each junction (represented by the red dots in Figure 3.10) based on the nearest points derived from the grid made using QGIS. After applying these changes, the entire network was selected, and edge operations were performed to straighten the elevation of all edges. This step was crucial to ensure the proper functionality of the simulation.

To ensure realistic road inclinations, a maximum limit of 0.18 radians (approximately 10.3º) was imposed. This precautionary measure was specifically applied to the S2 scenario, which featured steeper slopes, while the baseline scenario had a maximum inclination of 0.10 radians (approximately 5.7º). By confining the inclinations within this range, the simulation maintains a more precise representation of the terrain, thereby enhancing the overall realism of the model. Finally, Figure 3.10 displays an excerpt from the network of both scenarios, illustrating the road inclinations in radians.



(i) Inclination values (Baseline). (ii) Inclination values (S2)

Figure 3.10: Netedit: network excerpt from Baseline and S2 scenarios.

Chapter 4

Results

This chapter presents a comprehensive analysis and discussion of the simulation results obtained from a total of 15 diverse scenarios. These scenarios encompass a combination of five different delivery scenarios and three distinct Slope scenarios, each combination simulated individually. The variations in these scenarios include simulations involving various types of vehicles, such as combustion vans (ICE), including the scenario where the vehicle engine remained operational during most stops (ICEv2), electric vans (ELV), large electric cargo bikes (CBL), and small electric cargo bikes (CBS). Additionally, the simulation considered three different terrain settings: the case study area with its actual altitude (Baseline), a flat terrain scenario (S1), and a scenario inspired by the altitudes of the historic center of Porto (S2).

The presentation and analysis of results are divided into three main categories: Operational performance (duration, length, and waiting time), energy consumption (fuel or electricity, depending on the vehicle type), and emissions (CO, CO_2, HC, PM_x, and NO_x).

4.1 Operational performance

This section focuses on analyzing and discussing the delivery performance derived from the delivery scenarios and slope scenarios. By examining key metrics related to the duration, length, and waiting time (traffic congestion), it is possible to gain valuable insights into the performance of different vehicle types. The route outputs from each scenario are presented in detail in Table 4.1.

The analysis of the operational performance of the ICE vehicles reveals several key findings. In the Baseline scenario, the route duration was 07:23:19, slightly longer than S1 (07:19:46) but shorter than S2 (07:38:39), with variations of only -0.8% and 3.5%, respectively. Similarly, the route length exhibited slight variations among the different terrains, as expected due to the inclinations affecting certain streets. Moreover, the waiting time for ICE vehicles increased as the terrain became more challenging, with S2 showing the longest waiting time (00:11:43).

The operational performance of ELV demonstrated similar performance to ICE vehicles. The route duration for ELV showed minimal variations across the three terrains, with variations of -0.8% (S1) and 4.1% (S2). The route length and waiting time followed similar patterns.

Table 4.1: Operational performance of the different e-commerce strategies for the different slope scenarios.

Delivery scenarios	**Route parameters**	**Slope scenarios**		
		Baseline	**S1**	**S2**
ICE and ICEv2	Duration (HH:MM:SS)	07:23:19	**07:19:46**	07:38:39
	Length (m)	23840.3	23802.8	24818.2
	Waiting time (HH:MM:SS)	00:08:53	**00:07:37**	00:11:43
ELV	Duration (HH:MM:SS)	07:23:35	07:20:15	07:41:35
	Length (m)	23840.1	**23802.6**	24818.0
	Waiting time (HH:MM:SS)	00:09:15	00:07:57	00:13:41
CBL	Duration (HH:MM:SS)	07:56:07	07:31:17	10:12:09
	Length (m)	30809.2	30765.5	32021.7
	Waiting time (HH:MM:SS)	00:10:01	00:11:04	00:21:37
CBS	Duration (HH:MM:SS)	09:08:56	08:57:00	*10:24:33*
	Length (m)	43892.9	43836.6	*45447.5*
	Waiting time (HH:MM:SS)	00:13:45	00:14:41	*00:30:38*

Note:
bold values : best results for each parameter.
italic values : worst results for each parameter.

