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Ph.D Thesis

Estimating the environmental and societal impact of new mobility services

Estimación del impacto ambiental y social de los nuevos servicios de movilidad

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SUMMARY

We all need transportation and its infrastructure not only to manage our daily tasks but also because few economic resources are located just where we would want them. However, transport is also a source of numerous negative externalities, such as road accidents, congestion in urban areas and lacking air quality. Transport is also a sector substantially contributing to climate crisis with more than 16% of global greenhouse gas emissions being a result of transport activities. Nevertheless, even though transport might be a necessity, its negative impacts could be limited or, some of them with a right approach, could even be avoided entirely.

Like in numerous other sectors we can turn to innovation to secure better efficiency of the overall system, and while transport has been stable for the second part of the XXth century, today there are numerous new mobility solutions enabled by connectivity, automation, and electrification. Electrification of the transport solutions coupled with development of renewable energy sources could result in lower greenhouse gas emissions as well as better air quality. While connectivity and automation could lead to a safer and more efficient road environment, reducing number of accidents and lowering congestion in urban areas. The most awaited transport innovation is of course an autonomous vehicle (AV), which would have the automation connectivity and electrification at its core.

Nevertheless, with each introduction of a new mobility service we can observe factors that could negatively contribute to the sustainability of the transport system – a chain of behavioural changes caused by introduction of entirely new possibilities. The literature review performed for the purpose of the thesis showed that introduction AVs could have a substantial impact on the way we behave. The identified behavioural changes caused by AVs are presented in a graphical manner on Figure 1 hereunder.

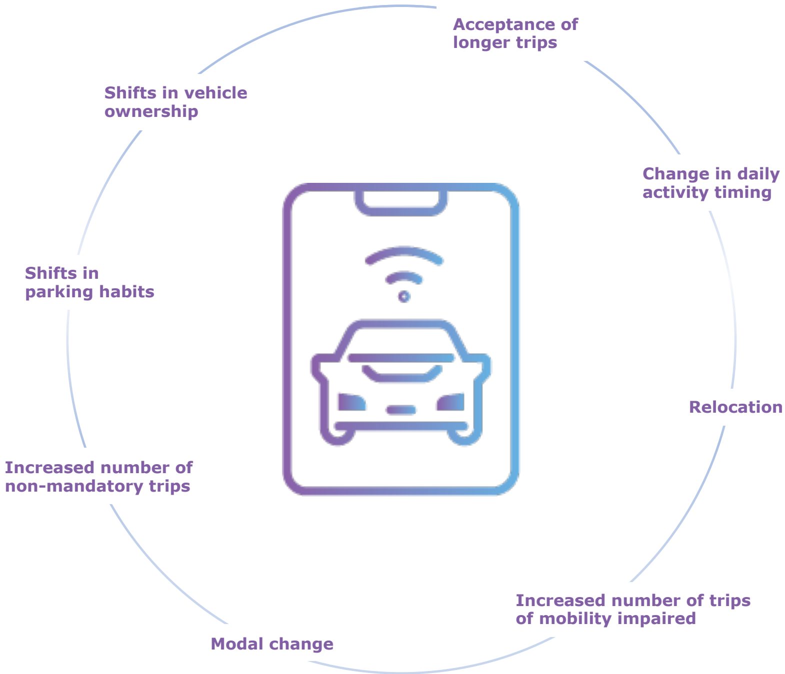

FIGURE 1 CATEGORIZATION OF BEHAVIOURAL CHANGES TRIGGERED BY SAVS

As transport system is heavily integrated with various other systems in urban areas and results in numerous negative implications there is a need to anticipate the possible triggered behavioural changes before they arise, causing a further depletion in overall urban sustainability. Such anticipation is usually done via transport modelling. Nevertheless, the today's modelling tools are often not agile enough and highly aggregated which complicates representation of new mobility services and the reaction to their deployment. Hence, for all reasons mentioned previously the first objective of the thesis is to identify how the introduction of new mobility services can impact the societal and environmental transport externalities. In particular the objective is to develop and validate a modelling framework able to capture the complexity of the transport system and to apply it to assess the potential impact of a shared autonomous vehicle – SAV. However, preparation of the model led to discovery of an unexplored component, namely the personal parking preferences of a privately owned AV. Uncovering those preferences became a second objective of the thesis. Thereafter, a third objective was added: to better understand how a last-mile delivery service, which does not necessarily lead to behavioural changes, could contribute to transport externalities.

In achieving the first objective a focus was put on an environmental rebound effect – environmental implications of introduction of SAV based service. The research mainly focused on investigating how the sizing of the fleet could impact the environmental rebound effect, as well as, which of the identified behavioural changes (Figure 1) would have the highest contribution to the negative externality. In the research we chose to use an agent-based demand estimation coupled with traffic microsimulation to investigate the performance of SAV-based systems in the context of a case study in Santander, Spain. The results of the study show that the deployment of a SAV based service could be environmentally beneficial due to fleet electrification and sharing of rides. Nevertheless, behavioural changes could indeed lead to a significant rebound effect. The maximum obtained rebound effect resulted in 42% higher CO_2 emissions. The behavioural change that resulted in the highest magnitude of environmental rebound effect was the induced demand caused by citizens participating in more nonmandatory trips. However, the negative environmental rebound effect could be minimised by an optimal fleet size. Such fleet size should facilitate that users willing to switch from private modes towards shared rides do so, while those opting for sustainable modes remain using them. Moreover, further land use policies could be used to support a sustainable uptake of SAVs. For instance, if cities were to follow the 15-minute city trend, which aims to secure all required services in a proximity to the residential area, the usage of SAVs for induced demand would be lower, as citizens would rather opt for an active mode on short trips as they do nowadays.

For the second objective – to provide empirical evidence on the preferences of parking in the future, once new parking strategies, enabled by vehicle automation, emerge a stated preference survey was used. The respondents were confronted with four parking strategies: i) on-street parking nearby ii) dedicated parking area on the outskirts of the city iii) cruising and iv) sending AV back home with changing wait time for the AV and a parking pricing policy. The results of the survey were analysed through a mixed logit with latent variables. Four latent variables were found to significantly impact the decision about the preferred parking option: environmental concern, innovativeness, AV acceptance and support for sustainable car-free cities. Moreover, several parking policy scenarios were analysed to unravel possible future implications. The results suggest that trusts towards AVs and innovativeness increase the probability of choice of unconventional parking strategies like allowing the vehicle to cruise or sending it back home. Therefore, whilst the massive deployment of AVs may still be a long way ahead, it is important to already encourage sustainable attitudes towards mobility in order to mitigate the risk of future negative externalities related to the uptake of those vehicles.

Whereas the third objective was achieved by developing a sustainability assessment framework for last-mile delivery solutions. The methodology integrated multi criteria decision making analysis, sustainability pillars and scenario analysis to best reflect the conflicting needs of stakeholders involved in the last mile delivery system. While the dedicated case study laid out the implementation of the framework for the Joint Research Centre in Ispra, Italy. In the study, six technological solutions (or combinations of technological solutions) were analysed: i) Euro 4 light commercial vehicle (LCV), ii) Euro 6 LCV, iii) electric LCV, iv) delivery droid (robot) coupled with Euro 4 LCV, v) delivery droid coupled with a depot station and vi) delivery droid coupled with eLCV. The results show that investment in delivery droids to assist the LCV, has low capital intensity and could lead to significant savings on the annual operational costs, whilst improving the environmental performance of the system, due to high energy efficiency and low energy consumption. Additionally, the introduced framework allowed to acknowledge and investigate the potential social sustainability shortcomings of this solution in terms of safety and equity. Conducted analysis reveals how different stakeholder preferences affect the outcome of the analysis, supporting informed decision making and strategy aligned policy making.

Overall, the main purpose of this research was to investigate how the introduction of new mobility services could impact the negative externalities of transportation. The results suggest that technology in this case could not solve all issues arising from transportation but could only support a sustainable transition. Along, the technological development a citizen and sustainability focused policy making is needed. However, if the deployment of transport services is to seriously lower the negative externalities a collaboration between service providers, regulators, citizens and academia is needed. In that way the services could be codesigned in living laboratories, where citizens could have a say in their development. Such procedure could be the most effective in terms of securing the sustainable transport sector in the future.

LIST OF PUBLICATIONS

Journal papers:

1. Garus, A., Alonso, B., Raposo, M.A., Grosso, M., Krause, J., Mourtzouchou, A., Ciuffo, B., 2022. Last-mile delivery by automated droids. Sustainability assessment on a real-world case study. Sustain. Cities Soc. 79, 103728.

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Abbreviations

ASC - alternative specific constants

AV - autonomous vehicle

CO_2 – carbon dioxide

CERTH/HIT - Centre for Research & Technology Hellas/Hellenic Institute of Transport

CFA - Confirmatory Factor Analysis

CO – carbon monoxide

CVRPTW - capacitated vehicle routing problem with time windows

EC – European Commission

eLCV - Electric light commercial vehicle

e-LVs - Electric L-category Vehicles

GDP - gross domestic product

GHG - global greenhouse gas

GVRP - green vehicle routing problem

IEA – International Energy Agency

JRC - the Joint Research Centre

KMO - Kaiser-Meyer-Olkin measure

LCA - Life Cycle Assessments

LCV - light commercial vehicle

MAVT - multi-attribute value theory

MCDM - multiple-criteria decision making

ML – Mixed Logit

MNL – Multinomial Logit

NL – Nested logit

NOx - Nitrogen Oxides

NMS – New Mobility Services

OD – origin destination

PM - particulate matter

PT – private transport

RMSEA - root mean square error of approximation

ROI - return of investment

SAE - Society of automotive engineers

SAV – shared autonomous vehicle

SO_x - Sulphur Oxidise

SP - stated preference

TAZ - traffic analysis zones

TBM - strip-based model

VAE - Variational Autoencoder

VHT - vehicle hours travelled

VMT - vehicle miles travelled

VOT - value of travel time

1. INTRODUCTION

This chapter provides a brief background to the research performed, followed by the mobility challenges faced by the regional and national authorities. Thereafter a brief analysis to whether those challenges can be efficiently overcome by the sole usage of technology is given. The following two sections of the chapter detail the research aims, questions, and present the contributions of the research. The last subchapter provides the detailed structure of the thesis.

1.1 BACKGROUND

Transport is one the main pillars of our society. The ubiquitous availability of transport opportunities and the possibility to reach almost any place in the world in a limited amount of time has fuelled and sustained globalization and the unprecedented economic growth of the last century (SZYMANSKI et al., 2021; World Bank, 2022). Nevertheless, the current rate of urbanization leads to numerous issues in spreading metropolis, such as congestion, air pollution and depletion of natural resources. Given that up to 2050, 68% of global population is said to live in cities (*The World's Cities in 2018*, 2018), we must quickly learn how to tackle and prevent urban problems, which we often do through better city planning and innovation.

Technological, especially connectivity advancements, of the XXI century have brought a paradigm shift to the seemingly stable transport sector. The technological possibilities, guaranteed demand for transport services and profitable business market have resulted in a plethora of new players and innovators disrupting the market. Nevertheless, transport innovation is not necessarily linked to lowering of negative externalities, either environmental or societal. For instance, dynamic ridesharing or carsharing services, could discourage users from frequenting the more sustainable public transport (PT) or micromobility resulting in more congestion and higher CO_2 emissions. Moreover, NMS such as electric scooter sharing if not managed and used properly could become dangerous not only to its users but also to other vulnerable social groups (Garus et al., 2022).

This research is an investigation into the potential impacts of NMS systems focused on estimating their potential costs and benefits in terms of transport externalities. The insights obtained through these investigations hopefully will provide insights for regional, national and transnational policymakers in regard to sustainable transport innovation deployment.

1.2 TRANSPORT CHALLENGES

Today, more than half the world's population lives in towns and cities and the percentage is growing. By 2050, 70 percent of the world is expected to live in cities and urban areas. The reform of urban mobility remains one of the biggest challenges facing policy makers around the world. This subchapter briefly presents the challenges facing the policymakers.

Urbanisation

Already more than a half population lives in urban areas, and this number is higher in some areas of the world. Exemplary, 75% European population lives in cities (Vandecasteele et al., 2019). Clearly, this rapid growth in urban population and wealth will translate into increased accessibility to jobs, services, and opportunities. For example, between 2000 and 2010, the world's urban population increased by roughly 650 million people. In general, an already dense and growing urban population means that the global challenges faced in relation to transport and mobility are intensified in urban areas.

The International Energy Agency (IEA) estimates that urban passenger travel increased by nearly 3 trillion annual passenger kilometres between 2000 and 2015 (IEA, 2020). The IEA predicts that with the current trends, global urban passenger mobility will double by 2050 and increase as much as 10-fold between 2010 and 2050 in rapidly urbanising, fast-growing regions in Southeast Asia and the Middle East. This will have substantial implications for the global annual urban transport energy consumption, which by 2050 will increase by more than 80% over 2010 levels, despite improved vehicle technology and fuel- economy enhancements. Despite, the fact that car ownership tends to be lower than the national average as people in cities prefer other modes of transport (i.e. public transport, walking and cycling) (European Commission and and United Nations Human Settlements Programme, 2016).

Safety

Road traffic accidents claim nearly 1.3 million lives annually. The traffic fatalities worldwide lead to more than 3,000 deaths per day. In addition to the pain, suffering and unnecessary loss of life, road traffic crashes impose economic costs on nations. These costs are much higher in developing countries where the quality of the road infrastructure does not meet safety standards. Globally, it is estimated that road traffic deaths and injuries cost countries between 1% and 3% of their gross domestic product (GDP), more than $500 billion each year globally (WHO, 2018).

Human error is responsible for 70-90% of motor vehicle crashes (NHTSA, 2015). A large proportion of these crashes could be avoided by using semi-automated and automated vehicles and there are currently very rapid developments aimed at removing humans, the key source of distraction and collision, from the driving equation by providing increasingly sophisticated technologies in vehicles.

Congestion

Traffic congestion results in significant cost bared by the society. It contributes to travel delays and environmental emissions, lost productivity and wasted time. Moreover, apart from the economic costs associated with sitting in traffic, the economic cost of congestion includes the opportunity cost associated with the loss of time (Downs, 2005). Productivity losses from road congestion account for approximately 1-2 % of the EU's GDP (European Commission and and United Nations Human Settlements Programme, 2016), whereas in Asia, it is estimated to cost the Asian economies around 2-5% of GDP (ADB, 2022). However, it is unclear whether the costs of congestion will continue to rise in the future given the constant promotion and development of public transportation and active transport modes, car-free zones in city centres and a widening offer of NMS.

Environment

Transportation activities are significant energy consumers, providing mobility to passengers and freight, which accounts for about 25% of world energy use (Rodrigue, 2020). As presented in Figure 1.1, more than 16% of global greenhouse gas (GHG) emissions were released by the transport sector (Ritchie et al., 2020). According to the European Commission, in 2015, 852.3 million tonnes of CO_2 were emitted by road transport in the EU countries, constituting more than 70% of emissions from all modes of transport (European Commission and and United Nations Human Settlements Programme, 2016).

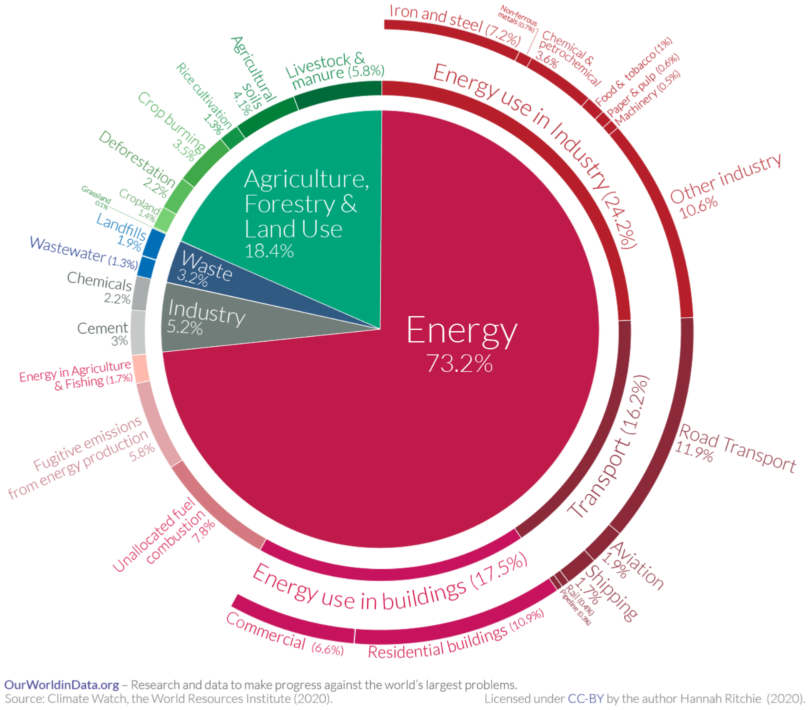

FIGURE 1.1 GLOBAL GHG EMISSIONS BY SECTOR SOURCE: (RITCHIE ET AL., 2020)

In addition to long-lived GHG, vehicles also emit aerosol particles as well as a wide range of short-lived gases, also including aerosol precursor species (Forster et al., 2007). Atmospheric aerosol particles have significant impacts on climate, through their interaction with solar radiation. In populated areas, they also effect air quality and human health (Forster et al., 2007). Moreover, transport also heavily contributes to air pollution, especially in urban areas. It is estimated that road transport is responsible for up to 30% of small particulate matter (PM) emissions in European cities and is the main cause of air-pollution-related deaths and illnesses (Karagulian et al., 2015).

Moreover, emissions caused by human activities from the transport sector have been growing more rapidly than those from other sectors (Righi et al., 2013). This growth is expected to continue in the future, due to increasing world population, economic activities and related mobility (Righi et al., 2013). In the year 2000, there were roughly 625 million passenger vehicles around the world, by 2022, this number had reached nearly 1 450 million passenger vehicles (Hedges & Company, 2022; International Energy Agency, 2013). The IEA expects that increased mobility will impose new challenges and anticipates urban transport energy consumption to double by 2050, despite ongoing vehicle technology and fuel-economy improvements (International Energy Agency, 2013).

Therefore, a strong focus on sustainable and urgent policies and infrastructure development will be required to mitigate air pollution, GHG contributing to climate crisis and congestion effects (Alonso Raposo et al., 2019). But would the stick and carrot from local government be enough to change our ways? In the end in many cultures still a car is perceived as not only a transport mode but a status symbol. Perhaps this problem, as many others, could be solved by new technologies, which would allow full connectivity, sharing and automation of vehicles? This will further be investigated in the thesis.

1.3 New mobility services as solution to transport externalities?

An understanding of a sustainable transport system is not unambiguous and could be highly subjective depending on a role of a stakeholder in the system. Therefore, there is an arising need to define the sustainable transportation system. The European Commission, offers a comprehensive definition (European Commission, 2020) of a sustainable transportation system:

1. Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations.
2. Is affordable, operates efficiently, offers choice of transport mode and supports a vibrant economy.
3. Limits emissions and waste within the planet's ability to absorb them, minimises consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimises the use of land and the production of noise.

Regional and national policymakers who plan and implement for the sustainable transport systems are increasingly recognising the role of smart technologies in improving the efficiency of existing infrastructure through better utilisation of the available infrastructure. These systems can significantly improve operations, reliability, safety, and meet consumer demand for better services with relatively small levels of investment. Cities, as our planet, could be looked at as a complex network of interconnected systems, which can provide as an opportunity for infrastructure management. An Internet of Things comprising sensors, monitors and video surveillance all communicate with each other to enhance infrastructure capability and resilience, capturing volumes of data to make sure that the changes made in the system will be efficient. Through data mining, artificial intelligence and predictive analytics tools, smart infrastructure systems can help city managers monitor the performance of vital infrastructure, identify key areas where city services are lagging, and inform decision makers on how to manage city growth and make our cities more liveable.

Nevertheless, the interconnection between urban systems could also pose as a threat, as a failure of one of the systems could lead to a catastrophic chain reaction. Exemplary, a disclosure of personal data from the transportation system, could lead to tracking and hacking of citizens. Moreover, with possibilities opened by connectivity, electrification and automation, there is now a myriad of NMS entering the markets. As they are often untested in urban areas and their introduction could lead to lowering the sustainability of the transportation system. Exemplary, an introduction of shared electric scooters in numerous cities, has resulted in a variety of problems, from struggles for blind individuals who cannot see a wrongly parked scooter to lack of regional and national policies with regard to those vehicles. Therefore, a question arises, whether the future transportation system, in which an autonomous vehicle (AVs) or shared autonomous vehicles (SAVs) are introduced would be sustainable? In the end the self-driving car could be potentially more disrupting than an electric scooter. Would a plethora of citizens now opting for active transport mode switch their preference towards a comfort of an SAV? Perhaps personal AVs owners would ask their vehicles to just drive around the block for a couple of hours if they were unable to find a parking spot close enough to their location? Maybe one would not take a bus to the cinema on the other side of town just because their seats are comfier but taking a self-driving vehicle for a couple more minutes does not seem like such a struggle for this incredible comfort while watching a movie.

All those changes could pose as a threat to the sustainability of the transport system and should be carefully assessed and responded to by transport policymakers before the innovations are deployed. Sustainable transport policies and intervention measures provide opportunities to meet the needs and demands of citizens and businesses in urban environments. Setting a city on a course towards sustainable transport requires a roadmap and a holistic vision, which could be built only by understanding the plausible consequences of implementing new technologies.

1.4 Thesis objectives and research questions

The main objective of this research is to develop an understanding of environmental and societal implications of NMS. Detailed research questions faced in the study are following:

1. In which way the NMS could alter behaviour changes and change transport demand of their users? [O1]
2. What are the environmental impacts of the behavioural changes (environmental rebound effect) caused by the SAV based service deployment in a mid-sized European city? [O2]
3. What is the relationship between the fleet size of the SAV-based service and the environmental rebound effect? [O3]
4. What would be the preferences of parking in the future, once new parking strategies, enabled by vehicle automation, emerge? [O4]

5. How could the parking costs and wait times adjust the future parking preferences for and AV? [O5]
6. In which way the new last-mile solutions could be investigated? [O6]
7. Whether last mile delivery droid-based system would be overall sustainable? [O7]

1.5 Statement of contribution

This research investigates numerous novel topics related to the deployment of NMS and assists in understanding how transport innovations could impact the urban systems. Moreover, the results of the study focus on policy impacts which could mitigate negative externalities related with transport systems. The key findings and contributions of this research are as follows:

1. Literature review section aims to comprehensively explore and efficiently present the research field of incorporating travel behaviour changes linked to the deployment of NMS into demand models. Those behavioural changes could be numerous and significantly impact the transportation system as a whole. Nevertheless, they were often omitted by modellers who focus on updating the supply side of models. The systematic literature review aims to prove useful for the scientific community and urban planners in the development of more accurate demand estimations. The summary and categorisation of all behavioural changes linked to the NMS that causes them, and a following methodologies for their implementation in demand modelling frameworks is the main contribution of the literature review chapter in hope of easing the task of representing behavioural shifts more accurately. [O1]

2. Chapter 3 aims to investigate in which way and to what extent the behavioural shifts may amplify or mitigate the environmental benefits of SAVs. Regarding the expected benefits of SAVs, a careful assessment of CO_2 emissions is considered, as per the urgency to reduce the GHG emissions. Environmental impacts on air pollution are also presented. According to the knowledge of the authors, this is the first attempt to estimate the environmental rebound effect of the behavioural changes linked to the SAVs deployment using the activity-based demand estimation combined with micro traffic simulation. Moreover, Chapter 3 provides further understanding of how each studied behaviour change, caused by deployment of SAVs, contributes to the environmental factors. The activity-based demand estimation introduces numerous personal attributes to the utility functions of the discrete choice models at all the levels of the activity-based model (ABM), which in previous studies consisted mostly of travel times and monetary costs. Furthermore, Chapter 3 provides results based on multiple in-vehicle value of travel time (VOT) decrease

assumptions after SAVs introduction, whereas the previous studies provided results based on singular VOT assumption. The study is put forward in the hope that it will serve policy makers and regional governors in their strive for a sustainable uptake of SAV technology. [O2], [O3]

3. Chapter 4 provides empirical evidence on the preferences of parking in the future, once new parking strategies, enabled by vehicle automation, emerge. The study focuses on a hypothetical scenario in which autonomous vehicles are privately owned and used in a similar manner to today's private cars. In particular the chapter presents the results of a stated preference (SP) survey in which respondents are confronted with four parking strategies: i) on-street parking nearby ii) dedicated parking area on the outskirts of the city iii) cruising and iv) sending AV back home. To the best of the authors' knowledge, no previous work has engaged with citizens to understand possible parking preferences hitherto. The results of the study are expected to support transport modelers in their simulation studies and impact assessments about future scenarios involving the use of AVs and to give first hints to urban planners to conceptualize the city of the future. [O4], [O5]

4. Chapter 5 aims to lay out a multiple-criteria decision making analysis (MCDA) framework altered for sustainability assessment of innovation in the last mile delivery and apply it to real case study. The framework was adapted to investigate and assess the conflicting needs of the system stakeholders. Moreover, the study includes an application of the framework to the last-mile delivery system of the Ispra site of the Joint Research Centre (JRC) of the European Commission in Italy. The case study lays out and assesses six alternatives of handling the postal services: i) currently used Euro 4 light commercial vehicle (LCV), ii) Euro 6 LCV, iii) electric LCV (eLCV), iv) delivery droid (robot) coupled with Euro 4 LCV, v) delivery droid coupled with a depot station and vi) delivery droid coupled with eLCV. The assessment is one of the first studies to investigate automated delivery droids, which could become a frequent addition to the urban landscape in the near future. [O6], [O7]

1.6 Thesis organisation

The rest of the thesis is structured as follows. In Chapter 2, a comprehensive review of the literature on impacts of user-focused and last-mile NMS. This chapter provides a detailed overview of the literature and a categorisation of the behaviour changes related to NMS deployment.

Chapter 3 discusses the study focused on investigating the environmental rebound effect of SAV-based service deployment. It provides insights onto links between the environmental rebound effect and the size of the SAV fleet.

In Chapter 4, a study focused on the future parking strategies of a privately owned AV is presented. The study investigates plausible preferences of parking the AV as well as the plausible impact of cost and wait time on those preferences.

Chapters 5 lays out a methodology and a case study to investigate the environmental and societal impact of last-mile delivery droids.

Chapter 6 presents all the findings of this research and discusses policy insights. Finally, Chapter 7 summarises the key findings of this doctoral research and discusses the future research directions.

2. Literature Review

This chapter presents an extensive review of the current literature on disruptive technologies, vehicle automation, and shared mobility on demand systems. The subchapter 2.1 provides an insight into measuring impact of user-centred NMS providing the overview of the NMS, categorisation of travel behaviour changes triggered by the user-centred NMS and the incorporation of those behavioural changes into travel demand models. Last section of the 2.1 section specifies an overview of impact that the user-centred NMS have on traffic and related transport externalities. Meanwhile, subchapter 2.2 is focused on measuring the impact of last-mile delivery solutions, providing the overview of innovative last-mile solutions, the methodologies used for their impact assessment and their results. Finally, subchapter 2.3 provides an overview of the gaps found in literature.

2.1 Measuring impact of user-centred new mobility solutions

The existing modelling methods are often not agile enough to respond to a quickly updated offer of NMS (Antoniou et al., 2019). Moreover, our mobility preferences and behaviour change once new transport options become available. For instance, Uber, a ride-hailing application that was non-existent 15 years ago, is claiming to operate 14 million trips each day in more than 700 cities worldwide ('Company Information | Uber Newsroom', 2018). Sharing economy solutions bridge the gap between using and owning a vehicle. Electric scooter sharing, a service first introduced in 2017, has a market size estimated at $18.6 billion ('Electric Scooters Market Size | E-scooters Industry Report, 2030', 2020). Carsharing users are discouraged from buying an additional vehicle (Le Vine and Polak, 2019), whereas bikesharing market could grow as much as 30% annually in the coming years ('Bike Share | Cycling Industries Europe - The voice of cycling businesses in Europe', 2019). Each of the NMS introduced could trigger additional behavioural changes, by extending the offer available to the end user and presenting new usage opportunities.

Profitability of those new business models and added technological advancement will result in further update of transport services (Antoniou et al., 2019). It is a major challenge for transport planners who must learn how to respond quicker and more effectively with the aim to lower the negative externalities caused by the introduction of NMS. Therefore, to ensure that transport models remain useful, not only the supply side of the models needs to be updated. We need to also project the imponderable behaviour changes triggered by the deployment of NMS and represent them in the demand side of the models, to better understand the consequences of innovation deployment.

The well-known transport demand model is often based on a sequential decision-making process of individuals: whether to make a journey, what the destination of the journey should be, the mode of transport to be used, and lastly the route to follow. The sequence is known as a trip-based model

(TBM), with steps being: trip generation, spatial (or zonal) distribution, modal choice and route choice or assignment. Over the years, complementary modelling steps have been added to the model (such as time departure model) and plethora of new techniques for existing modelling steps was developed to improve the overall quality of the methodology. There are numerous methods used to model each step, however all of TBM results are obtained in aggregated form, often with omission of the personal characteristics that could influence individual's decision making processes (Cordera et al., 2019).

In response to the limits of an aggregated approach and to denote travel demand more realistically, novel agent-based models and especially activity-based models (ABMs) were developed. ABMs are based on a theory that travel demand derives from people's needs or desires to participate in variety of activities. Some of those could occur at homes, but in many cases these activities are located outside their homes, resulting in the need to travel (Ortúzar and Willumsen, 2011). ABMs try to mimic how an analysed population plans and schedules their daily travels. Therefore, those models are based on behavioural theories concerning decision processes about whether to participate in an activity, where to participate in those activities, when to participate in activities, and how to get to these activities. The forecasting of rational decision-making processes, incorporated into ABM models is generally done using discrete choice models. These statistical methods are used to recognise factors influencing the decision and assess their impact on the decision-making process (The Second Strategic Highway Research Program, 2015).

The NMS concerned in the paper include carsharing, dynamic ridesharing, micromobility sharing, as well as personal and shared autonomous vehicles (all definitions of NMS services are provided in subchapter 3.2). The authors have decided to consider those NMS, and omit others (such as the hyperloops, urban air mobility or cable cars), as there are the first modelling results already available for the chosen NMS. Furthermore, only studies that concerned AVs of Level 4 and Level 5 of automation, according to the SAE were included in the review (SAE International, 2018). The reason being that self-driving cars (either in slightly limited or full capacity) would have the highest influence on travel behaviour changes, freeing the driver from cautiously steering the wheel.

To best understand how NMS are incorporated into travel demand models, it is worth to look at the key aspects of the studies: location, considered population, objective and software and data used. The analysis shows that the deployment of NMS is global, and the behavioural changes caused by it in principle are universal, as the reviewed studies Asia, Australia, Europe as well as North America.

Moreover, it is worth to look at the population size for each study, to grasp the potential differences in results obtained from studies from variously populated areas. Majority of the studies, focus on the current population of analysed areas, although notably some try to project the future population, to better represent the usage of NMS that are not yet available such as AVs or SAVs. For that case the studies assume year 2030 (Harper et al., 2016; Oh et al., 2020), although the horizon of adoption and implementations of AVs and SAVs in cities is disputed in literature (Litman, 2017). Moreover, majority of the studies analyse the entire population of metropolitan areas, however several studies decided to simulate a fraction of the population for the purpose of lowering the computational costs of the analysis (Basu et al., 2018; Levin and Boyles, 2015; Nahmias-Biran et al., 2020).

As for the objective of the study two main goals are identified. Firstly, the study could assess the impact that NMS could have on traffic or other transport externalities, often analysing various policy or adoption scenarios. Secondly, the study could be an implementation framework either for the modelling methodology (TBM or ABM) or for an open-source platform.

The software most prominently used across the studies are the agent-based simulation platforms: MatSim, developed at ETH Zurich and TU Berlin, that supports ABM and SimMobility, an activity-based agent model developed at MIT.

As for the used datapoints, the researchers most often used rather traditional datasets and data collection tools for demand modelling (such as census data for the purpose of population synthesis in agent-based model and zonal allocation for TBM, and household travel survey or trip diaries to generate the actual demand for trips). Nonetheless, a number of studies opted for a more innovative approach by using data sources that only recently became available such as GPS trace data, smart card data or NMS statistics (Azevedo et al., 2016; Nahmias-Biran et al., 2020; Oh et al., 2020).

Table 2.1 provides characteristics of all studies that tried to methodologically estimate and represent the behaviour changes linked to deployment of NMS, sorted alphabetically according to the name of first author. For each study information on the location, population size, objective, software and used datapoints.

The remaining parts of this section lay out the key takeaways from the comparative review of studies on incorporation of travel behaviour changes linked to deployment of NMS into travel demand estimation. The comparison of reviewed studies is made according to the considered NMS (Section 2.1.1), incorporated travel behaviour changes (Section 2.1.2), demand estimation methodologies along with modelling practices and assumptions (Section 2.1.3) and obtained results (Section 2.1.4). The studied dimensions were chosen not to be exhaustive but rather to capture how modelling techniques and assumptions are used to represent various behaviour changes and the extent of their impact on the results.

TABLE 2.1 CHARACTERISTICS OF REVIEWED STUDIES

Reference	Location	Population size	Objective	Software	Demand related data
Azevedo et al. (2016)	Singapore, Singapore	4.06 million (m)	Assess the performance of SAVs under various regional transport and service policies.	SimMobility	Land use data: residential building, firm, and school locations and characteristics, Household Travel Survey (2008 and 2012), GPS taxi trace data, public transport smart-card data
Balac et al. (2015)	Zurich, Switzerland	1.62 m	Assess the performance of carsharing under various regional transport and service policies.	MatSim	Census and Travel Diaries
Basu et al. (2018)	Singapore, Singapore	351 000 (~10% of Singapore)	Evaluate the impact of SAVs introduction on mass transit.	SimMobility	NA
Bischoff et al. (2019)	Charlottenburg, Berlin, Germany	37 000	Evaluate the impact of AVs parking strategies on waiting times and parking search time.	MatSim	Census and Travel Diaries
Caggiani, Camporeale and Ottomanelli (2017)	Molfetta, Italy	60 000	Estimate revenues from congestion road tolls to finance a free-floating bike-sharing system along with repositioning.	Matlab	Census
Chen and Kockelman (2016)	Grid city based on Austin, USA	2.3 m	Estimate SAVs market shares.	MatSim	Census, regional trip data
Chen, Liu and Wei (2019)	Sioux Falls, USA	182 000	Assess the performance of dynamic ridesharing under various regional transport and service policies.	NA	Modified Sioux Falls static OD matrices
Childress et al. (2015)	Puget Sound region, USA	4.2 m	Evaluate the impact of AVs on transport system.	Daysim	NA
Ciari, Bock and Balmer (2014)	Metropolitan area of Berlin, Germany	4.5 m	Assess the performance of carsharing under various service policies.	MatSim	Census data and on travel diary surveys
Coulombel et al. (2019)	Metropolitan area of Paris, France	13.1 m (assumed 8% grow)	Estimate environmental rebound effect linked to dynamic ridesharing	TransCAD	Regional trip survey (Enquête Globale Transport) and road count data
Dias et al. (2020a)	NCTCOG area, USA	6.5 m	Develop a framework to represent AVs and their behavioural implications in TBM.	TransCAD	Census and Household Travel Survey
Harper et al. (2016)	USA	74 m seniors (2030 estimation) and 20.1 m non-drivers	Estimate increase in travel due to extra activity of mobility impaired in the presence of AVs.	NA	Census and Household Travel Survey
Hebenstreit and Fellendorf (2018)	NA	NA	Implement station-based electric and regular bike-sharing systems in MatSim platform.	MatSim	NA
Heilig et al. (2018)	Metropolitan area of Stuttgart, Germany	2.5 m	Implement carsharing services in an agent-based model for the first time for a period longer than a day (a week).	mobiTopp	Census and Household Travel Survey
Heilig et Al. (2017)	Metropolitan area of Stuttgart, Germany	2.3 m	Estimate SAVs fleet size necessary to handle projected travel demand.	mobiTopp	Census and Household Travel Survey
Hörl, Erath and Axhausen (2016)	Sioux Falls, USA	84 110	Assess the performance of SAVs under various regional transport and service policies.	MatSim	Census data and static OD-matrices

Reference	Location	Population size	Objective	Software	Demand related data
Lavieri et al. (2017)	Puget Sound Region, USA	NA	Estimate adoption rates of personal AVs and SAVs.	NA	Census and Household Travel Survey
Levin and Boyles (2015)	Downtown Austin, USA	NA	Develop a framework to represent AVs and their behavioural implications in TBM.	NA	Household Travel Survey
Liu et al. (2017)	Grid city based on Austin, USA	2.3 m	Evaluate the impact of SAVs pricing levels on travel demand.	MatSim	CAMPO's travel demand predictions for 2020. OpenStreetMap (OSM) file
Martínez and Viegas (2017)	Metropolitan area of Lisbon, Portugal	2.8 m	Estimation of city impacts related to deployment of two SAVs services - taxi-like one and on demand autonomous minibus.	NA	Census, Household Travel Survey and Travel Diaries
Martínez et al. (2017)	Metropolitan area of Lisbon, Portugal	2.8 m	Assess the performance of carsharing under various regional transport and service policies.	Aimsun	Census, Household Travel Survey and Travel Diaries
Millard-Ball (2019)	San Francisco Bay area, USA	NA	Evaluate the impact of personal AVs parking strategies on transport system.	SF-CHAMP ABM	SF-CHAMP ABM demand input
Nahmias-Biran et al. (2020)	Singapore, Singapore	351,000 (~ 7% that of Singapore)	Evaluate the impact of SAVs on accessibility levels.	SimMobility	Land use data: residential building, firm, and school locations and characteristics, Household Interview Travel Survey (2012), Uber statistics
Oh et al. (2020)	Singapore, Singapore	6.7 m (2030 projected population)	Evaluate the impact of SAVs pricing and adoption levels on transport system.	SimMobility	Land use data: residential building, firm, and school locations and characteristics, Household Interview Travel Survey (2012), SP results
Rodier, Alemi and Smith (2016)	San Francisco Bay area, USA	883 000	Evaluate the impact of dynamic ridesharing adoption on vehicle miles travelled (VMT).	SF-CHAMP ABM	2000 Public Use Microdata Sample and 2010 census data and 2-day travel diaries
Truong et al. (2017)	Victoria, Australia	NA	Estimate additional daily trips generated by closing the gap in travel need at different life stages through AV introduction.	NA	Victorian Integrated Survey of Travel and Activity (VISTA) 2007–2010
Vyas et al. (2019) (2019)	Metropolitan area of Columbus, USA	2 m	Evaluate the impact of AVs on transport system.	CT-RAMP2	The Columbus ABM demand data
Wadud, MacKenzie and Leiby (2016)	NA	NA	Evaluate the impact of SAVs on travel demand and GHG emissions.	NA	Household travel survey
Wang, Winter and Tomko (2018)	Yarra Ranges, Australia	158 000	Implement people's preference to their social networks' friends and the flexibility of daily activities to improve the dynamic ridesharing matching.	NA	Census, Victorian Integrated Survey of Travel and Activity (VISTA) 2009–2010
Wang, Kutadinata and Winter (2016)	Yarra Ranges, Australia	158 000	Implement of the flexibility of space and time of daily activities to improve the ridesharing matching.	NA	Census, Victorian Integrated Survey of Travel and Activity (VISTA) 2009–2010
Wen et al. (2018)	Major European city	159 000	Develop a framework for the design, simulation, and evaluation of integrated AVs as a first and last mile supporters of public transportation.	NA	Census, household travel survey and travel diary surveys from 2005 to 2014
Yin et al. (2018)	Metropolitan area of Paris, France	13.1 m (assumed 8% grow)	Estimate environmental rebound effect linked to dynamic ridesharing.	TransCAD	Regional trip survey (Enquête Globale Transport) and road counts
Zhang, Guhathakurta and Khalil (2018)	Metropolitan Area of Atlanta, USA	2.1 m of households	Evaluate the impact of AVs on vehicle ownership.	CPLEX optimizer	2011 travel survey data from Atlanta Metropolitan Area and synthesized Atlanta trip profile from the Atlanta ABM

Reference	Location	Population size	Objective	Software	Demand related data
Zhang, Liu and Waller (2019)	Sioux Falls, USA	NA	Evaluate the impact of various AVs parking strategies on a transport system.	CPLEX optimizer	Census data and static OD-matrices

2.1.1 REVIEW OF NMS

In the majority of the studies only one NMS is considered, but some of the researchers have considered a mix of available services, most often analysing SAVs and dynamic ridesharing (7) or SAVs and private AVs (3). Most of the studies analysing a single NMS focused on privately owned AVs (8) and SAVs (7), as a potentially disruptive new mean of transport, followed by dynamic ridesharing (6), carsharing (4) and micromobility (2). In Table 2.2 the reader will find a summary of NMS considered in reviewed studies.

TABLE 2.2 CLASSIFICATION OF REVIEWED STUDIES ACCORDING TO THE CONSIDERED NEW MOBILITY SERVICES

Study	Carsharing	Dynamic ridesharing	Micromobility sharing	Private AVs	SAVs
Azevedo et al. (2016)		X			X
Balac et al. (2015)	X				
Basu et al. (2018)		X			X
Bischoff et al. (2019)				X	
Caggiani, Camporeale and Ottomanelli (2017)			X		
Chen and Kockelman (2016)					X
Chen, Liu and Wei (2019)		X			
Childress et al. (2015)				X	X
Ciari, Bock and Balmer (2014)	X				
Coulombel et al. (2019)		X			
Dias et al. (2020a)				X	
Harper et al. (2016)				X	
Hebenstreit and Fellendorf (2018)			X		
Heilig et al. (2018)	X				
Heilig et al. (2017)		X			X
Hörl, Erath and Axhausen (2016)					X
Lavieri et al. (2017)				X	X
Levin and Boyles (2015)				X	
Liu et al. (2017)					X
Martínez and Viegas (2017)		X			X
Martínez et al. (2017)	X				
Millard-Ball (2019)				X	
Nahmias-Biran et al. (2020)		X			X
Oh et al. (2020)		X			X
Rodier, Alemi and Smith (2016)		X			
Truong et al. (2017)				X	X
Vyas et al. (2019)				X	
Wadud, MacKenzie and Leiby (2016)					X
Wang, Winter and Tomko (2018)		X			
Wang, Kutadinata and Winter (2016)		X			
Wen et al. (2018)		X			X
Yin et al. (2018)		X			
Zhang, Guhathakurta and Khalil (2018)				X	
Zhang, Liu and Waller (2019)				X	

Autonomous Vehicles

AV is a vehicle capable of performing all driving functions under all conditions (Litman, 2020a). Although there is great uncertainty regarding the deployment horizon and market penetration of AVs, the research related to their adoption has been sprouting.

There is already a speculation of plausible market adaptations. Researchers predict that AVs could be privately-owned or shared that are expected to be a taxi-like service allowing users to reserve the vehicle for a single ride. It is also predicted that rides could be private, shared or the whole service could be handled with higher occupancy vehicles, such as minibuses (Masoud and Jayakrishnan, 2017; Maurer et al., 2015).