In contrast, the performance of the cargo bikes highlighted notable differences across the terrains. The CBL route duration in the Baseline scenario was recorded as 07:56:07, while S1 exhibited a shorter duration of 07:31:17. However, S2 demonstrated a significantly longer duration of 10:12:09, indicating a variation of 28.6%. The route length and waiting time also followed this trend. These results could be attributed to the need for two cargo replenishment stops at the warehouse. This need is a unique feature of the adopted cargo bikes, as their load capacity does not allow the delivery of all packages in a single trip. Another reason is the 'weak' technical properties of CBL, such as slower acceleration, indicating that CBL faces greater challenges and delays in more inclined environments.

CBS demonstrates similar characteristics in its results. The route duration for CBS exhibited an increase across the different terrains, with the Baseline scenario recording a duration of 09:08:56, S1 recording 08:57:00, and S2 recording 10:24:33. Likewise, this can be attributed to the technical disabilities of the cargo bike, like its speed or max load. In fact, the small load space of CBS implies 7 returns to the warehouse for cargo replenishment.

When comparing the performance of different vehicle types, several observations can be made. ICE and ELV exhibited similar performances, with comparable durations and route lengths across the scenarios. However, cargo bikes (CBL and CBS) faced challenges in more inclined terrains, particularly CBL.

While CBL exceeded the 8-hour mark for the delivery duration in S2, CBS exceeded in all scenarios. This emphasizes the significant impact of multiple cargo replenishment stops on the overall delivery performance of cargo bikes, resulting in increased length and duration compared to other vehicle types.

In addition, CBS exhibits a longer duration of over 1 hour compared to CBL in the baseline scenario, accumulating, on average, over 13 km more than CBL due to the need for seven return trips to the warehouse. This demonstrates that even though CBL is slower than CBS, with its higher load capacity, it is capable of completing deliveries more quickly.

4.2 Energy consumption

Evaluating the efficiency of delivery strategies requires a thorough assessment of fuel and electricity consumption. Detailed information regarding these consumption figures can be found in Table 4.2. The evaluation incorporates the ICEv2 scenario, which examines the fuel consumption when the engine does not shut off at every stop.

Table 4.2: Delivery vehicles' energy consumption for the different slope scenarios.

Delivery scenarios	Parameters	Slope scenarios		
		Baseline	S1	S2
ICE	Fuel (kg)	2.45	**2.32**	2.88
ICEv2		3.60	3.51	*4.09*
ELV	Electricity (Wh)	*5242.0*	5210.1	5215.0
CBL		547.6	**499.8**	790.3
CBS		598.3	561.5	735.6

Note:
bold values : best results for each parameter.
italic values : worst results for each parameter.

Additionally, Figure 4.1 visually depicts a comparative analysis of ICE fuel consumption between the Baseline scenario, S1, and S2, providing a clear overview of the variations across different terrains.

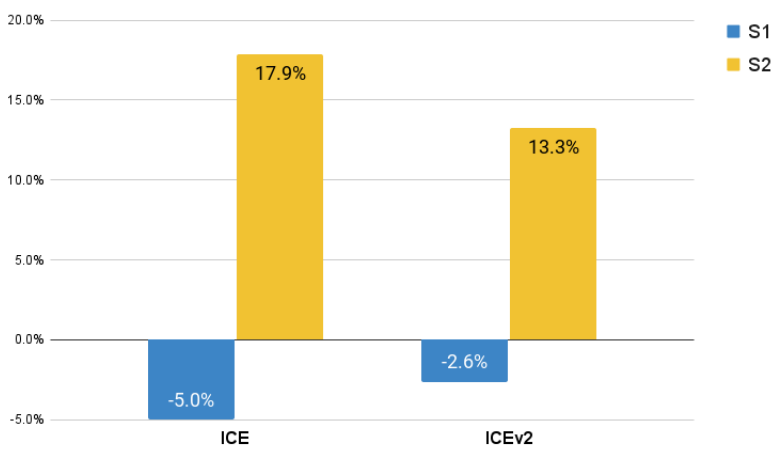


Figure 4.1: ICE and ICEv2 scenarios fuel consumption relative to baseline.