The uncertainty of market adoption is also reflected in the analysed studies. Out of 23 studies that included demand estimation for autonomous driving, 10 assumed that AVs would be privately owned and 12 that the vehicles would be a shared fleet. Moreover, the study of Martinez and Viegas (2017) considered two services that SAVs could provide - a taxi-like service and autonomous minibuses on-demand. Another exemplary solution, tested only in one study was that analysed by Wen et al. (2018), who considered a first and last mile service supplementary to public transport. This not uniform approach suggests that the future AV deployment strategy is yet to be determined, with researchers analysing how the autonomy of the vehicle will impact the rate and preference towards ownership. Moreover, the implementation strategy for the AVs could vary not only across countries but also across cities, which could incorporate national or regional policies and environmental strategies, as already suggested by review and backcasting studies (Alessandrini et al., 2015; González-González et al., 2020; Litman, 2020b; Papa and Ferreira, 2018; Stead and Vaddadi, 2019).

Carsharing

Carsharing provides its users with access to a fleet of vehicles on an hourly or minutely basis. The service could be twofold: station based or free-floating. Station-based carsharing requires users to pick up a car from the designated station and drop it off, at the same station (round trip), or a different one of the same provider (one-way) (Münzel et al., 2018). Free-floating carsharing service allows users to book and return a car at any location within the operational area (Kortum et al., 2016). A substantive amount of research regarding carsharing has already been made. The trends include optimisation of the operation of carsharing systems and analysis of successful business models (Münzel et al., 2018), with recent focus on user preferences. The findings of survey-based studies show that carsharing users are often young (Becker et al., 2017), well-educated (Shaheen et al., 2018), environmentally conscious (Costain et al., 2012), high-income individuals from high-density areas (Dias et al., 2017).

As for the reviewed studies only 4 out of 35 tried to estimate the demand for carsharing under behaviour changes assumptions. Nevertheless, the carsharing is likely to be replaced by SAVs in the future, which could explain the small interests in including carsharing services in future-oriented demand estimations.

Dynamic ridesharing

Ridesharing allows users to share a trip with others preventing usage of more than one vehicle to reach a similar destination, whereas dynamic ridesharing is arranged on a per-trip basis, securing flexibility for its users (Levofsky and Greenberg, 2001). Incorporation of ridesharing into travel models have mostly focused on optimisation of matching algorithm, with randomly generated demand.

Nevertheless, 13 out of 35 reviewed studies tried to estimate the demand for dynamic ridesharing services along with the consideration of its impact on overall demand. As SAVs based services could increase their efficiency by offering shared rides for their users, 7 of the 13 studies considered dynamic ridesharing of SAVs. Moreover, two studies focused on another innovative dynamic ridesharing concept that matches users who live in close proximity or could know each other through social media community (Wang et al., 2018, 2016). Remaining studies looked at the currently available dynamic ridesharing services, which simply connect the user with the driver.

Micromobility sharing systems

Micromobility refers to a variety of small transport modes operating at low speeds, typically below 25 km/h, such as bicycles, electric bicycles, or scooters (ITDP, 2019). In this paper, the authors focus on novel shared micromobility systems and their impact on everyday mobility choices. Research related to micromobility sharing systems has mostly focused on software enhancement, as well as city regulation of those systems (Lo et al., 2020).

Micromobility is often omitted in transport models, hence representing the smaller interests in demand estimation studies. Out of the 35 reviewed studies only two looked at the behavioural implications of micromobility and tried to incorporate them into demand estimation methodology (Caggiani et al., 2017; Hebenstreit and Fellendorf, 2018). In the light of electric micromobility boom as well as regional and urban policies direction towards car free zones and rising interest in sustainable living trend more studies should consider this modal choice.

2.1.2 Travel behaviour changes triggered by NMS

Travel demand models try to reproduce the mechanisms influencing travel choices and behaviour of a certain population in response to the transport opportunities available and based on various studied assumptions. The new options that transport innovators propose, change our mobility patterns and impact the everyday life in cities. It is crucial for policymakers and regional governors to predict how individuals could behave under various scenarios to best accommodate the needs of citizens. The first step towards that prediction is the understanding of plausible behavioural implication of innovation.

Upon the review of numerous articles that treated on the subject the authors have classified those changes to be following: i) Acceptance of longer trips, ii) Change in daily activity timing, iii)

Increased number of nonmandatory trips, iv) Increased number of trips of mobility impaired, v) Modal change, vi) Relocation, vii) Shifts in parking habits and viii) Shifts in vehicle ownership. None of the reviewed studies has considered all of the identified behavioural changes, with study by Vyas et al. (2019) omitting just the relocation aspect, and study by Childress et al. considering 5 behavioural shifts (2015). Moreover, the most frequently considered behavioural shift was a modal change with 31 studies incorporating it, following with acceptance of longer trips (12 studies), changes in daily activity timing (7 studies), shifts in parking habits (5 studies), increased number of nonmandatory trips (4 studies), incre4ased number of trips of mobility impaired (4 studies), shifts in vehicle ownership (4 studies) and relocation (2 studies). The incorporation of found changes in travel behaviour in the reviewed studies is summarised in Table 2.3

TABLE 2.3 CLASSIFICATION OF REVIEWED STUDIES ACCORDING TO THE CONSIDERED BEHAVIOURAL CHANGES

Study	Acceptance of longer trips	Change in daily activity timing	Increased number of nonmandatory trips	Increased number of trips of mobility impaired	Modal Change	Relocation	Shifts in vehicle ownership	Shift in parking habits
Azevedo et al. (2016)	X	X			X			
Balac et al. (2015)					X			
Basu et al. (2018)	X	X			X			
Bischoff et al. (2019)								X
Caggiani, Camporeale and Ottomanelli (2017)					X			
Chen and Kockelman (2016)					X			
Chen, Liu and Wei (2019)					X			
Childress et al. (2015)	X	X	X		X		X	
Ciari, Bock and Balmer (2014)					X			
Coulombel et al. (2019)	X				X	X		
Dias et al. (2020a)	X		X		X			
Harper et al. (2016)				X				
Hebenstreit and Fellendorf (2018)					X			
Heilig et al. (2018)					X			
Heilig et al. (2017)	X				X			
Hörl, Erath and Axhausen (2016)					X			
Lavieri et al. (2017)							X	
Levin and Boyles (2015)					X			X
Liu et al. (2017)					X			
Martínez and Viegas (2017)					X			
Martínez et al. (2017)					X			
Millard-Ball (2019)								X
Nahmias-Biran et al. (2020)	X	X			X			
Oh et al. (2020)	X	X			X			
Rodier, Alemi and Smith (2016)					X			
Truong et al. (2017)				X	X			
Vyas et al. (2019)	X	X	X	X	X		X	X
Wadud, MacKenzie and Leiby (2016)			X	X				
Wang, Winter and Tomko (2018)	X				X			
Wang, Kutadinata and Winter (2016)	X				X			
Wen et al. (2018)					X			
Yin et al. (2018)	X				X	X		
Zhang, Guhathakurta and Khalil (2018)					X		X	
Zhang, Liu and Waller (2019)		X						X

Acceptance of longer trips

The reduced travel times, decrease in perceived VOT or drop of travel costs, result in an increase in accessibility levels and following higher tolerance of travelling. Therefore, certain individuals might decide to travel to areas further away to satisfy the journey purpose, prolonging the trip.

As an AV allows for multitasking, the value of in-vehicle time could be perceived as less burdensome than in other modes resulting in a decrease of VOT (Kolarova et al., 2019). Additionally, it is expected that efficient driving as well as platooning could lead to an increase in road capacity and a decrease in travel times (Childress et al., 2015). Moreover, it is expected that automation of vehicles would lead to operational cost reduction (Litman, 2017). Likewise, the reduced travel time and decrease of VOT could lead to elongation of the trips. A hypothesis confirmed by an experiment that tried to capture behaviour changes caused by autonomous driving by giving individuals access to chauffer services (Harb et al., 2018).

Due to the split of monetary costs between users, dynamic ridesharing is expected to lower the cost of travelling, whereas potential congestion reduction caused by higher vehicle occupancy could shorten travel times. The reduction of costs and potential reduction in travel time will increase the accessibility and possibly encourage people to travel further away and elongate the trips (Coulombel et al., 2019).

Change in daily activity timing

The reduction in VOT time as well as the decrease of costs could also trigger individuals to tolerate travelling in more congested conditions, altering the schedule of a given individual (Childress et al., 2015). Additionally, as users of SAVs and private AVs will not have to worry about finding a parking location for their vehicles and reaching the final destination from it by foot, the daily schedule could change as well, allowing those individuals to leave the households later without risking being late (Zhang et al., 2019). Therefore, the deployments of AVs, SAVs as well as dynamic ridesharing could cause people to change the daily activity timings.

Increased number of nonmandatory trips

The behavioural studies predict that a decrease in VOT, travel times as well as lower travel costs could also encourage users to participate more often in non-mandatory, leisure activities (Childress et al., 2015; Coulombel et al., 2019; Harb et al., 2018). Therefore, the deployment of personal AVs as well as SAVs and dynamic ridesharing could result in an increased number of non-mandatory, leisure trips. However, predicted behavioural change is not often considered in the studies, as only 4 studies that analysed AVs, SAVs or dynamic ridesharing have decided to implement the behavioural change in the demand model.

Nevertheless, the demand estimation studies should look for methodologies to implement the increase in number of non-mandatory trips in their calculations, as the experiments that try to investigate the behaviour changes caused by AVs suggest that individuals will indeed increase the number of their non-mandatory trips. That is because they are willing to use an AV more often than regular car as it allows them to use the vehicle under the influence of alcohol or at night when they would be too tired or sleepy to drive themselves (Harb et al., 2018).

Increased number of trips of mobility impaired

Elderly, youth, mobility and visually impaired, and others without a driver's license could use AVs for travelling alone as it does not require driving abilities. Therefore, AVs (as well as SAVs) could increase the number of trips that people from those groups generate (Truong et al., 2017). The increase of accessibility for those individuals is often mentioned as one of the most significant advantages of AVs. Nevertheless, the impact of this increased accessibility on demand estimation is often omitted in the analysis made as of today (only 4 out of 23 studies on AVs decided to fully or partially consider this demand induction in their analysis).

Modal Change

Modal change is the most obvious behaviour change caused by introduction of all considered NMS. Therefore, majority of the studies reviewed for the purpose of this analysis have introduced it in their models. For this analysis, it is assumed that the modal change behaviour was considered if the study tried to understand the factors that determine the modal choice. If the study did not include any behavioural modal choice model, but rather assumed that the demand would be fully covered by AVs this review does not consider the study to incorporate modal change as a behavioural change. The same is true for the studies that consider a partial demand covered by AVs, but rather than analysing which individuals are prone to shift to other modes, draw the sample randomly.

The reduction of VOT, travel costs and travel times could further influence user preferences towards dynamic ridesharing and AVs resulting in additional modal shifts from more sustainable options such as public transport or micromobility (Childress et al., 2015). A similar outcome can be seen with carsharing, as carsharing tends to attract people that use public transport for their commute rather than private car (Ciari et al., 2014; Martínez et al., 2017).

The observed change in travel behaviour related to the implementation of micromobility sharing system is a modal shift, often on short walking distances (Efthymiou et al., 2013a). However, bike-sharing can also replace public transport, private car, or taxi (Shaheen et al., 2013).

Relocation

A number of studies predict that with the decrease in in-vehicle value of travel time, costs or travel times, caused by AVs deployment and adoption of dynamic ridesharing services, individuals may choose to relocate further from their main activity location, which could potentially result in urban sprawl (Azevedo et al., 2016), (Coulombel et al., 2019). Nevertheless, relocation was only considered in two of the reviewed studies, namely by Coulombel et al. (2019) and Yin et al. (2018) who tried to assess the environmental rebound effect of dynamic ridesharing services in Paris.

Nevertheless, studies predict that the sprawl and relocation could be stopped if we adopt a shared model of AVs. In which the imbalance between demand and supply of SAVs would result in price increase of services in sprawled-out areas, as more empty rebalancing trips would be needed to fulfil all travel request, increasing the operational costs for the fleet manager (Chen and Kockelman, 2016). That means that per mile costs in densely populated areas would be lower than in those sprawled (Gruel and Stanford, 2016). This outcome could stop individuals from relocating, provided that the shared mobility would significantly impact the vehicle ownership rates.

Shift in parking habits

The fact that an AV does not require the driver to be present in the car, enables new parking options for personal AVs' users. Researchers have indeed already predicted that the land dedicated to parking could be cut short drastically due to the deployment of SAVs (Bischoff et al., 2019; Duarte and Ratti, 2018; Fagnant and Kockelman, 2015; Litman, 2020b; Zhang et al., 2015). In the remainder of the section, the main sources regarding future urban parking predictions are briefly presented.

Firstly, a group of studies have tried to qualitatively foresee the parking revolution that will result from the ability of the vehicle to park by itself. Researchers predicts that in densely populated areas and at the final destinations of many travels, parking will be done in collective garages situated in less desirable locations than city centres (Bischoff et al., 2019; Heinrichs, 2016). Moreover, those collective garages are expected to be more land efficient than the parking areas nowadays, as the space per vehicle will decrease due to obsolescence of room required to open the vehicle's door, and the space to allow comfortable access to vehicle users (Nourinejad et al., 2018). Recent studies performed by Levin et. al and Lai et al. already aim to design the collective parking lots of the future, in which vehicle repositioning and parking spot sharing would be easy and efficient (Lai et al., 2021; Levin et al., 2020).

Alternatively, AVs could opt not to park at all, cruising on the streets and waiting for a signal from their passengers (Bischoff et al., 2019; Millard-Ball, 2019), which would result in higher vehicle miles travelled (VMT), congestion and resulting fuel/energy consumption and pollution[1]. The fourth parking strategy identified in the literature relates to sharing the vehicle with other household

[1] Even in the case of electric vehicles, brakes and tires particles can substantially affect air quality especially in the case of increased VMT and congestion

members, and it assumes that once AV drops off its passenger at a given location it would return home to serve other household members (Vyas et al., 2019).

Therefore, the reviewed literature suggests that the user could potentially choose one of the following four strategies (Bischoff and Maciejewski, 2016; Levin and Boyles, 2015; Millard-Ball, 2019; Vyas et al., 2019):

- The vehicle could drop off its user and start looking for an available parking spot nearby, relocating if there is a limit on permitted duration of parking.
- The vehicle could drop off its user and park in a dedicated garage area on the outskirts of city or central business district.
- The vehicle could drop off its user and return to the home location to serve other household members or wait for the principal user's orders.
- The vehicle could drop off its owner and start driving in nearby locations until called again by the user, in so called cruising strategy.

The latter three strategies could potentially result in an increase in-vehicle miles travelled (VMT), and CO_2 emissions. Shifts in parking preferences have been the focus of five of the reviewed studies, with three of those placing their solemn focus on investigation of shifts in parking behaviour.

Shifts in vehicle ownership

In response to NMS deployment, preferences for vehicle ownership could shift. Researchers agree that vehicle ownership could change as result of carsharing and SAVs deployment (Jiang et al., 2019; Lavieri et al., 2017; Le Vine and Polak, 2019; Shaheen et al., 2018) . Wide availability of mobility as a service in form of SAVs could discourage numerous users from owning a personal AV. SP survey studies have confirmed that in presence of a SAVs on-demand service multi-vehicle household would be willing to dispose of one or more of their vehicles (Menon et al., 2019) and that highly educated, young individuals living in dense urban areas are more drawn to SAVs rather than personal AVs (Jiang et al., 2019; Lavieri et al., 2017)

Moreover, surveys conducted among carsharing users prove that access to carsharing services impacts vehicle ownership, as users, tend not to buy an additional vehicle (Le Vine and Polak, 2019), or even dispose their old one (Shaheen et al., 2018).

A categorisation and summary of behaviour changes caused by deployment of NMS is presented on Figure 2.1.

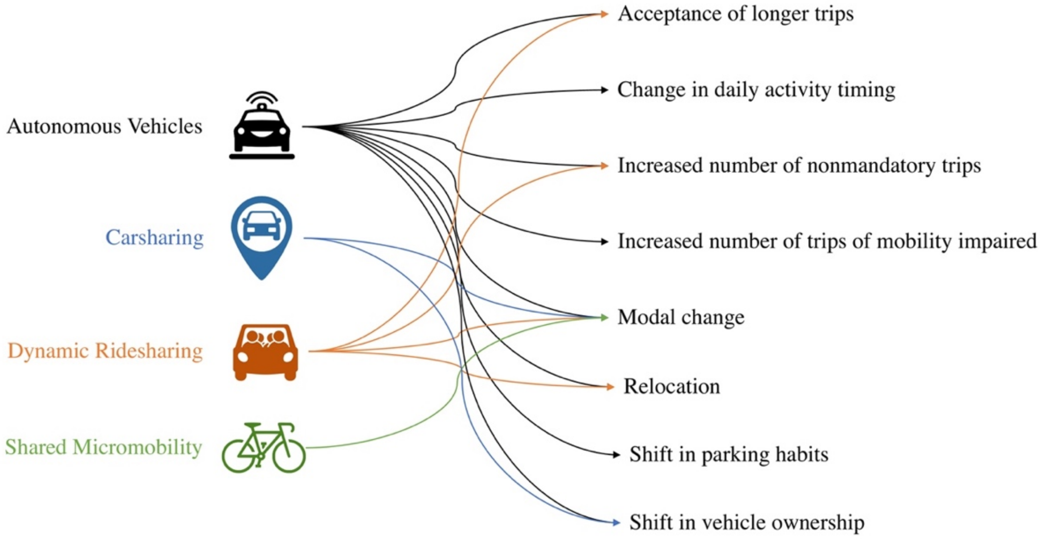

FIGURE 2.1 SUMMARY OF IMPACT OF NMS ON TRAVEL BEHAVIOUR

2.1.3 INCORPORATION OF TRAVEL BEHAVIOUR CHANGES IN TRANSPORT DEMAND MODELS

Behaviour changes cause a struggle for demand modellers, as the current demand estimation methodologies keep proving not agile enough to the changing mobility offer and its implications (Antoniou et al., 2019). Furthermore, the deployment and adoption of NMSs, especially AVs, could mean a major paradigm shift for all transportation, and a disruptor when it comes to behaviour changes. Hence, the utmost importance of mirroring the foreseeable behaviour in the demand estimation models.

In this section, the review of modelling techniques and key assumptions used in reviewed studies are presented to the reader. The studies are categorised according to the modelling framework used. The categories stand as ABM (21 studies), TBM (4 studies), and other estimation methods (9 studies).

For each of the categories, the key modelling changes or assumption that try to incorporate behaviour changes caused by NMS are presented for various parts of the modelling activity.

Thus, TBM is traditionally divided into a four-step modelling sequence (i -iv) with an extra vehicle ownership model (v) and other notable changes:

i. Trip generation
ii. Trip distribution
iii. Modal choice
iv. Route assignment
v. AV ownership
vi. Other changes

Activity-based models are divided into following modelling steps:

i. Activity scheduling
ii. Modal choice
iii. Destination choice
iv. Time of day choice
v. AV ownership
vi. Other changes

As for the demand estimation methodologies outside of the TBM and ABM frameworks, each model is reviewed individually as their approaches often vary.

The key modelling techniques and assumptions used in TBM, ABM and other identified methodologies that concern behaviour change estimation, are presented in Table 2.4, Table 2.5 and Table 2.6 respectively.

TABLE 2.4 MODELLING TECHNIQUES USED IN TRIP-BASED MODELS

Study	Considered NMS	Modelling step	Behaviour change	Modelling practice
Dias et al. (2020a)	AV	Trip generation	Increased number of nonmandatory trips	Assumed scenario-based 5%/10% increase in number of trips for households owning an AV
		Trip distribution	Acceptance of longer trips	Reduction of generalised travel cost between zones by 25% for AV owners
		Modal choice	Modal change	Reduction of VOT for AV owners by 25% as compared to the regular car
		AV ownership	Shifts in vehicle ownership	Binary logit model based on individuals' household income (survey-based study) with assumed 40% penetration rate.
Levin and Boyles (2015)	AV	Modal choice	Modal change and Shifts in parking habits	Nested logit model of choice between: AV parking nearby, AV repositioning, and transit. Utility functions made of parking fees, fuel costs and VOT.
		AV ownership	Shifts in vehicle ownership	Scenario analysis of AV availability for five classes of population divided by VOT (1.15$ to 22$).
Coulombel et al. (2019) and Yin et al. (2018)	Dynamic ridesharing	Trip distribution	Acceptance of longer trips	Assumed lower average travel time due to reduction of congestion.
		Modal choice	Modal change, Shifts in parking habits	Multinomial logit model with utility functions of each mode made of VOT and monetary costs. Monetary cost is split evenly between ridesharing users.
		Other changes	Relocation	The potential relocation assessed in a coupled land-use model by incorporating a decrease in average travel time and cost.

TABLE 2.5 MODELLING TECHNIQUES USED IN ACTIVITY-BASED MODELS

Study	NMS	Modelling step	Behaviour change	Modelling practice
Azevedo et al. (2016), Basu et al. (2018) and Nahmias-Biran et al. (2020)	SAV with ridesharing	Modal choice	Modal change	Change in the utility functions. Utility of SAV based on individual preferences towards taxis with 40% (Azevedo et al., 2016; Basu et al., 2018) or 33% (Nahmias-Biran et al., 2020) monetary cost.
		Destination choice	Acceptance of longer trips	
Bischoff et al. (2019)	AV	Other changes	Shifts in parking habits	Private AVs choose from three parking strategies: parking on a free but time limited parking spot, parking at a garage with unlimited capacity nearby and cruising in range of 2000 m while waiting for the user. Parking strategy and assumed AV penetration (10% or 20%) is subject to scenario analysis.
Chen and Kockelman (2016)	SAVs	Modal choice	Modal change	Modal choice between private vehicle, transit and SAV determined by MNL model. The utility functions consist of VOT and monetary costs. VOT is assumed to be 50% of hourly wage of modelled individual for personal trips and 100% of hourly wage for business or work trips. VOT in SAV is decreased to 35% of regular private vehicle ride. Monetary costs of SAV subject to scenario analysis: simple distance-based, origin- based, destination-based, and combination of origin and destination pricing. The origin and destination pricing are designed to minimise the empty rides required for relocation.
Childress et al. (2015)	AV and SAV	Activity scheduling	Increased number of nonmandatory trips	Three AVs scenarios: in all 30% assumed capacity increase and VOT reduced to 65% of regular car for AV owners. In the SAV scenario where all vehicles are shared the flat cost of travel is assumed at $1.65/mile.
		Modal choice	Modal change	
		Destination choice	Acceptance of longer trips	
		Time of day choice	Changes in daily activity timing	
		AV ownership	Shifts in vehicle ownership	Simulated population divided by income. Scenario-based analysis of AV availability. AVs are either available to high income households (with VOT higher than $24) or a full market penetration is assumed. Last scenario assumes that all vehicles are shared.
Heilig et al. (2017)	SAV with ridesharing	Modal choice	Modal change	Mode and destination choices determined in a nested logit model (NL), in which private car is unavailable. The utility of using SAV is modelled as the utility of "private car as a passenger" option with a reduction of monetary costs by 70% per mile.
		Destination choice	Acceptance of longer trips	
Hörl, Erath and Axhausen (2016)	SAV	Modal choice	Modal change	Modal choice based on MNL model in which utility functions consists of VOT and monetary costs. VOT for SAV option modelled at 65% of a private car. Waiting for an AV modelled at twice the VOT of car travel. SAV monetary costs assumed at $0.85/mile
Liu et al. (2017)	SAV	Modal choice	Modal change	Modal choice based on MNL model in which utility functions consists of VOT and monetary costs. In-vehicle VOT for SAV option modelled at 50% of a private car in-vehicle VOT. Waiting for AV modelled at twice the VOT of car travel. Cost of SAV is subject to scenario analysis and consist of distance-based fee of $0.50, $0.75, $1 or $1.25 per mile and a fixed cost of $1, $2, and $3 subject to the starting location of the trip (urban, suburban and extra urban areas).
Martínez and Viegas (2017)	SAV (two services: taxi-	Modal choice	Modal change	SAVs replace private cars, buses, and taxis which are not available as modal choices. A modal choice determined by a nested logit model along with a series of sequential rules that form a rational decision-making process. Rules concern length of the trip, transit pass ownership, and a number of transfers.

	like and minibuses)			
Oh et al. (2020)	SAV with ridesharing	Modal choice	Modal change	The alternative specific constants in the utility function and willingness-to-pay for SAV are based on current taxi utilities, tuned so that the proportion of SAV mode shares to rail shares is similar to that predicted by the estimated mode choice model on the weighted stated preference sample under different pricing assumptions. The price of SAV is subject to scenario analysis and studied at 75%, 100%, 125% fare of a taxi.
		Destination choice	Acceptance of longer trips	
Vyas et al. (2019)	AV	Activity scheduling	Increased number of nonmandatory trips, Increased number of trips for mobility impaired	Assumed scenario-based 25%/50% decrease in VOT as compared to a regular car. The mobility impaired are allowed to use the AV if they are a part of a household that owns one. AV availability for children subject to the scenario analysis of age required for a child to use AV by themselves.
		Modal choice	Modal change	NL model to assess modal choice along with parking strategy. Assumed scenario-based 25%/50% decrease in VOT as compared to a regular car.
		Destination choice	Acceptance of longer trips	
		Time of day choice	Changes in daily activity timing	
		Modal choice	Shifts in parking habits	NL model to assess parking behaviour implemented on a modal choice level. Traveller can park an AV in close proximity or send the car back home making it available to other household members.
Balac et al. (2015)	Station-based carsharing	Modal choice	Modal change	Modal choice determined by MNL. The utility functions include the VOT and travel time as well as monetary costs. For carsharing in-vehicle travel time is modelled as a regular car, access and egress times are modelled at value of walking time. Monetary costs include fixed rental fee, rental time fee and distance fee.
Ciari, Bock and Balmer (2014)	Free-floating carsharing	Modal choice	Modal change	The utility functions include the VOT and travel time as well as monetary costs. For carsharing in-vehicle travel time is modelled as a regular car, access and egress times are modelled at value of walking time. Monetary costs include fixed rental fee, rental time fee and distance fee. There is a cap on rental time fee to represent available services.
Heilig et al. (2018)	Station-based and free-floating carsharing	Modal choice	Modal change	Modal choice determined by MNL based on the results of SP. Carsharing option is available for individuals without private vehicles. The utility functions include socio-demographic variables, land use, travel time, and cost. The cost of carsharing is based on available services: 0.29€ for free-floating service and 2.80€ per hour and 0.23€ per kilometre for station-based service.
Martínez et al. (2017)	Station-based carsharing	Modal choice	Modal change	Modal choice determined by MNL based on the results of SP. The utility functions include socio-demographic variables, land use, travel time, and monetary cost. The cost of carsharing is based on available services: 0.29€/min and 0.19€/ min when the car is reserved.
Rodier, Alemi and Smith (2016)	Dynamic Ridesharing	Modal choice	Modal change	Identification of trips that meet the maximum income and minimum trip length conditions for which ridesharing is a modal option. Ridesharing mode determined upon individual acceptance of departure time flexibility, proximity and group size.
Chen, Liu and Wei (2019)	Dynamic Ridesharing	Modal choice	Modal change	Agents divided between those with mode set and those with mode choice. Final ridesharing mode choice for flexible agents based on the earliest arrival time at destination.
Wang, Kutadinata and Winter (2016) and	Dynamic Ridesharing	Modal choice	Modal change	The number of shared rides is maximised, subject to time and space limitations and detour tolerance. Priority is given to social network friends.

Wang, Winter and Tomko (2018)		Destination choice	Acceptance of longer trips	Ridesharing users are changing the destination if a driver is heading for a similar activity location.
Hebenstreit and Fellendorf (2018)	Micromobility	Modal choice	Modal change	Modal choice determined by MNL model. The utility of bike-sharing consists of access and egress times as well as the likelihood of finding a bicycle on an origin station and available parking place at the destination station.

TABLE 2.6 MODELLING TECHNIQUES USED IN STUDIES BASED ON OTHER METHODOLOGIES OF DEMAND ESTIMATION

Study	Considered NMS	Behaviour change	Modelling practice
Lavieri et al. (2017)	AV, SAV	Shift in vehicle ownership	Multinomial probit kernel for the discrete choices to assess what factors and attributes impact the level of interest of individual in owning AV or using a SAV service. The level of interest was measured at 5-point grading scale.
Truong et al. (2017)	AV, SAV	Modal change	Scenario based analysis. In the first scenario 10% of public transport trips made by members of households, where there are fewer motor vehicles than people of driving age, are assumed to switch to AVs and 20% of public transport trips by members of no car households are assumed to switch to AVs. Second scenario also introduces an assumption that 10% of travellers switch from walking and cycling to AVs.
		Increased number of trips of mobility impaired	Increasing trend in number of trips at aged 30-65 decrease of trips at age 44-67 are assumed to be a natural. Gaps in travel need for the 12–17 age group and for the 18–24 and 25–29 age groups are measured by the differences between the actual travel need curve and the linear extrapolation of the natural increase trend, gaps in travel need for the 66–75 and 76+ age groups are measured by the differences between the actual travel need curve and the linear extrapolation of the natural decline trend.
Wadud, MacKenzie and Leiby (2016)	SAV	Increased number of non-mandatory trips	Assumed scenario based 50-80% reduction in VOT and 60-80% reduction in insurance costs, a fraction of operational costs.
		Increased number of trips of mobility impaired	The decline in travel activity between ages 44 and 62 represents the natural rate of decline in travel needs, and that the accelerated decline after age 62 represents travel that is foregone due to impaired driving abilities. The demand that could be filled through automation is calculated as the difference between the actual demand and the linear extrapolation of the age 44–62 trend.
Wen et al. (2018)	Public transport compliment with SAV	Modal change	NL model based on the historical observations, simulated level of service and fare and AV preference assumptions. The fare is estimated based on a similar Uber service with base fare: $0.83, distance fare $0.55/km, time fare: $0.11/min. System performance is evaluated and returned to the mode choice in a feedback loop. The level-of-service indicators are: service rate, wait time and detour factor.
Harper et al. (2016)	AV	Increased number of trips of mobility impaired	Assumptions: Non-drivers travel as much as the drivers within each age group and gender. Elderly drivers without any travel-restrictive medical condition in the youngest elderly cohort (65–74) travel as much as working age adults (19–64) within each gender. Elderly drivers with and without any medical conditions will travel as much as a person 65 years of age within each gender. Working age mobility impaired adult drivers (19–64) will travel as much as working age adults without medical conditions in each gender. Elderly drivers with travel restrictive medical conditions in the youngest elderly cohort (65–74) will travel as much as working age adults within each gender.
Millard-Ball (2019)	AV	Shifts in parking habits	Private AVs owner can choose from three parking strategies: parking on a free but time limited parking spot and changing a spot after required time, returning home to park and cruising. The chosen strategy is the one minimising the costs. Cost of the first strategy is modelled as the cost of drive towards a parking location in a free on-street space and return to the owner. The cost of repositioning is assumed as marginal. In the second strategy the cost consists of driving home and back to the user. Driving cost of $0.13/mile is assumed for both strategies. For the cruising strategy the cost is speed dependent and minimised by finding the routes with lowest travel speeds.

Zhang, Guhathakurta and Khalil (2018)	AV	Shift in vehicle ownership	100% of AV market penetration is assumed. The greedy scheduling algorithm is used to minimise AVs needed to satisfy the travel demand of all household members in each household. If there is not enough time to relocate the AV to serve all household trips the vehicle could not be replaced. Otherwise, if all trips generated by the household could be met with less vehicles, the vehicle ownership of the household is reduced. for households that can reduce vehicle ownership an optimization Mixed-Integer Programming problem is used to determine the minimum amount of unoccupied VMT generated during AV repositioning process.
Zhang, Liu and Waller (2019)	AV	Change in daily activity timing	Joint equilibrium of AV route parking location choice. The AV users are assumed to omit the walking time for parking location to their activity location, leaving the house later. The assumptions are that for the early arrival commuters marginal saving in early schedule delay cost is larger than the marginal increase in the cost of self-driving AV to find a parking space.
		Shifts in parking habits	The AVs select an appropriate parking location, which will minimize the total individual travel disutility based on a joint evaluation of distance travelled and cost. In line with the parking choice and the willingness to minimize individual travel disutility, the AV chooses shortest paths with minimal travel time.

Trip-based models

Not many studies have decided to implement the NMS behavioural changes into TBM, as the aggregated nature of those models limits the potential of implementing shared services.

On the trip generation level, the behavioural changes that lead to induced travel demand (such as increase in non-mandatory activities and increased number of nonmandatory trips) are represented. This is reflected in one of the TBM based reviewed studies, which implemented this behavioural change in the model, through the scenario-based assumption of the increase in number of trips for AVs owners (Dias et al., 2020).

The changes made in trip distribution step of the model could reflect the higher acceptance for longer trips. The implementation of this behaviour change was performed in the reviewed studies, through assuming a lower generalised cost (or time) of travel in the generalised cost origin-destination (OD) matrix (Yin *et al.*, 2018; Coulombel *et al.*, 2019; Dias *et al.*, 2020a) .

The modal choice level of the model incorporates the modal changes caused by introduction of new services. In the reviewed papers the researchers have developed either multinomial logit models (MNL) (Coulombel et al., 2019; Yin et al., 2018) or nested logit models (NL) (Levin and Boyles, 2015) which allowed to determine the modal choice. Reflection of changes caused by introduced NMS was made through assumed reduction of VOT (for AVs) (Dias et al., 2020) and assumed lower cost of travel (dynamic ridesharing) (Yin *et al.*, 2018; Coulombel *et al.*, 2019).

Shifts in vehicle ownership were also analysed in reviewed studies that implemented the TBM. Certain researchers based their studies on the assumption that high-income individuals are more likely to adopt innovation. Based on income classes, the AV availability was assigned to households. The penetration rate was either subject to scenario analysis (Levin and Boyles, 2015) or assumed (Dias et al., 2020). Nevertheless, this approach could be misleading, as the tendency to switch for an innovative solution could be motivated by other factors such as age, costs, or perceived safety and sustainability (*Expectations and concerns of connected and automated driving*, 2020), with SP based study even concluding that income levels are not significant for the AV adoption (Menon et al., 2019).

Activity-based models

Behaviour changes related to NMS deployment are more often implemented in ABMs, which allow to better represent decisions of individuals based on their socioeconomic profile. A share of reviewed studies was agent-based developed in simulation platforms such as MatSim, SimMobility or mobitopp. Agent-based models are used for precision in spatial and temporal representation of the supply side, a key for a faithful representation of shared services. While, the activity-based model (ABM) is a string of decision making processes implemented in the form of a series of discrete choice models (typically MNL or NL), therefore some of the changes implemented (such as decrease of VOT) could be made on all levels of the model with a single assumption.

A small share of researchers have decided to implement changes on the activity scheduling step of the model, which reflect an increased number of non-mandatory trips and increased number of trips of mobility impaired. Implementation of increased number of non-mandatory trips was made through assumed decrease in VOT (in a range from 25 to 50%) (Childress et al., 2015; Vyas et al., 2019). Changes in activity timing, caused by AVs deployment, were implemented analogically.

Increased number of trips of mobility impaired was not studied sufficiently in the ABMs, as only one study decided to consider any changes. Vyas et al. (2019) assumed that AVs would be available as a modal choice for children with a scenario-based minimal age requirement . No other demand inductions caused either by additional activity of the elderly or those with no driving license or disabled were considered in the reviewed studies that implemented an ABM.

On the destination choice level of the model, usually a MNL or NL, acceptance of longer trips was considered. Several researchers have decided to implement this behavioural change in ther ABMs. For AVs the implemented changes consisted of assumed VOT reduction (25-50%) with a VOT considered as in regular car (Childress et al., 2015; Hörl et al., 2016; Liu et al., 2017; Vyas et al., 2019). If the utility of the choice was modelled after a taxi service, only a change of cost was assumed (30-40% decrease due to elimination of driver) (Azevedo et al., 2016; Basu et al., 2018; Heilig et al., 2017; Nahmias-Biran et al., 2020; Oh et al., 2020).

The modal choice step of the ABM, which incorporated modal changes, was most often modified by the researchers. Nevertheless, the reviewed models often did not consider socioeconomic attributes and individual preferences as factors that could influence modal shifts. The modal choice is frequently determined by a MNL, following the maximal utility theory, determining the choice based on overall utility of each option. However, utility functions often included only assumed perceived VOT, and monetary cost (Chen and Kockelman, 2016; Hörl et al., 2016; Liu et al., 2017; Vyas et al., 2019). For which, the changes in behaviour were often implemented through assumption of VOT decrease as compared to the regular car (25%-50%). Omitting the importance of individual preferences, which could be crucial, especially when it comes to unfamiliar modal choices such as AVs.

Alternatively, the utility of the SAV option was modelled as a taxi or as "private car as passenger", by reducing the costs of travel (40-70%) (Azevedo et al., 2016; Basu et al., 2018; Heilig et al., 2017; Nahmias-Biran et al., 2020; Oh et al., 2020). The cost of SAV and AV operation was often assumed as a fraction of taxi service or private car, or subject to scenario analysis. Nevertheless, constant cost assumption could be misrepresentative as SAV services could function, with costs varying based on current supply and demand. Whereas the cost of private electric AV operation is also difficult to determine as it highly depends on national energy transformation and electricity mix.

Furthermore, the assumption that VOT is constant for all trip purposes could be misleading, as survey-based studies suggest that it could vary depending on trip purpose, estimating VOT decrease at 30-40% for commuting trips (Steck *et al*., 2018) and zero for leisure trips (Kolarova et al., 2019). Only one study implemented a differentiation of VOT subject to the purpose of the trip, claiming VOT to be 100% of wage for business trips and 50% for leisure trips (Chen and Kockelman, 2016). The variety of perceived value of travel time in different modes was also insufficiently represented as only one study implemented the alteration in value of time in regard to waiting for SAV service or being inside. Hörl, Erath and Axhausen (2016) assumed that waiting for an AV is twice as valuable as riding inside.

Modal choice for studies focusing on carsharing often incorporated more socioeconomic attributes to utility functions based on survey-based responses - an already available solution for which an adequate SP study could be more straightforward and subject to less bias as it is a mode users could be already familiar with, as opposed to not yet available mobility options like AVs (Heilig et al., 2018; Martínez et al., 2017). Moreover, the costs of carsharing were also easier to determine as simply the costs of available services were implemented in the utility functions (Balac et al., 2015; Ciari et al., 2014; Heilig et al., 2018; Martínez et al., 2017). The difference in VOT was also exemplified in some of the studies, as the value of access and egress time was modelled as value of walking and value of using the service as value of travelling with regular car (Balac et al., 2015; Ciari et al., 2014).

Modal choice in studies that focused on dynamic ridehailing was subject to numerous additional limitations and requirements such as the latest arrival time, the maximum income of users and departure time and group size (Rodier et al., 2016; Wang et al., 2018, 2016; Wen et al., 2018).

Finally, changes in parking habits were studied only in two of the reviewed studies in a modal choice step in NL models, where one of the nests contained various AV parking possibilities (Bischoff et al., 2019; Vyas et al., 2019). The parking option was determined based on the maximal utility. The utility of parking covered the costs of each parking strategy. The approach, however, could be misleading, as individuals may opt for a given parking strategy for reasons other than financials.

Additionally, a share of studies implemented an assumption of an increase in road capacity, which impacts the utility functions by changing the travel time. Assumptions can vary for different road types and AV market penetration or could be constant. However, those assumptions could be optimistic as driving efficiency of AVs could be subject to regional policies for instance in the case of dedicated lanes for platooning (Litman, 2020a), a situation not considered in reviewed studies.

Other methodologies

Although TBM and ABM are used most often for demand modelling, a number of reviewed studies have drawn from other methodologies to estimate the behaviour shifts. Incorporation of those methodologies into TBM or ABM might not be straightforward, either because of aggregation of population (in case of TBM) or because of necessity to include an additional modelling step supported by supplementary assumptions (in case of ABM). The behavioural changes that were studied in methodologies outside of the typical demand estimation were i) the increased number of trips of mobility impaired, ii) shifts in parking habits and iii) shifts in vehicle ownership.

The studies that focused on estimating the demand induction caused by increase in accessibility for mobility impaired, followed a string of assumptions about the needs of travel for three demographic groups, which could potentially have the highest impact: elderly, disabled and nondrivers. For instance, Harper et al. (2016) assumed that nondrivers and disabled would travel as much as their age and gender non-disabled driving counterparts in the population. Whereas the elderly were assumed to travel as much as the younger working adults in the population. To better denote the natural demotion of travel needs, Truong et al. (2017), following Wadud et al. (2016), proposed to analyse the current travel demand for population and assume that early age increase in travel and late age decrease represent the natural changes in the need to travel. The induction of demand was estimated to be the difference between the natural travelling needs and the current demand. Nevertheless, both approaches neglect the fact that the travelling patterns may change drastically once AVs are introduced, encouraging the population to participate in more leisure, non-mandatory activities, including the mobility impaired.

An assumption that the travel demand will not change was also made by studies trying to assess the future vehicle ownership. Zhang et al. (2018) proposed a model that analysed the current travelling patterns of household to see if reduced number of AVs could satisfy the demand by relocating the vehicle between the household members. Nevertheless, the proposed approach proposed ignored the possibility of development of alternative business models and a shift in vehicle ownership towards sharing economy, a factor considered by Lavieri et al. (2017) who developed a multinomial probit kernel model based on a survey data to assess the future vehicle ownership vs. sharing preferences in the USA.

Researchers that chose to look beyond the TBM or ABM methodologies also focused on assessing he future shifts in parking habits caused by vehicle automation. The studies followed an assumption that users would choose the most cost-effective parking strategy. The costs were modelled as operational driving costs (distance based) and an assumed parking fee (Millard-Ball, 2019; Zhang et al., 2019). Moreover, Zhang et al. (2019) tried to analyse the changes in daily activity timings caused by the fact that AV can drop off its user in front of the activity location, and no extra time is needed for egress or looking for a parking spot. Nevertheless, the adopted cost minimising approach, ignores entirely the personal preferences for parking, as users might prefer to make the vehicle available to other household members or otherwise would prefer it to keep it parked nearby because of environmental concerns or other factors.

2.1.4 Impact of NMS on traffic and related externalities

Regional traffic implications

Reviewed studies tried to assess the impact of NMS on urban congestion, which is a major transport negative externality in numerous urban areas. The researchers assessed that dynamic ridesharing could lower traffic volumes during peak hours by more than 20% (Coulombel et al., 2019; Yin et al., 2018), whereas deployment of AVs could result in an increase in congestion of up to 28% (Basu et al., 2018; Oh et al., 2020). Furthermore, due to the variety of assumptions and selective behaviour change incorporation, the results tend to contradict one another. For instance, Dias et al. (2020a) predicted 2% increase in average speeds, while Levin and Boyles (2015) argued that the average speeds would in fact decrease. Chen and Kockelman (2016) stated that increase in Vehicle Hours Travelled (VHT) is expected in networks with high transit usage and a decrease in networks with high private vehicle usage. Nevertheless, despite congestion implications, the cost and VOT reduction of travelling would result in higher accessibility levels.

Number of trips could also be used as a proxy for congestion implications of AV deployment, but the results are found to be similarly contradictory suggesting 46% decrease (Heilig et al., 2017), stability (Azevedo et al., 2016) or 2.7% increase. Those differences are a result of distinctive assumptions in regard to the future AVs adoption strategies and levels as well as a selective and various behaviour changes implementation. For instance, Heilig et al. have assumed that the cost of the SAV would be 70% lower than a passenger vehicle, while Azevedo et al. opted for a 40% reduction compared to a taxi. Low cost of SAV service assumed by Heilig could therefore, result in numerous agents to opt out of public transport or walking towards SAV, which in turn results in higher congestion.