Comparing the baseline scenario to the flat terrain scenario (S1), a decrease of 5% in fuel consumption is observed. The baseline recorded a value of 2.45 kg. However, as the terrains become more challenging with higher elevations, such as in S2, there is a notable increase of 17.9% in fuel consumption, reaching 2.88 kg.

Furthermore, in the ICEv2 scenario, there was a decrease of 2.6% in fuel consumption in S1 and 13.3% in S2. This relative decrease, compared to ICE, can be attributed to the ICEv2 scenario having higher base values, which are influenced by the parameter of keeping the car running during most stops. This finding demonstrates the sensitivity of ICE vehicles' fuel consumption to changes in elevation, indicating that higher inclinations have a significant impact on resource usage.

Figure 4.2 illustrates the comparison of fuel consumption between the ICEv2 and ICE scenarios. It is worth noting that both scenarios have a total duration of planned stops of 6 hours and 20 minutes, which significantly affects fuel consumption and emissions throughout the day if the car's engine remains on. The data from the ICEv2 scenario reveals a substantial increase in fuel consumption across all three scenarios, averaging 47%. This highlights the impact of frequent short stops during a working day.

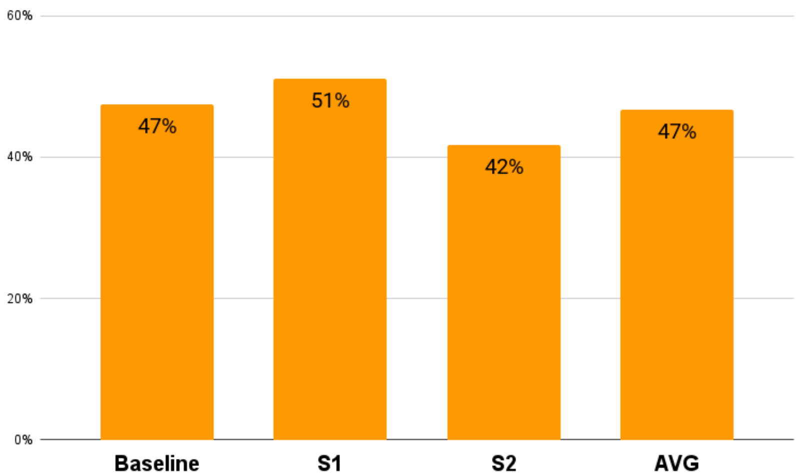


Figure 4.2: ICEv2 scenarios and average fuel consumption relative to ICE's.

The analysis of ELV electricity usage, seen in Figure 4.3, reveals interesting findings across the different scenarios. In the baseline scenario, ELV consumed 5242 Wh of electricity during its entire route. The electricity consumption remained relatively consistent in S1 with a slight decrease to 5210.1 Wh. Similarly, in S2, ELV exhibited a comparable electricity consumption level of 5215 Wh. These results suggest a consistent performance of ELV in terms of energy usage across different terrains.

Analyzing the electricity consumption of CBL across the scenarios reveals notable variations. In the baseline scenario, CBL consumed 547.6 Wh of electricity, and as expected in S1, there was a slight decrease in electricity consumption to 499.8 Wh (-8.7%). In contrast, S2 exhibited a significant increase in electricity usage, reaching 790.3 Wh, indicating a substantial increase of 44.30%. These findings suggest that CBL vehicles face greater energy demands in more inclined terrains, which aligns with the route data analysis. The inclinations of the terrain have a significant

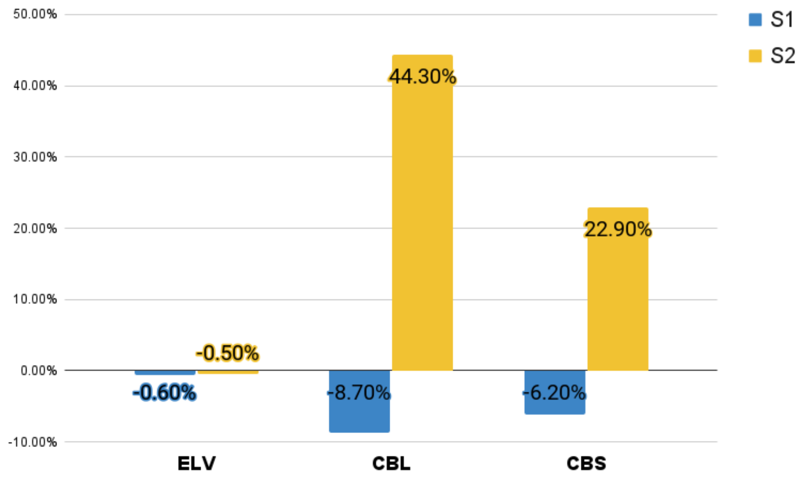


Figure 4.3: Electric vehicles' consumption relative to baseline.