Analysts, who tried to assess the demand induction caused by accessibility gains for mobility impaired, agree that the AV deployment will result in increased number of trips. With Truong et al. (2017) expecting 4.14% increase in number of trips caused by higher activity of the elderly, whereas Harper et al. (2016) predict 9% non-drivers could increase VMT by 9% while elderly drivers and those with medical conditions could increase VMT by 2.2% and 2.6% respectively.

Most often, the estimation of regional traffic implications of introduction of NMS is reflected through an analysis of VMT. The analysed studies state that ridesharing could decrease VMT by

19% (Rodier et al., 2016) Papers that study the impact of AVs on VMT have contradictory results. Martinez and Viegas (2017) state that if private cars, buses, and taxis were replaced by SAVs, with the possibility of ridesharing, VMT could decrease by 30%. Whereas, other studies that incorporate additional behavioural shifts implicate that VMT would increase by 3-20% (Childress et al., 2015; Dias et al., 2020; Vyas et al., 2019) with two studies indicating a 60% rise (Wadud et al., 2016), also due to repositioning and empty rides of SAVs (Hörl et al., 2016). Basu et al. (2018) tried to analyse how the VMT of SAV services is distributed coming to a conclusion that 60% of total VMT is spent while travelling with a passenger, 35% while going for pick-up or parking, and 5% for empty vehicle cruising. Visibly, the VMT is higher in the studies that considered numerous behavioural changes and assumed a lower VOT for SAVs (Table 2.5), resulting in a higher uptake of a service.

Nevertheless, the findings of all those studies heavily depend on the extent to which behavioural changes were implemented, thus making their results incomparable and partial.

Regional policy implications

Effective policies towards new solutions could alter the behaviour of individuals, serving the vision of policymakers. Therefore, a number of reviewed studies have also assessed various policy measures aimed at transport management and VMT reduction. Vyas et al. (2019) predict that increasing parking costs could result in as high as 15% increase in empty AV trips. Bischoff et al. (2016) also studied the implications of parking policies predicting that with 10 and 20% AVs penetration the average time needed to find a parking spot decrease by 5 to 15% if AVs park on regular spots, 9% to 16% if AVs use garage and 6 and 20% if the AVs are cruising. Parking strategies were also assessed by Millard-Ball (2019) who estimates that free on-street parking with repositioning is preferred by 13% of users, typically for long stays, returning home is adopted by 8% of users, mainly by individuals who live close to the centre and 40% of users would adopt cruising which is the cheapest option.

Oh et al. (2020) tried to assess the impact of a different policy measure in presence of SAVs service introduction – capping the vehicle population, which resulted in a 4% decrease in VMT. The regional policy driven results did not only focus on AVs and SAVs deployment, as Balac et al. (2015) claim that carsharing is used three times more often provided one-way trips are allowed.

User preferences

In terms of user preferences, reviewed studies most often focus on the modal shifts. Introduction of AVs and SAVs could have the largest impact on the change of modal preferences, with studies predicting that around 80% of public transport trips could be replaced by SAV (Azevedo et al., 2016; Hörl et al., 2016) and more than 60% by AVs (Levin and Boyles, 2015). Oh et al. (2020) suggest a more conservative number claiming that 24.8% of public transport users, and 75% of taxi users would opt for SAVs in the future. Basu et al. (2018) second the claim stating that taxi users would benefit from lower cost of SAV services. Certain reviewed studies also point to the decrease in walking, claiming that 57% of walking trips could be replaced by SAVs (Hörl et al., 2016). Nevertheless, those results could vary according to the length of the trip, as some researchers predict that even with SAV services widely available walking and cycling could be the preferred mode on short trips under 2 km (Heilig et al., 2017). The variety of the resulted impact on the user preferences is a result of various VOT, cost and behavioural shifts assumptions, with studies that assume lower monetary costs and higher VOT reduction, obtaining higher SAV market uptake.

It would seem that unrestricted introduction of SAVs services could lead to a significant cannibalization of public transport. Nevertheless, reviewed studies also point at the reduction of private car usage with Chen and Kockelman (2016) claiming that 90% of SAV trips were previously handled by private cars, and Oh et al. (2020) identifying that 20.2% SAV users previously chose their private cars. The difference could be caused by varied assumption of the cost of SAV used by Chen and Kockelman (2016), which made the SAV trips more accessible to all income groups basing the price on agents' income with simultaneous decrease in VOT spent in the SAV. Moreover, SAVs do not necessarily have to replace the public transport services, but could rather complement them and serve as first and last mile support, as proven by Wen et al. (2018), who found that SAVs with public transport connection could replace 43% of park and ride trips and 10% of car trips.

Introduction of AVs and SAVs will also highly impact the vehicle ownership preferences, with claims that younger and high educated individuals, living in urban areas are more inclined to own AV or use SAV services (Lavieri et al., 2017). Moreover, if the current demand was not subject to changes, automation of vehicles could result in 9.5% decrease in ownership, as one vehicle could be shared by couple of household members with self-relocation. Besides, with 15 minutes permissible delay the vehicle ownership declines even further (by 12.3%) (Zhang et al., 2018).

The results also unravel the usage preferences for carsharing. Suggesting that various types of carsharing are used for different purposes, free floating carsharing used more often by young users (Martínez et al., 2017) and commuters, and station based carsharing for leisure purposes (Ciari et al., 2014). Studies that predict modal shifts changes caused by carsharing indicate that 26%-30% of car users, 23% of bike users, 22%-32% of public transport users and 17% of walking trips could switch to carsharing (Ciari et al., 2014; Martínez et al., 2017). Moreover, the results of analysis of Heilig et al. (2018) prove that carsharing is used provided the optimisation of fleet size and operation.

Dynamic ridesharing preference results prove that a rise in user trust could be a major enabler for the adoption of technology, as users prefer to rideshare with someone form their social network circle (Wang et al., 2018).

NMS market potential and management

The studies that looked at the market potential of NMS focused on predicting the market penetration of SAVs services. Depending on the assumptions on VOT implications, model of costs and fares used in the study as well as fleet size, the results varied, estimating the SAV penetration anywhere from 5.8% to 43% (Chen and Kockelman, 2016; Hörl et al., 2016; Martinez and Viegas, 2017; Oh et al., 2020). Moreover, results of Oh et al. (2020) suggest that the achievable sharing rate of SAV rides could be significant with 65% of trips shared, which potentially could alleviate negative externalities of transport. The sharing rate, however, could be subject to location of SAV implementation with various preferences across the continents.

Moreover, a couple of reviewed studies looked at the fleet management and profitability. Wen et al. (2018) have found that economy of scale relation between the fleet size and demand for the service. Nevertheless, Chen and Kockelman (2016) who examined the relationship between the profitability for the fleet manager and the fare levels, claim that it is more appealing to businesses to target the high income earners, whose VOT is more substantial and would be willing to pay more for the ability to multitask during the commute. The study also proved that zone-dependent fares could be a tool used for rebalancing of the fleet, minimising the empty rides and possibly limiting the urban sprawl.

Environmental implications

Environmental implications of NMS introduction were not the major concern of the majority of the studies that included travel behaviour changes, as only two studies focused on AVs and two studies performed by fellows from the same research group focusing on dynamic ridesharing reported any environment related results. All those studies report a positive environmental effect of the innovation introduction and adoption, through CO_2 emission reduction. Nevertheless, Coulombel et al. (2019) claim that the reduction could be three times as high if not for the following behavioural implications of dynamic ridesharing introduction. While, Wadud et al. (2016) claim that, a shift from privately owned, privately used vehicles to SAVs might decrease energy, vehicle travel and emissions in several ways, either through more efficient driving and platooning or through pooling the rides in higher than 5 occupancy vehicles. As environmental impact of AVs is a major topic of this thesis a review of further studies that did not incorporate any travel behaviour changes is included hereunder.

Numerous researchers, who signalise the potential impact of this innovation on air, land, water, noise and light pollution (Fagnant and Kockelman, 2015; Silva et al., 2022). Researchers predict that the impact of SAVs on noise and light pollution would be generally positive due to vehicle electrification, lower congestion and ability to drive without lights respectively (Silva et al., 2022). The current literature predicts that the impact of SAVs on land, water and air would be somewhat compound and heavily dependent on the way the vehicles would be deployed. Namely, the studies predict that if the SAVs lead to acceptance of longer trips and possible relocation due to lower value of travel time, SAVs could trigger a further urban sprawl negatively impacting the land and water (Silva et al., 2022). Moreover, if the intake of SAVs would cause a substantial increase in vehicle kilometres travelled, the system emissions could also increase, erasing the positive effect of fleet electrification and shared mobility (Fagnant and Kockelman, 2015; Silva et al., 2022).

Due to the high importance of the topic there are already studies that tried to estimate the environmental effect of SAVs, through numerous methodologies such as: system dynamics and energy optimisation models based on previous studies results (Kopelias et al., 2020), as well as traffic simulations at all levels – macro, meta and micro (Silva et al., 2022), or even life cycle assessment (Gawron et al., 2019). As per the demand estimation methods of the traffic simulation studies, the majority of the studies used the agent-based approach (Berrada and Leurent, 2017; Jing et al., 2020), simulating hypothetical grid networks, slices of a real transport network or an entire network of a city (Jing et al., 2020; Silva et al., 2022).

In the reported results the researchers tended to gravitate towards estimating their demand for electricity and charging infrastructure. This is caused by a potentially disruptive change in the magnitude and daily patterns of electrical energy demand (Jones and Leibowicz, 2019). Since the focus of the studies laid often on the energy system performance, the demand for the SAVs was not heavily explored, with majority of the studies assuming either the market share of the trips handled with SAVs or its coverage of entire or doubled travel demand (Golbabaei et al., 2021; Jones and Leibowicz, 2019; Silva et al., 2022).

As per other reported environmental results the researchers have focused on estimating the CO_2 emissions, however the obtained results depend on the fleet size, pricing and energy mix of a simulated system (Jones and Leibowicz, 2019; Silva et al., 2022). Gawron et al. estimated that a fleet of SAVs in Austin, Texas could result in up to a 60% reduction in CO_2 emissions with respect to combustion-engine vehicles with a potentially higher decrease if the energy mix turns more renewable (Gawron et al., 2019). Further studies, claimed that the price for SAVs, fleet size and charging strategies could influence CO_2 emissions, with various results from Texas, Lisbon and New York estimating the reduction in emissions anywhere between 16.8% and 73% (Liu et al., 2017; Lokhandwala and Cai, 2018; Martinez and Viegas, 2017; Miao et al., 2019).

The extent to which substantial behaviour changes related to SAVs introduction will have an impact on CO_2 emissions (known as rebound effect) has not yet been assessed according to the knowledge of the authors. However in the light of findings provided by Coulombel et al. (Coulombel et al., 2019), who indicate the rates of the rebound effect of dynamic ridesharing, such type of study needs to be conducted, as our hopes for achieving more sustainable transportation with SAVs could be premature. Moreover, looking at the current environmental focus of numerous urban areas, there is arising growing need of impact assessment of SAVs deployment on transport environmental externalities such as energy consumption, CO_2 emissions and air quality.

2.2 Measuring impact of last-mile delivery solutions

Demand for logistic services in our cities is said to continue to increase, due to shift toward business to consumer (B2C) e-commerce, intensified by the current Covid-19 pandemic ('COVID-19 Impact on e-Commerce & Online Payments, Worldwide', 2020). As compared to the traditional offline market, e-commerce creates new issues for the companies as well as other stakeholders– the main one being the complexity of logistics, and in particular the last-mile delivery, aimed at delivering the products from the transport hub to the final customer (Allen *et al.*, 2018). The last mile is the least efficient leg of the delivery process, making it the most expensive for the companies, because of challenging target service levels, the small dimension of orders and the high level of dispersal of destinations (Macioszek, 2018). Apart from operational complexity, there are numerous environmental and social externalities related to last-mile delivery, Ranieri et al. (2018), point at air pollution, GHG emissions contributing to climate change, noise pollution, infrastructure wear and tear, congestion and road accidents among others. Therefore, it's of vital importance to thoroughly assess and estimate the impact that innovation in last-mile delivery could have on cities before their implementation.

2.2.1 Review of innovative last-mile solutions

The field of last mile delivery has been growing in importance along with the e-commerce. This subchapter provides a brief overview of innovative vehicles and concepts used for last-mile delivery.

Innovative vehicles

New engine technologies did not omit the last-mile delivery market. Innovative last-mile delivery vehicles could be BEVs or fuel-cell electric vehicles. Nevertheless, those innovations are not without their disadvantages such as lack of proper charging or refuelling infrastructure and a limited driving range. Moreover, EVs could still take a lot of precious space in the city and induce traffic. Therefore, a selection of Electric L-category Vehicles (EL-Vs), such as mopeds and motorbikes, as well as quad, tricycles and other small vehicles with three or four wheels were introduced on the market. Those vehicles are agile, with low impact on the city, need less space than regular vehicles and could be useful for delivering small parcels. Within the category of bicycles and tricycles, cargo bikes have been developed in recent years (Ranieri et al., 2018b). EL-Vs, smaller and lighter than traditional means, are very useful to achieve these goals because they reduce delivery time with no lost parking time required, fuel consumption, air and noise emissions.

Automated delivery

Derived from the military sector, the autonomous and unmanned systems are divided into Unmanned Aircraft Vehicles, also called drones, and land unnamed vehicles, called droids.

Transport and delivery companies have tested drones to deliver parcels: DHL with PaketKopter, Amazon with Amazon PrimeAir, Google with Project Wing and recently GeoPoste with GeoDrone. Moreover, new start-ups such as Starship or Yape have started to test out innovative automated droids moving on land (Shaheen and Cohen, 2020).

Reception points

The use of proximity stations or proximity points is an innovative strategy to improve the last mile delivery efficiency, particularly to distribute small- and medium-sized goods. This approach is based on the use of a depot station where goods can be stored when the customers are not at home until they can pick them up, thus avoiding the risk of unsuccessful delivery.

2.2.2 Methodologies used for last-mile impact assessment

With last mile delivery gaining significance, researchers have turned their interest towards its broad impacts. A literature review conducted by Kiba-Janiak et al. (2021) suggests that, before the popularization of e-commerce in 2016, a limited number of studies focused on optimising traditional last-mile solutions, whereas, after 2016 and the establishment of the e-commerce industry, a steeply growing number of academics focused on introduction and analysis of innovation in last mile delivery solutions. A further study connecting external factors impact on e-commerce and following environmental implications was proposed by Cheba et al. (2021). The authors found a link between internet and mobile access, macroeconomic conditions and social situation and the degree to which shopping is made online, confirming the complexity of future freight demand.

As new mobility solutions have been proposed, studies to assess their potential impacts have also started to appear. Literature proposes a variety of tools and methods for impact assessment, starting with Life Cycle Assessments (LCA) and environmental impact assessment, going through diverse frameworks proposed by numerous researchers (Ramani et al., 2011; Sala et al., 2015; Yigitcanlar and Dur, 2010) and ending with system dynamics and MCDA models.

For instance, in the field of last mile delivery, De Mello Banderia et al. (2019) have developed a framework that allowed a comparison of diesel LCVs, eLCVs and an electric tricycle in terms of social, environmental, and economic impacts. Giordano et al. (2018) followed a LCA method to compare diesel LCVs against battery electric vehicles. The two studies analysed total capital and operational costs as well as GHG emissions. Moreover, Giordano et al. also considered air quality and De Mello Banderia heart rate of the postman.

Extended MCDA analysis for delivery using mobile depots complemented by cargo bicycles was performed by Verlinde et al. measuring the economic, societal, environmental and transport impact (2014). Economic (capital and operational costs) and environmental (carbon monoxide, nitrogen oxides, non-methane hydrocarbons, particulate matter, and GHG emissions) impact assessment of mobile depots was also a topic of a case study performed in Buenos Aires (Marujo et al., 2018). MCDA was conducted by Navarro et al. (2016) while assessing the alternative urban freight system, that relies on cargo micro-distribution and electric tricycles in Barcelona and Valencia. The authors have focused on economic (capital and operational costs), environmental (PM, SO_2.NOx, VOC, CO and GHG emissions), transport energy (the fuel consumption and energy consumption) and operation (vehicles used, shipments, vehicles km, shipments/km, weight, tour-driving time) dimensions.

Impact assessment of another type of bicycle, namely a cycle rickshaw trolley, was performed by Sarma Sadhu et al. (2014). The authors have conducted a survey with drivers to assess the impact on environment (CO, CH_4, NO_X, PM and GHG emissions), fuel savings, traffic congestion and wellbeing of rickshaw drivers (safety, employment and psychological impact).

For what concerns automated freight innovations, to the best of the authors' knowledge, there is still only a limited number of studies due to the limited information concerning the capabilities and the characteristics of these new systems. Among the first attempts to study the impact of new mobility solutions, Chiang et al. (2019) have performed a green vehicle routing problem (GVRP) study for drones supported by internal combustion engine delivery vehicles, focusing on costs and sustainability implications. The authors opted for a comparison of GHG emissions and variable costs of delivery for business as usual, delivery using the drones and combination of vehicles. Moreover, Stolaroff et al. (2018) have estimated the energy consumption and total life cycle emissions of parcel delivery with drones, based on assumed warehouse development according to the current battery ranges of the drones. As for the delivery droids, Jennings and Figlozzi, tried to estimate their impact on freight efficiency (2019) as well as total energy consumption and emissions (2020).

2.2.2 Impact of last-mile delivery services

The outcomes of the previously reviewed studies, suggest that the BEVs or hybrid vehicles could both bring the costs down and the emissions (by as much as 30%). (de Mello Bandeira et al., 2019; Giordano et al., 2018). The results suggest that a monetised value of saved emissions of CO_2 emissions and, more significantly, NOx, PM2.5 and PM10 would exceed the costs of purchasing a new LCV. Which means that governments might be willing to pay enough, through incentives and taxation, to offset current cost differences between diesel and BEV technologies.

As per the results for the EL-Vs, the studies indicate that their impact could be majorly positive. The analysis of Marujo et al. (2018) points out that the GHG emissions and local air quality pollutants can be significantly cut by the use of cargo tricycles and mobile depots in the last mile delivery (−52% of CO2; −19% of CO; −58% of NOx; −20% of NMHC and −49% of PM emissions respectively). In the study the researchers have showed that in the case of Rio de Janeiro 11 out of the 15 considered neighbourhoods the cargo bike yields favourable local delivery cost per route. While, a study performed on the impact of cargo tricycles in Europe, by Navarro et al. (2016), showed that this last mile delivery method could lead to almost 5000 litters of fuel and 1.9 Tn of GHG emissions saved per annum. Navarro et al. also repots a high social acceptance for the last-mile tricycles, favourable impact on noise nuisance and a lower space occupancy. Finally, the study focusing on rickshaw last-mile deliveries in Delhi yielded positive results for the environment and considerable fuel savings due to an optimised routing available to smaller vehicles (Sadhu et al., 2014). Moreover, deliveries performed by rickshaws lead to a positive impact on safety and on access to employment.

The results of studies focused on drones show that as the number of customers increases, the number of vehicles required, and the carbon emissions also increase. Nevertheless, a 20% drop in emissions could be achieved by opting to use drones rather than LCVs (Chiang et al., 2019). Similar results were obtained by Stolaroff et al. (2018), who estimated the total life cycle emissions of using a small or a large drone compared to Diesel, Natural gas and Electric LCVs in the US. The results show that a small drone can lower the emissions by half as compared to an electric LCV, while the total lifecycle emissions of a largo drone could even exceed that of a delivery truck due to high consumption of warehouse electricity. Moreover, the authors claim that the total energy and emissions used to deliver packages up to the start of each pathway are assumed to be similar for either ground delivery or drone delivery.

Lastly, there are few studies concerning the environmental impact of last-mile delivery with automated droids. However the up-to-date studies suggest that the adoption of sidewalk droids may not be as effective as the adoption of larger road frequenting droids, when it comes to energy consumption, emissions, and parking utilization when service areas are located far from the depot (Figliozzi and Jennings, 2020). In addition, the reduction of on-road travel when deploying sidewalk droids comes at the expense of additional travel on sidewalks. This creates new externalities and potential issues related to pedestrian safety and sidewalk congestion.

2.3 Identified gaps in literature

This subchapter provides an overview of identified literature gaps, which will be addressed as the scope of this thesis. Additionally, each of the identified literature gaps is connected to the research objectives listed in subchapter 1.4.