impact on the energy consumption of CBL vehicles, necessitating additional energy to overcome the elevation challenges.

In the baseline scenario, CBS consumed 598.3 Wh of electricity. S1 showed a slight decrease in electricity consumption to 561.5 Wh, representing a reduction of approximately 6.2% compared to the baseline. However, in S2, there was a noticeable increase in electricity usage to 735.6 Wh, indicating a rise of approximately 22.9% compared to the baseline. These results demonstrate that CBS vehicles face increased energy demands in more inclined terrains, similar to the difficulties experienced by CBL vehicles, albeit with slightly less intensity.

The analysis of electricity usage in different scenarios highlights distinct performance characteristics among electric vehicle types. ELV vehicles demonstrate consistent energy consumption across all terrains, while CBL and CBS vehicles face challenges in more inclined terrains, resulting in increased electricity usage.

An intriguing observation in the S2 scenario is that the CBS covers approximately 13 km more than CBL while consuming 7.44% less electricity when compared to CBL. However, this association does not hold true in the baseline and S1 scenarios, where the CBS consumes more electricity. This indicates that in regions with steeper inclines, CBS is more efficient than CBL.

4.3 Emissions

This chapter focuses on the crucial assessment of emissions data and its role in evaluating the environmental impact of diverse delivery strategies. Detailed insights into the levels of CO, CO_2, HC, PM_x, and NO_x emissions generated by ICE vehicles are presented in Table 4.3. To illustrate the comparison of emissions from ICE among scenarios S1 and S2 relative to the baseline, Figure 4.4 showcases the emissions comparison graphically.

Table 4.3: ICE and ICEv2 emissions for the different slope scenarios.

Delivery scenarios	Parameters		Slope scenarios		
			Baseline	S1	S2
ICE	Emissions (mg)	CO	1023.9	**1012.3**	1119.9
		CO_2	7611049.1	**7231454.3**	8973190.2
		HC	1250.1	**1246.6**	1345.0
		PM_x	**659.6**	671.2	678.8
		NO_x	993.2	**965.0**	1124.7
ICEv2	Emissions (mg)	CO	1273.3	1266.2	*1375.8*
		CO_2	11224793.9	10929322.6	*12715182.1*
		HC	1496.1	1496.4	*1596.3*
		PM_x	697.0	708.2	*715.3*
		NO_x	1320.9	1300.2	*1464.5*

Note:
bold values : best results for each parameter.
italic values : worst results for each parameter.

In scenario S1, there was generally minimal variation in emissions. CO_2 demonstrated the most substantial decrease, with a reduction of approximately 5.0% compared to the baseline. It is important to note, however, that PM_x was the only product that experienced an increase in emissions in S1, showing a modest rise of 1.8%.

Conversely, in scenario S2, substantial variations in the emission levels of most gases were observed. CO_2 displayed the highest variation, increasing by 17.9% relative to the baseline. This was followed by NO_x with a 13.2% increase, CO with a 9.4% increase, HC with a 7.5% increase, and PM_x with a slight increase of only 2.9%.

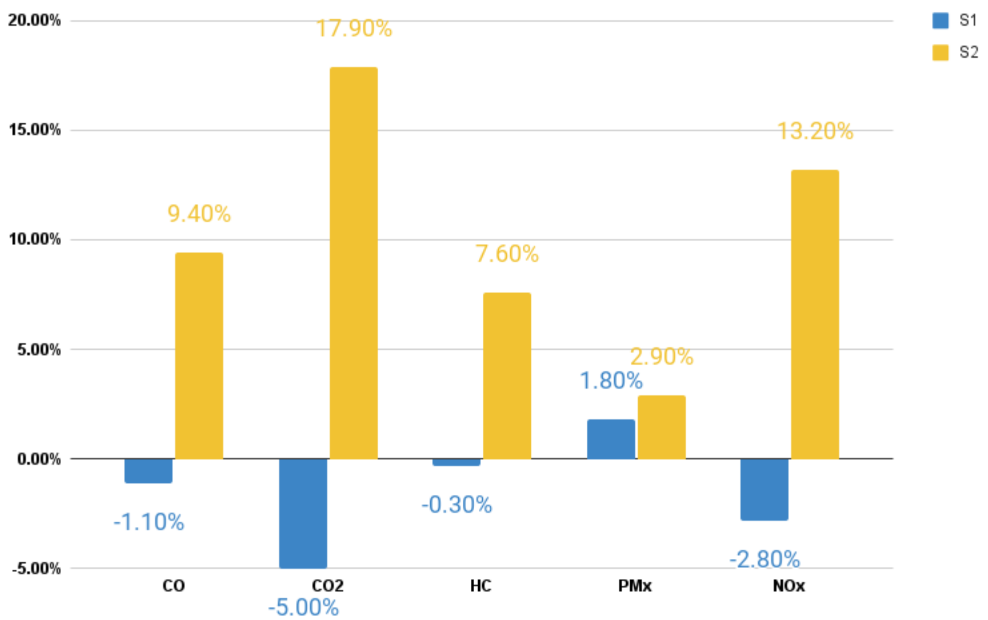


Figure 4.4: ICE scenarios emissions relative to baseline.

In Figure 4.5, the average emissions consumption of the ICEv2 scenarios is compared to the average emissions from the ICE scenarios.

The results show increases in all emissions, with CO_2 experiencing a substantial 47% increase, which is equivalent to fuel consumption, as seen in the previous section. Notably, NO_x, CO, and HC also exhibited significant increases.

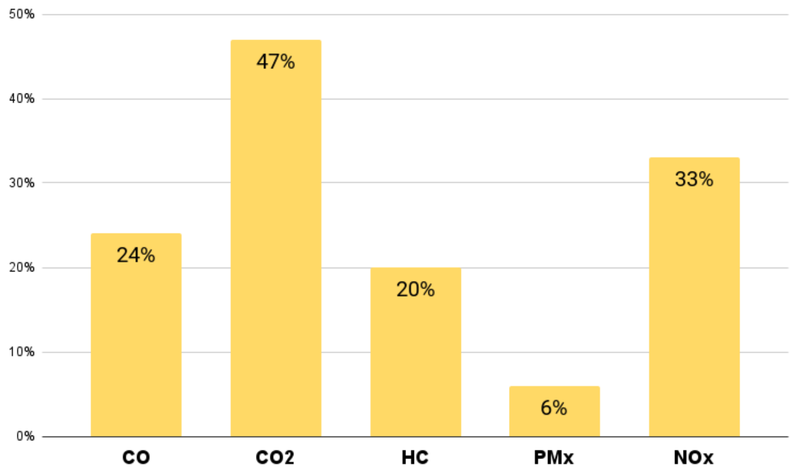


Figure 4.5: Average ICEv2 scenarios emissions relative to average ICE's.

Overall, the emissions data underscores the importance of considering terrain characteristics when assessing the environmental impact of vehicle operations. Steeper inclines, as observed in S2, can lead to higher emissions, particularly CO_2 and NO_x, which negatively affect air quality in urban areas and contribute to the greenhouse effect.

4.4 Discussion

The results obtained from the simulation-based evaluations in this study provide valuable insights into the impact and efficiency of different delivery vehicles across various scenarios. These findings have important implications for policymakers, authorities, and environmentally conscious companies operating in this field.

Electric vans offer several advantages as delivery vehicles. They provided comparable performance to ICE vehicles in all slope scenarios while producing zero emissions, contributing to improved air quality and reduced environmental impact. Additionally, they have the potential to lower operating costs due to reduced resource consumption and maintenance requirements [45]. However, it is essential to consider the higher initial cost and the availability and accessibility of charging infrastructure to ensure the practicality and feasibility of electric vehicle adoption [45].