2.3.1 *User-centred new mobility solutions*

- The extent to which substantial behaviour changes related to SAVs introduction will have an impact on CO_2 emissions (known as rebound effect) has not yet been assessed according to the knowledge of the authors. Research conducted by Coulombel et al. (2019) suggests that rebound effects caused by behavioural shifts could lower the benefits of innovation deployment to one third of its potential. In the light of current environmental focus of numerous urban areas, there is an arising need of impact assessment of NMS deployment on transport environmental externalities such as energy consumption, CO_2 emission, or air quality. Moreover, looking at the current environmental focus of numerous urban areas, there is arising growing need of impact assessment of SAVs deployment on transport environmental externalities such as energy consumption, CO_2 emissions and air quality. [O2], [O3]

- An understanding of how each identified and studied behaviour change, caused by deployment of AVs and SAVs, contributes to environmental factors could be of utmost importance for regional and national policymakers aiming at achieving greener and more sustainable regions, but has been up to date omitted by the researchers investigating the impact of SAVs. [O1], [O2]

- The behaviour changes linked to the deployment of NMS are often modelled as a fraction of demand. The behaviour changes linked to SAVs are most often implemented in scenario-based analysis that follows assumptions on future travel costs and decrease in VOT linked to the possibility to multitask in the vehicle. The said assumptions are changing the utilities of new options and therefore, the behaviour of modelled subjects that seek utility maximisation. Nevertheless, the used utility functions that consist of assumed VOT and costs often omit important individual traits, lifestyle choices and personal preferences which could heavily impact future decisions about NMS usage. Ideally, each step of the model (each discrete choice model) could consider socioeconomic attributes as well as user preferences to better mimic the individual, plausible human behaviour, contributing to a more adequate representation of the entire demand estimation. [O2]

- The previous studies did not provide any empirical evidence on the preferences of parking in the future, once new parking strategies, enabled by vehicle automation, emerge. Previous literature considered only the cost-minimising approach, ignoring entirely the personal preferences for parking. Moreover, no previous work has engaged with citizens to understand possible parking preferences hitherto. Such studies should be performed to understand how transport policies could be used to prevent negative implications of unsustainable parking of AVs. [O4], [O5]

2.3.2 Last-mile delivery solutions

- For what concerns automated freight innovations, to the best of the authors' knowledge, there is still only a limited number of studies due to the limited information concerning the capabilities and the characteristics of these new systems. Moreover, according to the knowledge of the authors, previously there were no sustainability assessment frameworks altered for last-mile delivery, that would incorporate all three sustainability pillars along an operational objective. Such framework could be insightful for city authorities while designing the future last-mile delivery strategy for their region. [O6]
- As for the delivery droids, Jennings and Figlozzi, tried to estimate their impact on freight efficiency (2019) as well as total energy consumption and emissions (2020). Nevertheless, none of the studies focused on a full operational and sustainability assessment of delivery droid against other popular last-mile delivery systems, which is the aim of this study. [O7]

3. INVESTIGATING THE ENVIRONMENTAL IMPACT OF SHARED AUTONOMOUS VEHICLES

The deployment of AVs is said to drastically change our mobility patterns and impact the everyday life in cities. Hence, it is crucial for policymakers and regional governors to predict how individuals could behave once this mobility option becomes available. The first step towards that prediction is the understanding of plausible behavioural changes implied by AVs. Nevertheless, transport innovation does not necessarily lead to lower negative externalities, either environmental or societal. Therefore, the second step is the comprehension of how the identified behavioural changes could impact the area in which AVs are deployed. This chapter aims to investigate in which way and to what extent the behavioural shifts may amplify or mitigate the environmental benefits of SAVs. Regarding the expected benefits of SAVs, a careful assessment of CO_2 emissions and air pollution is considered, as per the urgency to reduce the impact we have on our planet.

The chapter is structured in the following manner: the next section explains the methodology used to assess the environmental rebound effect of each behavioural shift. Section 3.2 depicts the experimental design and the analysed scenarios. The results of the study are presented in the following section. Finally, policy recommendations and chapter summary are described in sections 3.4 and 3.5 respectively.

3.1 METHODOLOGY

As previously mentioned, assessment of travel behaviour changes related to new mobility services is often made using agent-based models. These models are used for precision in spatial and temporal representation of the supply side, a key for a faithful representation of shared and innovative services. The demand side of the ABM, more specifically an activity-based model, allows to represent decisions of individuals based on their socioeconomic profile. By doing so, agent-based models are used to capture short and medium effects of transport policies. Nevertheless, to be able to simulate decisions of a population one must first understand and represent the assessed population. Therefore, for a proper estimation of the environmental rebound effect of SAVs, one requires an integration of the following tools:

- Long term models:
    - Population synthesis, which allows to create agents that represent the simulated population. In this study, the population synthesis was made using a deep generative modelling (Borysov et al., 2018).
    - Vehicle ownership and workplace location models obtained using discrete choice modelling.

- Activity-based demand estimation, that accounts for decision-making of agents at the individual levels (often in transport literature called activity-based model). An activity-based model was made using a demand part of a simulation platform – SimMobility (Adnan et al., 2015).
- SAVs operator, which accounts for fleet management, such as request to vehicle assignment and rebalancing of vehicles. SAVs fleet management was performed using the Aimsun plugin, which allows to connect vehicles to requests coupled with OR-Tools – an optimiser for fleet management (Perron, Laurent; Furnon, 2022).
- Traffic simulator, which translates the demand into a traffic simulation and allows to obtain the desired environmental impacts. A supply model of the considered network and traffic microsimulation was performed using Aimsun software (Aimsun, 2022).

Each of the briefly described tools and models are presented in more details in the following sections and their integration is represented on Figure 3.1 hereunder.

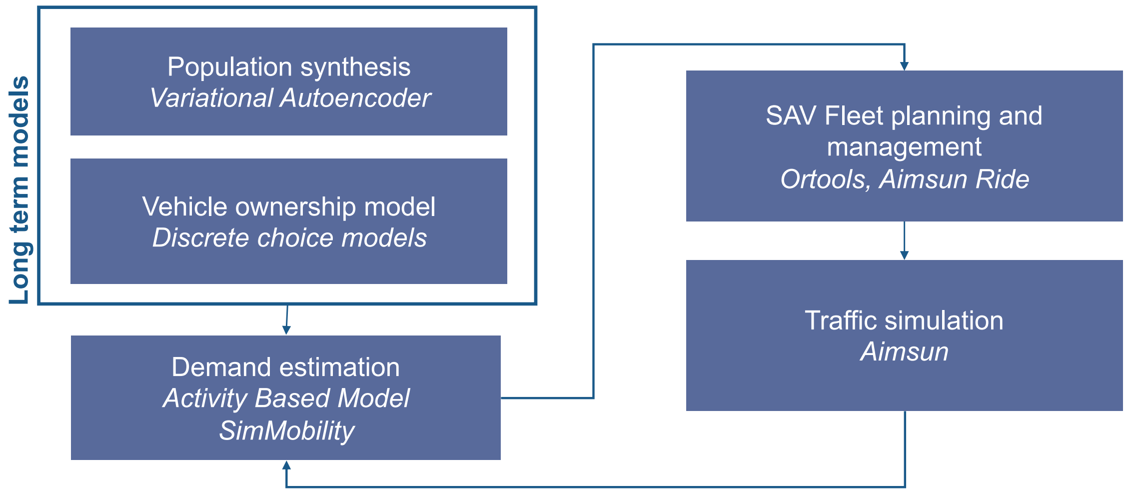

FIGURE 3.1 SIMULATION ENVIRONMENT

3.1.1 Demand

Long term models

Population synthesis was obtained using a deep generative modelling approach from machine learning based on a Variational Autoencoder (VAE) proposed by Borisov et al, which allows to represent the population with a higher number of modelled attributes. For further details on the process refer to (Borysov et al., 2018). The synthesised population attributes were: gender, age, employment status, education level, occupation, income, public transport subscription, driving license, zonal assignment and household assignment.

Parameters for the vehicle ownership model were estimated with MNL and mobility survey data. The choice set of the model was {0,1,2,3}. The estimated parameters for choice characteristics included: household size, age, and gender of the head of household, and household income. The probability of each of the choices was obtained with the MNL, while the final choice for the household was derived from a Monte Carlo random draw. Thereafter, the Monte Carlo random draw determined whether a given vehicle was an EV or combustion-engine vehicle. That assignment was made using a forecasted car fleet composition in Spain in 2040 (Amores et al., 2016; Sanchez and Planelles, 2018), for which existence of SAVs is often predicted (Haghighi et al., 2019; Litman, 2020a; Zhang and Wang, 2020).

Activity-based demand estimation

The activity-based demand estimation was employed in SimMobility - an open-source activity-based simulation platform (Adnan et al., 2015). In the study a fraction of SimMobility was used - a Pre-day simulator. The Pre-day module is an ABM, used to obtain daily activity schedules of the entire synthetic population, including the timing (arrival time and departure time) of each activity at a resolution of 30 min, the destination at zonal level and the travel mode for each tour (Oh et al., 2020). The detailed scheme of the Pre-day SimMobility model is presented on Figure 3.2 hereunder.

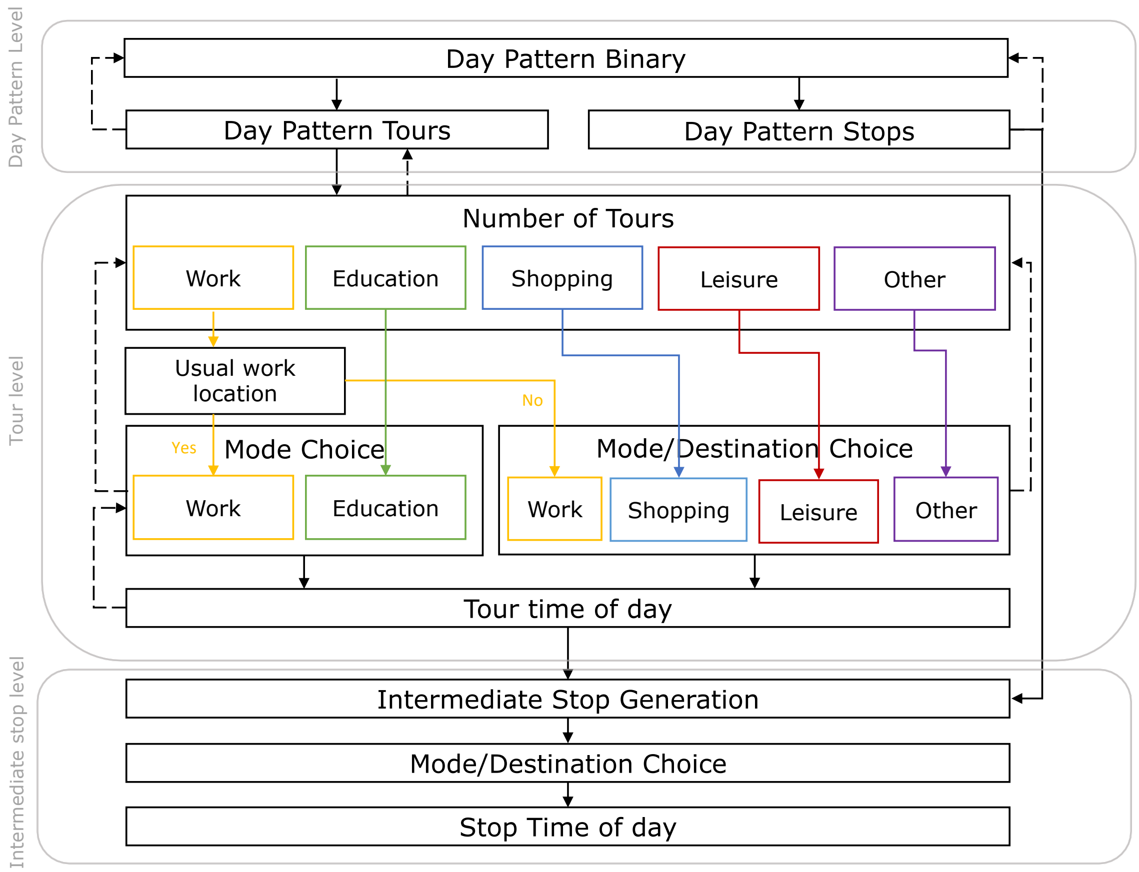

FIGURE 3.2 COMPONENTS OF THE PRE-DAY ACTIVITY-BASED MODEL IN SIMMOBILITY

The Pre-day ABM is a chain of hierarchical discrete choice models (MNL and NL) divided into three levels: the day-pattern level, the tour level, and the intermediate stop level. The discrete choice models allow to represent a singular choice of an individual between numerous alternatives (N), and therefore are often used in transport modelling (Ortúzar and Willumsen, 2011). The MNL is strongly linked with utility maximisation, theory and the probability (P) of an individual (i) chosing a given alternative (n) could be described as follows.

$$P_{in} = \frac{U_{in}}{\sum_{n=0}^{n=N} U_{in}}$$

While the utility (U) of chosing a given alternative is composed of a deterministic part – a vector of the explanatory variables as well the attributes of the alternative as the socioeconomic characteristics (X_{in}) of the individual – and of a stochastic component – an error term (ε) that accounts for all variables unknown or omitted by the modeler (Ortúzar and Willumsen, 2011):

$$U_{in} = \beta X_{in} + \varepsilon_{in}$$

Where β is the vector of parameters to be estimated.

The parameters of the utility functions for the chain of discrete choice models were obtained from the travel diaries using the Biogeme software (Bierlaire, 2020). Each utility function consisted of individual attributes as well as parameters tailored to the given model. The attributes used in the utility functions were: age, gender, main-activity type, occupation, household income, household size, household vehicle ownership, value of time, cost, alternative specific coefficients and logsums. Logsums are information from models that are executed later along the chain of models (marked with a dashed line on Figure 3.2). They are required in tour mode and mode-destination models and day pattern models and could represent the accessibility value in the utility choice models. The calibration of the demand estimation was made by changing the alternative specific constants to better represent the real traffic data in form of trip counts between the TAZs as well as results obtained from travel diaries. The three levels of the ABM are explained in more details hereunder.

The day pattern level

The day pattern level organizes tours and manages their sequence through the concept of day activity schedule. The day activity schedule is a pattern that defines the participation in activities as primary, and secondary. Primary activities are the mandatory tours (tours with a purpose of work or education) and secondary activities are intermediate stops within a particular tour (e.g., stopping for shopping coming back from work). Further executed models, in form of logsums, add detailed information about tours to the activity pattern such as sequence, timing, travel mode, destination of primary activity, and also the stops for secondary activities within tours.

The day pattern level includes three discrete choice models that predict occurrence of tours for considered purposes (work, education, shopping, leisure, and others) and availability of intermediate stops for various purposes. Those models are:

- **Binary model to predict if an individual travels or not**: A binary logit model that predicts if an individual will travel or not. The utility expression included alternative-specific constant and characteristics of the individual (occupation type, age, gender, household income, car ownership, motorcycle availability, logsums from the binary model for tour).
- **Model to predict the number of tours**: A MNL that predicts which types of tours will one engage in. The utility expression included alternative-specific constants, combination of constants, occupation type, gender, age, household size, household income, car ownership, availability of a motorcycle, constants for single tour, two tours and three tours, and logsums. The results are provided to tour level models to constrain the availability of each activity purpose.
- **Model to predict the exact number of stops:** A MNL that predicts number of stops that an individual makes during each tour she/he is engaged in. An individual can make either none, one or two stops during one tour. The utility expression included alternative-specific constants, combination of constants, occupation type, gender, age, household size, household income, car ownership, availability of a motorcycle, constants for single stop and three stops, and logsums. The results are provided to intermediate stop generation model to constrain the availability of each activity purpose.

The tour level

The tour level of the ABM model consists of further discrete choice models that predict the exact number of tours per type, destination, mode, and time of day (arrival time and departure time). These models provide detailed information for each predicted tour. Sequencing of tours is accomplished before modelling individual tours by assigning each of the tours predicted at day pattern level a priority number. The priority number is determined by the purpose of tour primary activity. The models within this level are:

- **Model for exact number of tours for each purpose**: logit or MNL that determine the number of tours of each activity purpose. For the education and work purpose there could be either one or two tours, for the remaining purposes there is also a possibility to engage into a third tour. The utility expressions included alternative-specific constants, occupation types, gender, age, household size, car ownership and logsums.
- **Usual/Unusual workplace:** binary logit model that determine whether an individual will work at her/his work location. The result of this model determines if it is necessary to

predicate work tour location. The utility expression included alternative-specific constant, occupation type, age, gender, and car ownership.

- **Mode choice models for work and education:** NL models used to determine the modal choice of an individual with an education or work at the usual location tour purpose. The available alternatives were: walking, car as a driver, car as a passenger, motorcycle, bus and SAVs in SAV based scenarios. The utility expression included alternative-specific constants, travel time divided into access and egress time, wait-time and in vehicle travel time, travel costs, occupation type, age, gender and household income.
- **Mode and destination choice models:** MNL models used to determine the modal and destination choice of an individual with a shopping, leisure, other or work at the unusual location tour purpose. The choice set is a result of a multiplication of available modes with the traffic analysis zones (TAZ). Variables included in the utility function could be divided in two categories, the first including the personal (gender, age, occupation type) and household demographic variables (car ownership) and the second including the destination and the mode to destination (travel cost, travel time divided into access and egress time, wait-time and in vehicle travel time, distance, alternative-specific constants). Purpose-specific variables derived from land-use characteristics are included in the model, as attractiveness of the zone.
- **Tour time of day:** A MNL used to determine jointly the arrival time and departure time for primary activity as a choice between combination of half hour blocks for arrival and destination time. The utility function consisted of trigonometric series alone as time-dependent constant and trigonometric series times dummy variables to reflect a time-dependence effect of that dummy variables. More could be found in (Ben-Akiva and Abou-Zeid, 2013). The dummy variables used in the models were: occupation type and gender.

The intermediate stop level

The intermediate stop level generates the stops within a previously determined tour. The models at the intermediate stop level predict the destination, travel mode and timing of the stops for the secondary activities with the following models:

- **Model for intermediate stop generation:** MNL that predicts if an individual will pursue an intermediate stop of each considered purposes or no intermediate stop at all. The utility expression included alternative specific constants, occupation type, gender, age and tour type dummies.
- **Mode and destination choice models for a stop:** MNL model used to determine the modal and destination choice of an individual with an intermediate stop. The model is analogous to the mode/destination models at the tour level. Variables included in the utility function

could be divided in two categories, the first including the personal (gender, age, occupation type) and household demographic variables (car ownership) and the second including the destination and the mode to destination (travel cost, travel time divided into access and egress time, wait-time and in vehicle travel time, distance, alternative-specific constants). Purpose-specific variables derived from land-use characteristics are included in the model, as attractiveness of the zone.

- **Model for intermediate stop time of day:** A MNL used to determine jointly either the arrival time or departure time for a stop depending on the leg of the tour. For stops in the first half-tour, available alternatives are bound by the time of arrival at home from the previous tour and departure time of current stop. For stops in the second half-tour, available alternatives are bounded by arrival time of the current stop and the end of day. The utility function consisted of trigonometric series alone as time-dependent constant and trigonometric series times dummy variables to reflect a time-dependence effect of that dummy variables. The dummy variables used in the models were: occupation type and gender.

3.1.2 Supply

Traffic simulator

The Pre-day simulation, as described previously, generated activity schedules for each individual in the population. The information was then processed using a Python script to represent the trip-chains of individuals in OD matrixes accepted as a demand input by the used traffic simulator – Aimsun Next. The traffic in Aimsun was simulated using microscopic traffic simulation with static path assignment combined with dynamic path reassignment for a random 30% of all vehicles. The supply model apart from simulating car and SAV trips also includes the public transportation simulation of the up-to-date bus schedule. The previously estimated behavioural parameters for the city of Santander were used for cars and buses. The SAVs were modelled adjusting the reaction times, car following model, lane changing and gap acceptance behavioural models to better fit the specifics of the autonomous vehicle and available literature (Nickkar and Lee, 2019) and using the Cooperative Adaptive Cruise Control module readily available in Aimsun.

Usage of microscopic traffic simulation in Aimsun allowed to obtain the inputs required to estimate the environmental rebound effect, by using the Battery Consumption Model and Panis et al. pollutant emission model (Int Panis et al., 2006), which are both integrated with the microscopic simulation. Nevertheless, because the microscopic traffic simulation was computationally and time-intensive, the authors decided to limit the simulation time to one day, assuming that at the end of the day the SAV fleet would return to its beginning state.

SAVs operator

The task of the SAVs operator is fleet management, which allows to match the ride requests to vehicles. This assignment was performed using capacitated vehicle routing problem with time windows (CVRPTW) optimised by Google OR-tools (Perron, Laurent; Furnon, 2022). The output that the fleet operator provides was optimised to handle all requests while minimising the total distance of the fleet. The fleet operator handles the requests for SAVs of singular passengers. The request includes the intended pick-up and drop-off locations, pick-up and drop-off time windows and number of passengers requesting the ride. The SAVs were assumed to resemble a regular car, with 5 pax capacity. Further assumptions on the requests concerned the maximum waiting time – set to 5 minutes and boarding time – set to 1 minute.

The fleet management was integrated with the traffic simulation via the Aimsun plug-in through a TCP/IP interface. The key features of the interface involved passing the information between the traffic simulator and the fleet operator. The requests were treated dynamically, i.e., one-by-one in the order they appeared from the SAVs operator. The Aimsun platform then simulated the execution of the requests given to the operator, updated the status of all vehicles in the fleet and performed a simulation against the historical traffic conditions.

3.2.3 Demand-supply integration

Demand–supply interactions are modelled thorough a Python controlling algorithm which triggers the SimMobility Pre-day model and Aimsun traffic simulation as subprocesses. Moreover, it provides necessary data processing to adjust the inputs to the required format for each used tool. The interaction of demand and supply allowed to achieve convergence of the study, based on the widely used relative gap convergence measure with a capped maximum simulations number at 100 (Ortúzar and Willumsen, 2011).

3.2 Scenarios and experimental design

This section provides further details concerning the characteristics of the study's location, the simulation scenarios of interest and the used performance measures. The research focus is to estimate the environmental impacts of SAVs in a mid-sized European city – Santander. To achieve this first a population synthesis along a calibrated demand and supply model for Santander are needed – to establish a current base case, a business-as-usual scenario. Further information about obtaining the business-as-usual scenario, analysed scenarios and studied key performance indicators are provided in this section.

3.2.1 Santander model

The analysis has used as case study the city of Santander in Spain (population 172 957) (Instituto Nacional de Estadistica, 2022) as it offered an optimal compromise between complexity of transport dynamics and overall size of the transport network to be simulated via microsimulation. In addition, Santander's municipality and the transport agency have made available detailed information about travel choices allowing a reliable estimation of the users' preferences. Used data included a transport diary survey of Santander population from 2013 (sample size 1 384) and the total population counts per each transport zone. Both data sources were used to obtain the synthesised population of Santander using the deep generative modelling approach (Section 3.1.1). The transport diary survey was used to obtain the required parameters for the demand estimation in SimMobility, and the estimated model was calibrated and validated using the travel diaries dataset.