Although Portugal is among the top 5 countries in the European Union with the highest number of charging stations, with 24.9 charging points per 100 kilometers of road [46], trailing only behind countries such as the Netherlands, Luxembourg, and Germany, further incentives in this market are necessary to achieve climate targets [47].

Electric cargo bikes are even more susceptible to a lack of charging infrastructure due to their lower range. To address this disadvantage, they can recharge their batteries while returning to the warehouse to reload cargo. However, to ensure a greater delivery range, an increased number of charging stations would be necessary in the city.

On the other hand, electric cargo bikes, particularly in less hilly regions, demonstrate their energy efficiency and potential as a sustainable delivery option. Companies operating in these areas can consider incorporating cargo bikes into their delivery fleets to enhance energy efficiency and reduce emissions. These bikes are highly energy-efficient, require minimal maintenance, and have a smaller carbon footprint compared to motorized vehicles [48]. They are particularly suitable for short-distance deliveries in urban areas with heavy traffic congestion, where they can navigate more efficiently, contributing to reduced traffic and improved air quality.

The ideal approach would be to utilize a combination of these different vehicles in the delivery fleet according to the demand, terrain inclinations, and the availability of recharge stations.

In conclusion, the analysis and utilization of simulation-based evaluations in this study provide valuable insights for policymakers, authorities, and environmentally conscious companies. The findings support the adoption of electric vehicles and the incorporation of sustainable practices in delivery operations. By considering the suitability of different vehicles in various terrains and implementing strategies like engine shutdown during deliveries, companies can enhance efficiency, reduce environmental impact, and contribute to a greener future.

Moreover, it is crucial to emphasize the importance of investing in charging infrastructure in cities to support the widespread adoption of electric vehicles. Greater investment in charging infrastructure will facilitate the expansion of electric vehicle usage and enable companies to effectively integrate electric vehicles into their delivery fleets.

Chapter 5

Conclusion

This chapter provides a comprehensive overview of the research conducted in this dissertation, presenting the final conclusions derived from the simulation of the defined scenarios and the analysis of the obtained results.

The summary of findings and insights gained from this research endeavor is provided first (Section 5.1), highlighting the key outcomes and implications. Subsequently, the limitations of the study are discussed (Section 5.2), acknowledging the constraints and potential areas for improvement.

Lastly, potential avenues for future research and publications are outlined, along with suggestions for possible enhancements that can be explored (Section 5.3 and 5.4).

5.1 Main contributions

Through simulation-based evaluations conducted in this study, various strategies for parcel delivery were assessed across different scenarios. The objective was to gain valuable insights into the impact and efficiency of different delivery vehicles, including internal combustion engine (ICE) vans, electric vans (ELV), and both large and small electric cargo bikes (CBL and CBS, respectively). These evaluations were performed in three distinct terrain slope scenarios: baseline (real inclinations of the case study area), flat, and steep (inspired by Porto's historic center area), focusing specifically on their effects on logistics operations. The analysis of results was divided into three main categories: Operational performance (duration, length, and waiting time), energy consumption (fuel or electricity), and emissions (CO_2, CO, HC, PMx, and NOx). Importantly, the study concentrated on a typical urban residential area within the city of Porto, ensuring consistency in terms of domain, traffic flow, and logistics demand across all scenarios. This approach facilitated fair and comprehensive comparisons and analysis. Moreover, the study's contributions were reinforced by a thorough literature review, which provided a solid foundation for understanding the current state of the field and the significance of this research.

Regarding the evaluation of demand vehicle scenarios, it was possible to conclude that the operational performance of ICE and ELV vehicles remained relatively stable across all slope scenarios, demonstrating their adaptability. However, cargo bikes experienced more significant challenges, both in terms of energy consumption and delivery performance, suggesting that these vehicles are not suitable for regions with significant slopes.

In the situation where the soil slope is steep (referred to as S2), among the four types of vehicles studied, it was found that ICE vehicles performed the best in terms of delivering all the packages within a given time frame. However, a drawback of using ICE vehicles in this scenario was a considerable rise in the emission of harmful gases, particularly carbon dioxide (CO_2), which contributes to the greenhouse effect and climate change. This negative impact on emissions was even more pronounced in the ICEv2 scenario, where the vehicle's engine remained idle during stops. In this case, there was a significant 47% increase in CO_2 emissions when compared to ICE scenarios.

The findings obtained highlight the importance of investing in electric vehicles. Electric vans (ELV) performed comparably to internal combustion engine vehicles (ICE) in all scenarios while producing zero pollutant emissions. Cargo bikes also performed well, particularly in less hilly regions, showcasing their energy efficiency. Furthermore, it is crucial to consider the practice of engine shutdown during deliveries to minimize environmental impact and fuel consumption. By actively promoting the adoption of electric vehicles and implementing measures like engine shutdown during stops, companies can enhance their delivery efficiency while effectively mitigating the environmental consequences associated with their operations.

These results have practical implications for companies seeking to evaluate and optimize their delivery strategies. The data obtained from this study can guide companies in making informed decisions, considering not only sustainability objectives but also logistics. By leveraging this knowledge, companies can balance environmental responsibility, operational efficiency, and cost-effectiveness in their delivery operations.

5.2 Limitations

Throughout this work, some limitations have been identified. One such limitation pertains to the estimation of certain parameters used in the creation of the scenarios, including the number of parcel orders, stop times, and loads. While these estimates were based on available data and official reports, it is important to recognize that they should be considered approximations rather than precise values.

Due to the unavailability of traffic data provided by the city of Porto, the estimation process relied on empirical analyses. Despite efforts to ensure accuracy, more specific traffic information is needed to enhance the precision of the simulation.

Lastly, it is essential to acknowledge that the results were generated from simulations with the same set of trips, which means they do not possess a statistically robust value. While this approach allows for the comparison of scenarios on equal terms, it is important to note that the results may not hold true for different demand patterns. Evaluating the model considering different trip distributions or days would be necessary to ensure the statistical validity of the results. However, due to the limited time constraints of this dissertation, such an analysis was not performed.

5.3 Future work

In order to enhance the robustness and generalizability of the findings, future work should consider conducting multiple simulation instances with varying trip sets. By exploring different trip configurations, researchers can validate the statistical validity of the results.

Additionally, addressing the limitations identified in this work requires incorporating more precise data sources and exploring alternative approaches for parameter estimation. Obtaining more accurate and detailed information on factors such as traffic management and trip characteristics would significantly enhance the reliability and validity of the findings.

Moreover, future research endeavors could emphasize the development of larger-scale simulation scenarios inspired by urban areas characterized by different altitudes and structures. Additionally, researchers can explore the evaluation of more parameters, such as noise levels. By incorporating a wider range of urban environments into the simulations and considering multiple parameters, researchers can delve deeper into understanding the influence of these factors on the effectiveness and efficiency of various delivery strategies.

The utilization of different delivery strategies, including smart lockers or other types of vehicles, is another point that can be improved. Investigating the potential benefits and challenges of implementing smart locker systems in urban delivery networks would contribute to developing innovative and sustainable delivery solutions.

By pursuing these avenues of future research, investigators can significantly advance the evaluation and understanding of urban delivery systems. By continuously striving to improve the efficiency, reliability, and environmental impact of delivery operations, it is possible to make valuable contributions to the field and drive positive change in urban logistics.

5.4 Publications

This dissertation served as the basis and inspiration for an article to be presented at the Euro Working Group on Transportation (EWGT) conference. This article consisted of aiming to identify the best strategies for e-commerce deliveries, among some scenarios, and assess their effectiveness in reducing the environmental impact through simulations.

- Vidal, K., Silva, V., and Fontes, T. (2023). Environmental impact of e-commerce deliveries. 25^{th} Euro Working Group on Transportation Meeting (EWGT 2023), Santander (Spain), 06-08 September. Extended abstract accepted for presentation.

The publication resulting from the extended abstract accepted for presentation in EWGT2023, presented in Appendix A, has been chosen for submission to one of the Special Issues of the conference. Specifically, it will be submitted to Special Issue 2: Transport policy innovations to improve transport efficiency. The target journal for this submission is "Transportation Research Part A: Policy and Practice". The work presented will be an extension of the work presented in this dissertation. The submission deadline for this publication is September 15^{th}.

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Appendix A

Publications