The comparison of simulated and trip diaries observed results concerning number of tours, aggregate trip mode shares and trips by time of day are presented hereunder on Figure 3.3. The results indicate that the base case model well represents the behaviour of Santander's population.

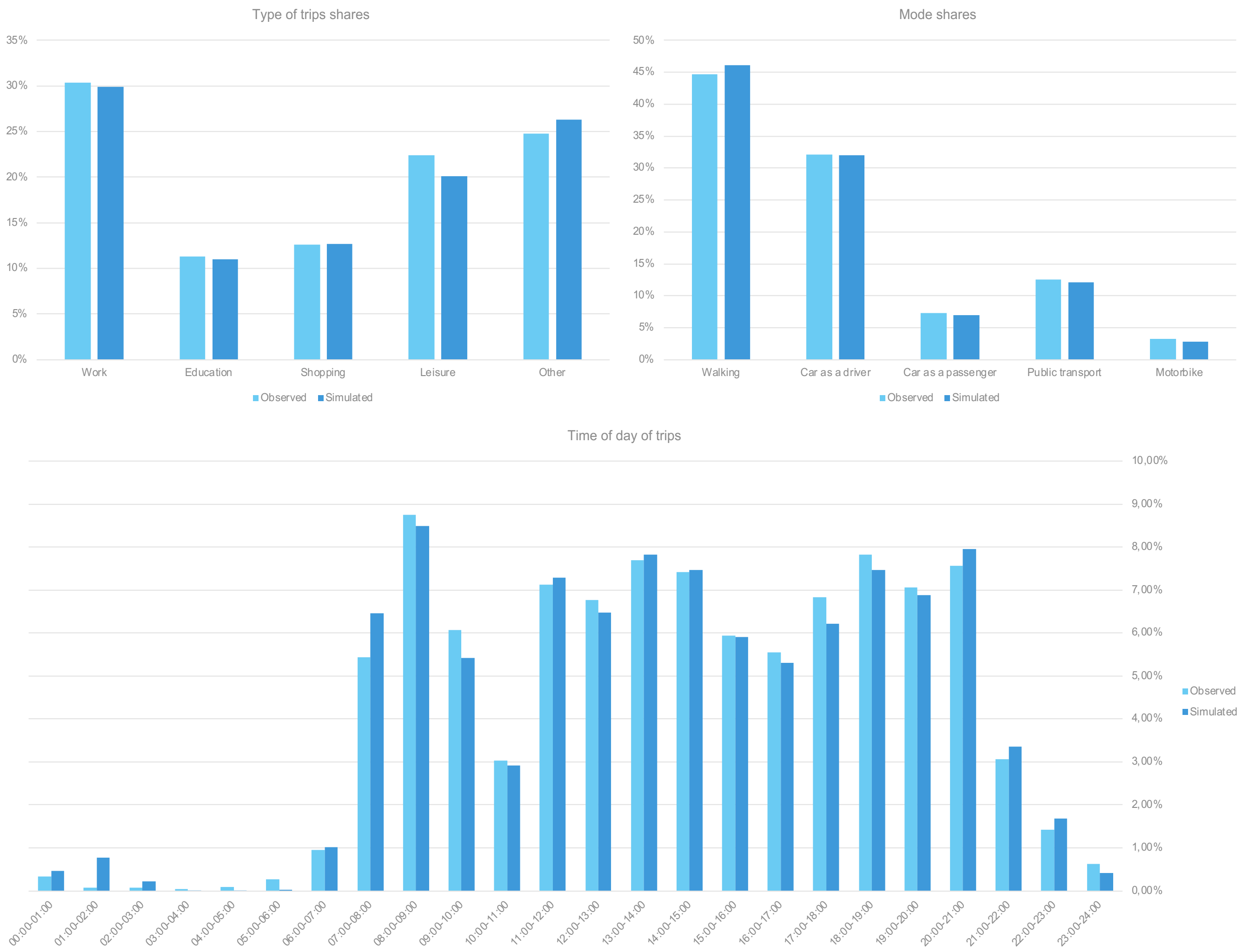

FIGURE 3.3 Comparison of observed and simulated base case demand results

The supply side of the model - Aimsun microsimulation model was set up to include the Santander's network copy. The supply model of Santander was developed and calibrated by the SUM Lab of University of Cantabria and is often used for the development of local transport policies along with the regional authorities. The used network included behavioural parameters for car trips as well as public transportation (bus) routes and schedules. The network of Santander is not considered to observe heavy traffic flows, therefore the impact of SAVs on traffic is not investigated. An overview of the simulation network is given in Figure 3.4.

FIGURE 3.4 SANTANDER NETWORK

The characteristics of the transport network representation that covers the urban region of Santander city were: Size (km): 11.00 x 6.00, Number of TAZs (Centroids): 113 (12 769 OD pairs), Number of Detectors: 230, Number of sections: 4 106, Number of nodes: 1 454, Type of signal controllers: Fixed (Krishnakumari et al., 2017).

3.2.2 ANALYSED SCENARIOS

Introduction of SAVs in the model was made by creating a new alternative in the mode and mode/destination choice models. The SAVs were modelled like a private car, with omission of access and egress time and addition of wait time. The parameter of the value of time of the wait time was equal to that of the wait time for the bus. While, the cost of the vehicle was distance assumed at 0.3$ per mile (Litman, 2020b). Those changes allowed to obtain a scenario in which SAVs are available, but the behavioural changes caused by the decrease in VOT and subsequent ability to multitask are not triggered.

Travel behaviour changes

As previously mentioned, the ability to multi-task in the vehicle could heavily impact the VOT and accessibility and trigger behavioural changes. To estimate the extent to which those changes could impact the environment following scenarios were run:

- **Change in non-mandatory trips**: Scenario used to simulate the modal shifts and acceptance of longer trips for the non-mandatory trips. Changes in the model considered the VOT in mode/destination choice models for shopping, leisure, and other type of trips.

- **Change in mandatory trips**: Scenario used to simulate the modal shifts of the main, mandatory activity (work or education). Changes in the model considered the VOT in work and education mode choice models.
- **Induced non-mandatory trips:** Scenario used to simulate the increased number of non-mandatory trips, by changing the β parameter of the logsums in models that determine the number of shopping, other and leisure trips to 50%, 70% ad 90% of the base one.
- **All changes:** Scenario used to simulate the cumulative effect of all the behavioural changes, by implementing all changes mentioned above in the demand estimation models.

Value of time

The considered VOT is still not determined, as SAVs are not yet available. Therefore, to investigate plausible environmental rebound effect the VOT reduction is subject to scenario analysis: 50%, 70%, 90% of in vehicle value of travel time of a private car. The reader might argue that the in-vehicle travel time of a shared ride would not be significantly lower than that of a car. Nevertheless, the VOT will significantly depend on the design of the SAV, which could be divided into personal areas, securing comfort, privacy and satisfaction for its clients (Stevens et al., 2019). Moreover, the interior of the vehicle could be adjusted for the purpose of the trip or a user type, which would significantly lower the value of travel time, validating the assumption.

Fleet sizing

One of the crucial tasks of the SAVs operator is fleet planning, as the size of the fleet can heavily impact both the performance of the service and the demand for it. In this study, the fleet size for each scenario was determined using The Decision Support Tool developed under the European Project MOMENTUM, by the Centre for Research & Technology Hellas/Hellenic Institute of Transport (CERTH/HIT) (Union et al., 2020). The Decision Support Tool allowed to estimate an optimised fleet size, which could secure the desired characteristics of a service: a reasonable maximum waiting time of 5 minutes and capacity of 5 passengers. To fleet size and appropriate start locations for the fleet were obtained using the appropriately transformed activity schedule from SimMobility and a polygon area of the network. Nevertheless, the fleet-sizing was subject to scenario analysis as to better understand how the fleet-size could contribute to the environmental impacts of SAVs. The scenarios considered were: a fleet size large enough to secure a 100% demand coverage provided by the activity schedule of a given scenario and 50%, 25% and 10% of the fleet required to cover and entire demand.

3.3.3 Key performance indicators

Energy consumption

Energy consumption performance show the electricity consumed by the SAV electric fleet and the electricity consumed by the electric private vehicles. The data was obtained from battery consumption models integrated into the microsimulation in Aimsun.

CO_2 emissions

The CO_2 emissions, though linked to the electricity consumption, are presented as results of the environmental analysis, because of their high climate crisis impact. The CO_2 emissivity results were obtained from the microsimulation (according to the Panis model) for the privately owned combustion engine vehicles and the total electricity consumption of privately owned EVs and SAVs. Then on the total emissions of the system were calculated assuming the electricity grid emissivity for the year 2040. The emissivity data was taken from the Spanish national strategy for decarbonisation and The European Environment Agency predictions (Climate Analytics, 2021; Report to the Arctic Council by Spain, 2020; The European Environment Agency, 2022).

Air quality

Air quality results are presented as NO_X and PM2.5 emissions. The data was obtained analogically to the CO_2 system emissivity.

Mode shares and VKT

Lastly, mode shares and total system VKT are presented as part of the analysis, as they can easily illustrate which modes have the highest potential to be replaced by a SAV fleet. Information which could be crucial for regional and national policymakers.

3.3 Simulation results

The results showed that, without SAVs, the CO_2, the NO_X and the PM2.5 emissions would be significantly higher due to higher dependency on vehicles with more emissive combustion engines. Moreover, the results showcased that the introduction of SAVs based services would not significantly impact the congestion in a mid-sized congestion-free city in Europe, as represented by the lower daily flows and similar average speeds in all the run scenarios. The results in more details are presented in this section according to the key performance indicators.

3.3.1 Energy consumption

Electricity consumption is an important indicator, as urban transportation tends to rely more heavily on the electrical power, with the electrification of public transport, private vehicles, last-mile delivery and micromobility. The results of this study show that introduction of any kind of SAV fleet could significantly increase the electricity consumption as compared to a fleet of privately owned combustion engine and electricity fuelled vehicles. The electricity consumption, with no additional behaviour changes, increases electricity consumption to 193% of the business-as-usual scenario (6 918 kWh daily) if a 10% or 25% of fleet is introduced, 198% in case of 50% of the fleet and 218% if the whole fleet is introduced. This shows that before the SAV fleets are introduced a proper charging strategy is needed to make sure that the vehicles do not negatively adverse the stability of the electricity grid as well as regain their cost-effectiveness by consuming cheaper electricity in off-peak hours.

Understandably, the increase in electricity consumption caused by the triggered behavioural changes has a lesser impact on the electricity consumption in case of the lower assumed VOT (90%) and lower fleet sizes. Nevertheless, the electricity consumption is similar for the 10% and 25% of fleet, as the trips with private EVs and SAVs balance each other out. The further increase in electricity consumption caused by introduction of 50% of total estimated SAV fleet is not substantial - by 5 percentage points. This shows that while the introduction of SAV fleets will increase the electricity consumption, an adequate size of the fleet could help optimise the surplus in electricity demand.

As per the behavioural changes, the increase in electricity consumption caused by changes in mandatory trips is not substantial as it is only caused by modal shifts for work trips (2%-9% increase as compared to the base case with SAV introduced). Changes in non-mandatory trips cause a higher increase in electricity consumption (3%-13%) as they trigger not only a modal change but also could lead to accepting a further location. While the induction of non-mandatory trips leads to 10-16% of electrical energy consumption increase, as entirely new trips are introduced for individuals who would like to participate in more non-mandatory activities. The overall increase caused by the behavioural changes is significant, estimated at 18-25% as compared to the base case scenario. For instance, in the case of no market regulations, where 100% of SAV fleet is available, this increase would equal to 880 MWh on annual basis, considering only working days.

The total electricity consumption for each of the analysed scenarios is presented in more details on Figure 3.5 hereunder.

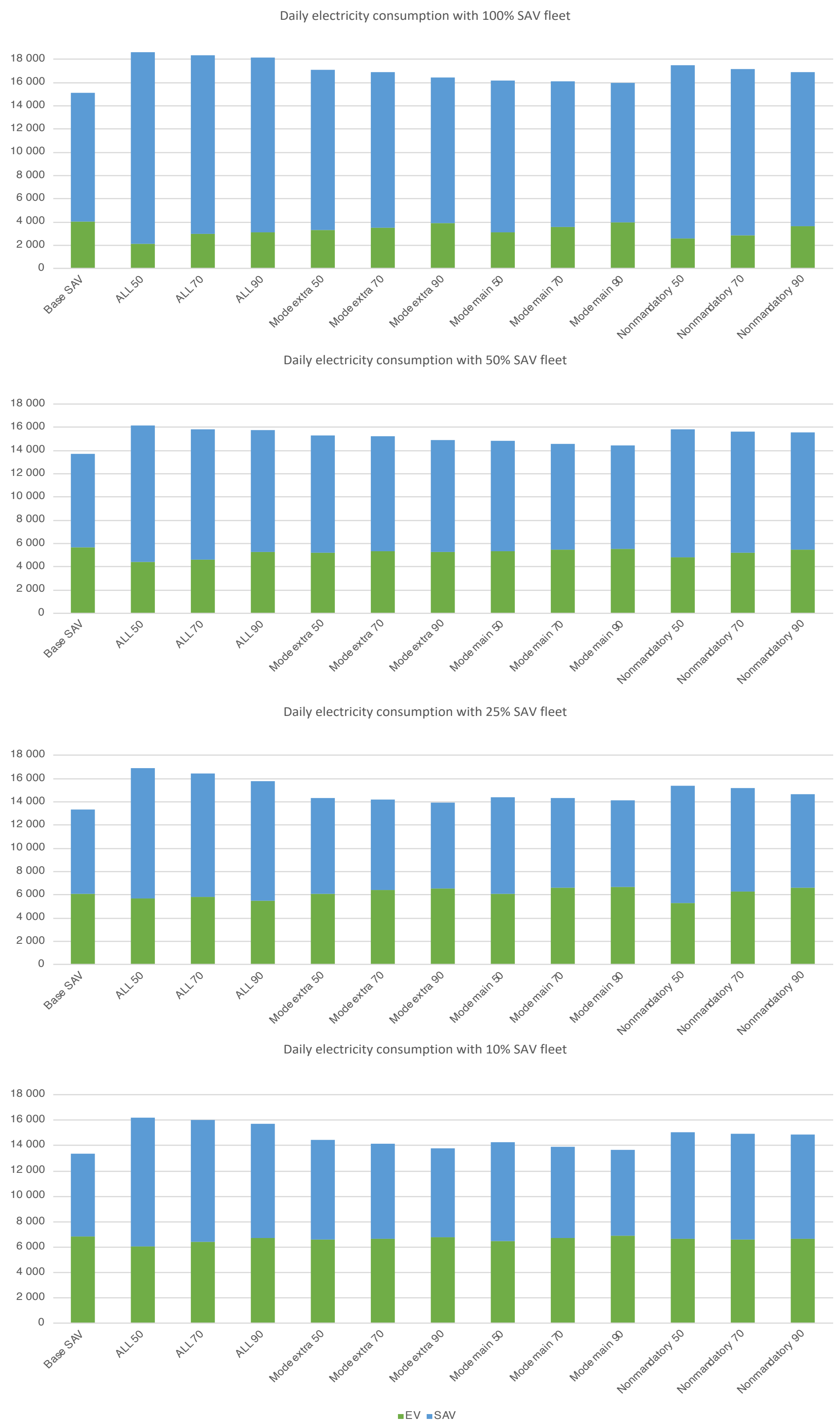

FIGURE 3.5 DAILY ELECTRICITY CONSUMPTION IN KWH FOR ANALYSED SCENARIOS

3.3.2 CO_2 EMISSIONS

The results of the base case scenario showed that indeed SAVs could have the potential to lower the environmental impact of the transportation system, with a potential to reduce the CO_2 emissions by 57% due to the electric motor and assumed targeted, highly renewable, energy mix in Spain for the year 2040. These results are in line with other performed case studies, which predict 16.8% to 87% drop in CO_2 emissions for various urban environments, powertrain and energy mix (Silva et al., 2022).

Nevertheless, the results obtained from the simulation showed that we can expect an environmental rebound effect as a consequence of SAVs deployment and the comfort and freedom those vehicles could offer. The lowest environmental change was caused by the modal change for main activity location trips. Nevertheless, the CO_2 emissions still increased by 7-27% as compared to the base scenarios, because of individuals switching to SAVs from more sustainable modes of transport, such as walking or public transport. The highest rebound effect from singular behavioural shift was caused by individuals opting to participate in more non-mandatory activities, which caused a 15%-36% rebound effect in the CO_2 emissions. If all the analysed behavioural shifts are considered (all) the CO_2 emissions are 18%-42% higher than those of a scenario in which the SAVs are introduced but do not trigger any behavioural changes (base SAV).

The rebound effect significantly reduces the positive environmental impact of the electric SAVs as compared to the scenarios in which all vehicles are privately owned (base no SAV). Moreover, the fleet size has an impact on the environmental rebound effect – with 50% of full fleet resulting in lower rebound effect as compared to the base scenario for the fleet. This is caused by a base of SAV clients large enough to support ridesharing, without triggering a larger modal shift from more sustainable modes. This entails that the SAVs system should be carefully designed and implemented by regional policy makers, to ensure that the final system is indeed environmentally sustainable. The CO_2 emissions for each of the analysed scenarios are presented in more details on Figure 3.6 hereunder.

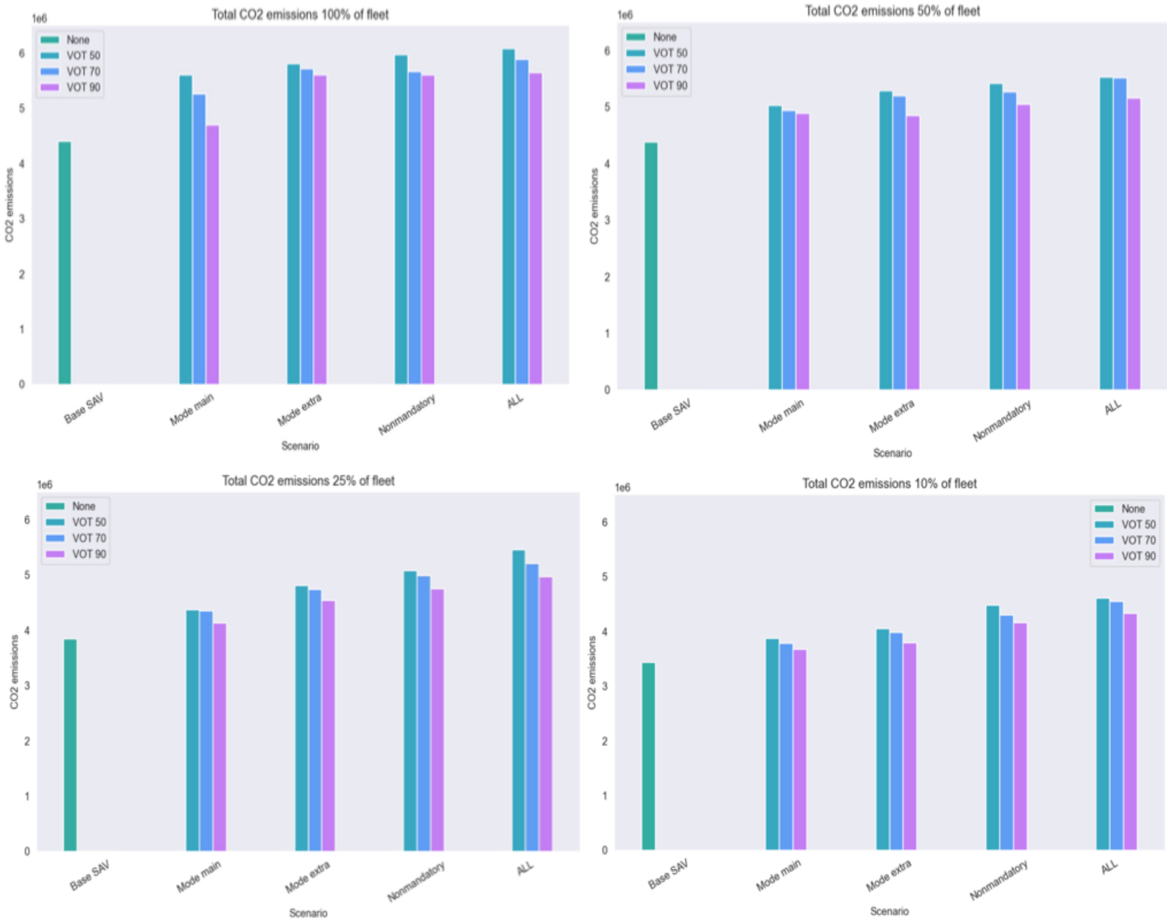

FIGURE 3.6 Daily CO2 emissions in grams for analysed scenarios

3.3.3 AIR QUALITY

The rebound effect of NO_x and PM emissions follows the previous patterns with higher VOTs resulting in higher rebound effect in absolute terms. However, in this case the scenarios with the bigger fleets result in lower emissions, as per low emissivity of the electrical grid. Nevertheless, again for the 50% of vehicles the increase in emissions is lower compared to the base case, as the SAV trips could be better optimised handling higher number of requests. The contribution of each behavioural change is also analogous to CO_2 emissions with NO_x emissions raising by 3% - 20% and PM by 2% - 15% because of changes in the main activity. Changes in the nonmandatory activities lead to 4% - 28% and 3% - 18% increase of NO_X and PM respectively, while inducing the number of non-mandatory trips results in 7% - 34% and 9 - 26% increase. All the changes combined show that the NO_X and PM emissions could increase by 12% - 49% and 13% - 36% respectively. Nevertheless, the changes could still be treated as sustainable, as even in the scenario with the biggest rebound effects the emissions do not surpass those of today.

The NO_x emissions for each of the analysed scenarios is presented in more details on Figure 3.7 hereunder, while the PM emissions are represented on Figure 3.8.

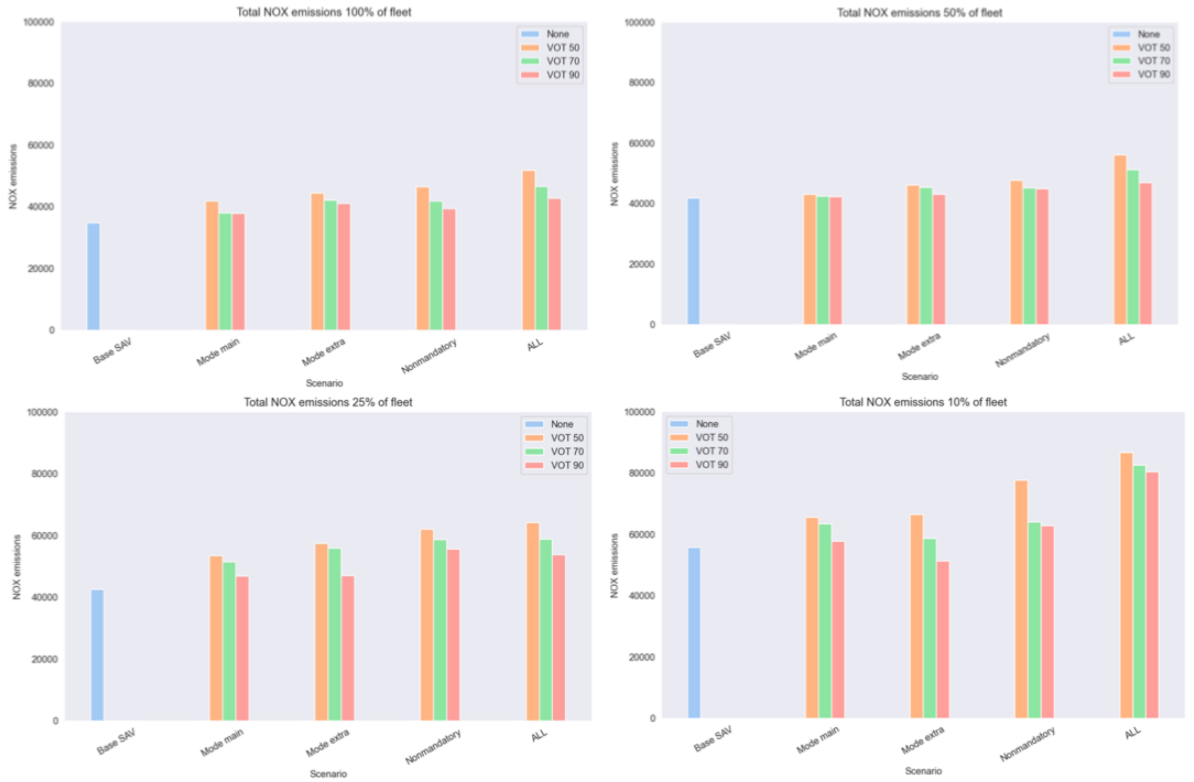

FIGURE 3.7 Daily NOx emissions in grams for analysed scenarios

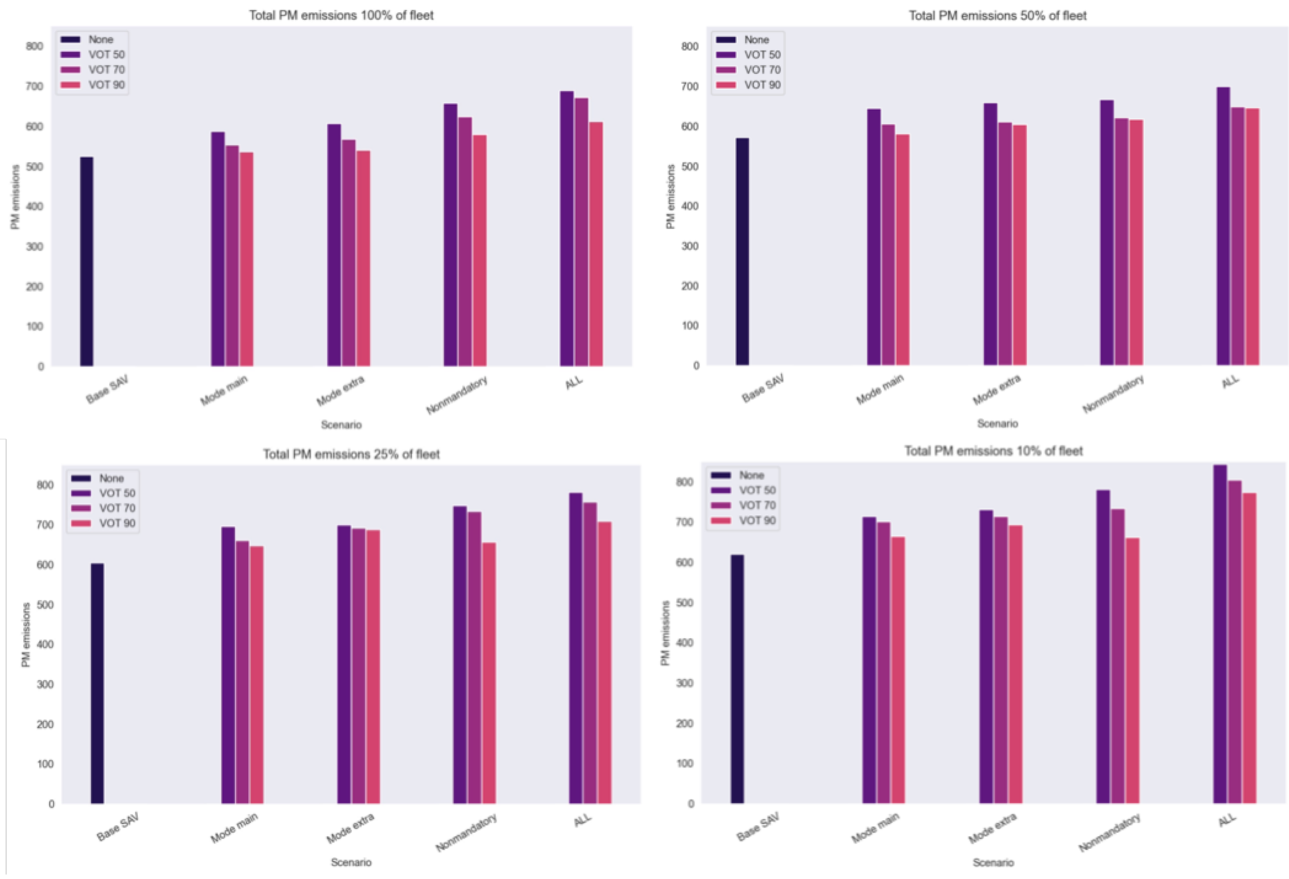

FIGURE 3.8 Daily PM emissions in grams for analysed scenarios

3.3.4 VKT AND MODE SHARES

The results of the analysis indicate that the introduction of the SAV fleet could lower the total VKT in the system under certain circumstances – firstly there should be no behavioural changes triggered by lowering the VOT (scenario base SAV) and secondly the fleet should be large enough to facilitate ridesharing and optimal vehicle usage. The VKT is the largest in case of a small vehicle fleet (10% and 25%), as there are numerous individuals relaying on their private vehicle. The VKT increase in the case of SAV fleet at 50% of the optimal fleet size is more sustainable because less individuals decide to switch from more sustainable modes such as walking or public transit. Moreover, the VKT increase in case of a full fleet is larger, as there are more individuals shifting from walking towards SAV (40% of trips versus 45% of trips), while the number of individuals opting to travel with their private vehicle is rather stable (29.6% versus 29.4%). The results obtained from this study prove that there is an environmentally optimal fleet size for the SAV fleet, which would lead to minimalization of the behavioural changes. This fleet size should be large enough to facilitate travel for individuals willing to switch from private modes, while securing a possibly highest share of sustainable travel. As the mode preferences could be highly regional the design of SAV services should be made in cooperation with the citizens. The design and implementation should also be made with the regional authorities, to secure a sustainable intake focused on optimising the emissions and environmental rebound rather than profits of private companies.

When it comes to the contribution of each behavioural change to the rebound effect the previously described patterns of the rebound effect hold true in case of the VKT increase. Nevertheless, it is important to notice, that the contribution of further changes to the VOT do not result in severe changes in VKT, manifesting the overall saturation of the daily activities in the analysed population. The VKT for each of the analysed scenarios is presented in more details on Figure 3.9 hereunder, while the mode share shifts for the scenario with all behavioural changes considered and VOT at 70% are presented on Figure 3.10.

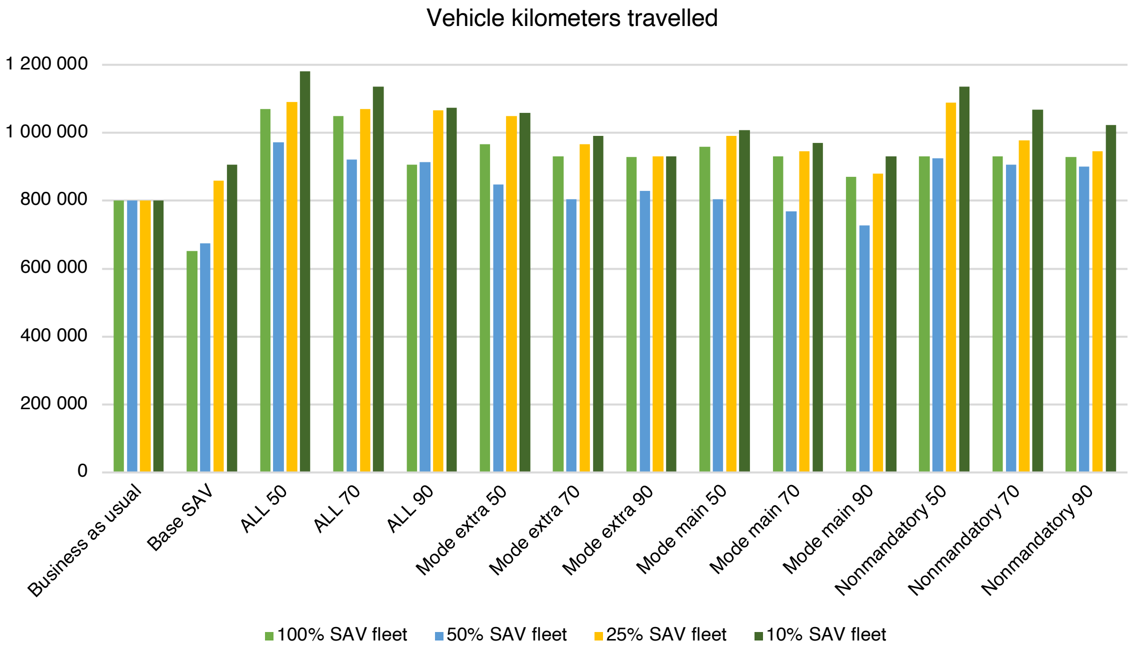

FIGURE 3.9 DAILY VKT IN KILOMETRES FOR ANALYSED SCENARIOS

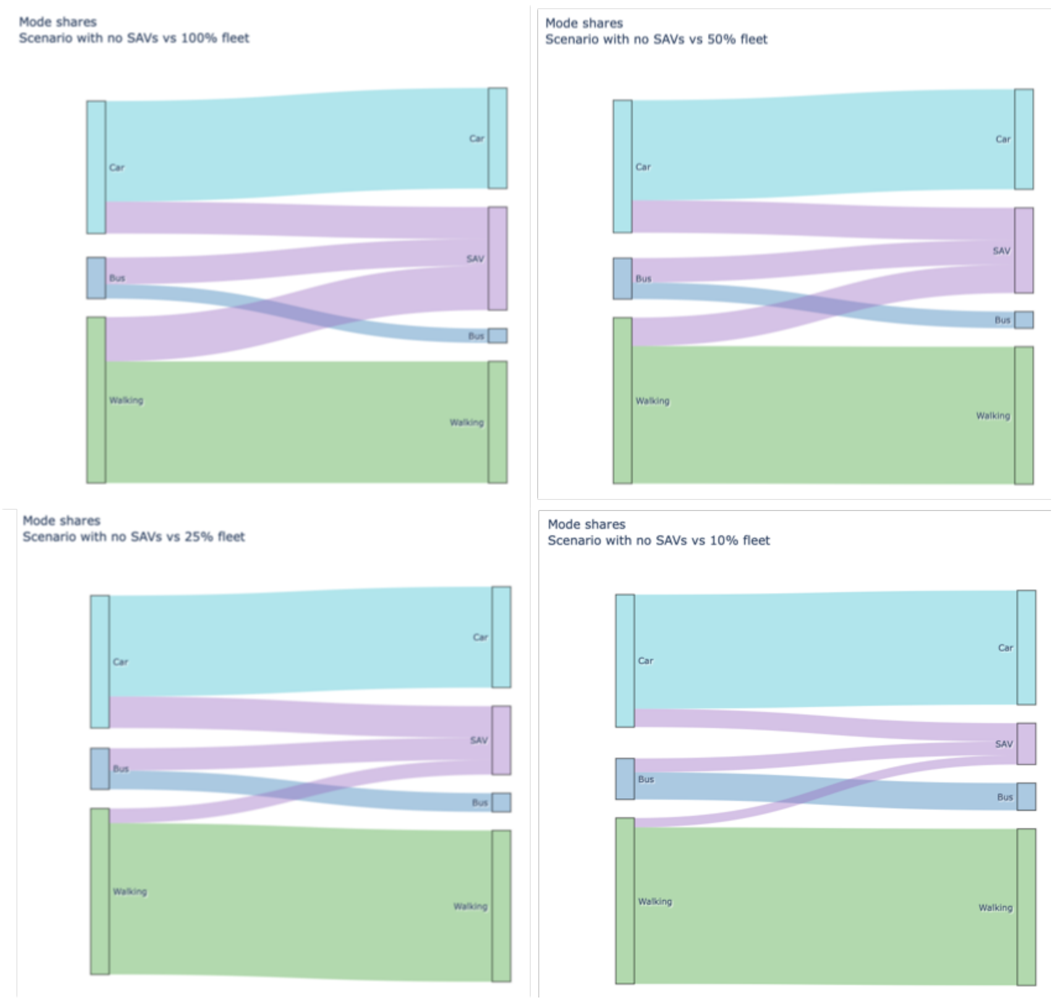

FIGURE 3.10 MODE SHARES SHIFTS BETWEEN SCENARIO WITH NO SAVS AND THE SCENARIO WITH VOT OF SAV AT 70% WITH ALL BEHAVIOURAL CHANGES TRIGGERED

3.4 POLICY RECOMMENDATIONS FOR SAVS DEPLOYMENT

Given the importance of the rebound effect, a central question is which complementary measures transportation authorities can take to maximize benefits of SAV deployment, while discouraging users from unintended reactions. The results of this study showed that the negative environmental rebound could be minimised by an optimal fleet size. Such fleet size should facilitate that users willing to switch from private modes towards shared rides do so, while those opting for sustainable modes remain using them. Therefore, the number of SAV vehicles should be capped and determined by the local authorities striving towards greener urban mobility. Moreover, the service providers, regulators and citizens could co-create the SAV based services, exemplary by designing the interior of the vehicles, to ensure its substantial uptake, as the results of this study showed that the rebound effect could be lowered if the car owners are encouraged to use SAV-based services.

Moreover, as the SAVs are expected to be battery-electric vehicles, a proper charging strategy is needed to make sure that the vehicles do not negatively adverse the stability of the electricity grid as well as regain their cost-effectiveness by consuming cheaper electricity in off-peak hours. Furthermore, the environmental rebound effect could be fully decreased by a transition to zero emission electricity grid. In such case the batteries in those vehicles could also serve as energy balancing asset, by adapting to a vehicle to grid charging pattern.

Lastly, as the highest environmental rebound effect was caused by the induction in participation in non-mandatory activities. Such effect could be lowered if cities were to follow the 15-minute city trend, which aims to secure all required services in a proximity to the residential area. If this was the case the citizens would not use the SAV fleet and chose modes preferred for short trips – such as walking or cycling. Therefore, such city development could be beneficial not only for today's transport challenges but also for that of tomorrow.

Besides these recommendations other measures could help maximizing the environmental benefits of SAVs deployment. The local, national, and transnational authorities should raise awareness of the sustainable mobility and the impact of individual's transportation choices. Those campaigns could help refrain sustainable modes users from shifting towards comfortable SAV services. Similarly, the application used to order SAV rides could be integrated with other mobility services to suggest a greener alternative whenever it would offer a quality of service comparable to SAVs.

To conclude, autonomous vehicles have been long awaited and are often referred to as the solution to achieve low carbon transportation and to limit climate crisis. Yet, user behaviors must be carefully considered when designing those services and the policies they should be subjected to in order to limit unintended consequences. While modelling can help anticipating users' reactions, large-scale experiments and cocreation are also needed to achieve the sustainable urban mobility.

3.5 Chapter summary

The full SAV deployment on our roads will certainly revolutionise transport in both urban and rural areas. Nevertheless, before we allow SAVs to roam our cities, we should strive to predict the impacts that they could have and prevent as many negative externalities as possible, especially considering transport's contribution to environmental pollution and climate crisis. The autonomy of those vehicles and the ability to share rides means lower travel costs, overall increase in road capacity, introduction of new parking strategies, ability to multitask in the vehicle and potential harvest of users currently not able to drive a conventional vehicle. Innovations that lower travel costs and travel times encourage users to participate in additional activities or to accept destinations further away either in the short or long term – possibly leading to relocation. These triggered behavioural changes could mitigate the initial benefits of SAVs deployment be it in terms of road traffic or pollutant emissions. Previous simulation studies that included the behavioural changes triggered by SAVs, as presented in detail in the literature review section, have focused on the efficiency of the transport system itself, without further investigating the environmental rebound effect of SAV deployment. This study's purpose was to estimate that environmental rebound effect of behavioural changes in terms of CO_2 emissions contributing to climate crisis and NO_X and PM2.5 emissions which negatively impact air quality. We believe this topic to be particularly interesting for transnational or national policymakers, urban planners as well as regional authorities, who need to take evidence-based decisions well ahead of the introduction of new technologies.

The environmental rebound effect is linked to behavioural changes, hence could only be obtained using methods that allow for singular representation of an individual in the investigated sample. This motivates the choice of an activity-based demand estimation representing the city of Santander in Spain in a simulation platform – SimMobility. The discrete choice models, which constitute the SimMobility Pre-day package, were estimated based on the travel diaries using Pandas Biogeme python library. The demand model was calibrated using the alternative specific coefficients in the discrete choice models and the weighted results of the travel diaries. Thereafter, the results of the demand model were an input of a microsimulation of traffic in the Aimsun Next software. The microsimulation of traffic allowed to use the environmental and battery consumption models, from which the estimated environmental rebound effect was obtained. The travel times were fed back into the SimMobility Pre-day package until convergence was achieved.

The results of the study show that the deployment of a SAV based service could be environmentally beneficial due to fleet electrification and sharing of rides. Nevertheless, behavioural changes could indeed lead to a significant rebound effect. The maximum obtained rebound effect resulted in 42% higher CO_2 emissions as compared to a scenario in which the SAVs are introduced but no behaviour changes linked to perceived lower value of in-vehicle time were introduced. For the NO_X and PM emissions the maximal rebound effect leads to 36% and 49% emissions increase respectively. The behavioural change that caused the highest rebound effect in all the scenarios was the participation of analysed individuals to a higher number of non-mandatory activities. While the modal choice for a work or education trip contributed to the lowest rebound effect out of the analysed behaviour shifts. The size of the fleet also contributed to various environmental rebound effect, with 50% of the full fleet (representing the market saturation) yielding lowest environmental rebound.

4. INVESTIGATING THE IMPLICATIONS OF INDIVIDUAL PREFERENCES FOR PARKING PRIVATELY OWNED AUTONOMOUS VEHICLES

As AVs are not available yet the researchers try to predict the way in which they would be used. Apart from the SAVs they predict that the vehicles could be also privately owned, which would open new parking strategies for their owners. To make sure those parking strategies are sustainable for the urban development there is a need for further research. For that purpose, a stated preference survey was conducted to obtain information about personal parking preferences.

Researchers have already tried to foresee how parking in the era of AVs would look like, concluding that the ability of the vehicle to park by itself could indeed radically change the land use in cities. Unless a radical shift in vehicle ownership rates will come with the deployment of SAVs, the suburban areas are expected to remain more or less the same, with an AV parked where a regular car is today. Yet, in areas of higher population density, neighbourhood parking zones or collective garages are expected to appear, guaranteeing the residents a parking spot nearby home. Further effects are expected at journey destination (leisure, shopping, work etc.), where AVs could simply drop their passengers and drive to an allocated parking space or a collective garage on the outskirts of the city (where the land is not as valuable in terms of monetary and social worth) (Duarte and Ratti, 2018; Heinrichs, 2016). Moreover, AVs might not need to find a parking spot at all, if the user or the vehicle would decide it would be most beneficial to simply drive around on the streets, waiting for the time to pick up its passenger (in so called cruising strategy) (Bischoff et al., 2019). And finally, if the passenger of the AV decides that she won't make use of the car in the near future, the vehicles could be sent back home to serve other household members (Litman, 2020b).

The aim of this chapter is to provide empirical evidence on the preferences of parking in the future, once new parking strategies, enabled by vehicle automation, emerge. The chapter focuses on a hypothetical scenario in which autonomous vehicles are privately owned and used in a similar manner to today's private cars. In particular the chapter presents the results of a SP survey in which respondents are confronted with four parking strategies: i) on-street parking nearby ii) dedicated parking area on the outskirts of the city iii) cruising and iv) sending AV back home. The results of the chapter are expected to support transport modelers in their simulation studies and impact assessments about future scenarios involving the use of SAVs and to give first hints to urban planners to conceptualize the city of the future.

The chapter is structured as follows. First the design and execution of the SP experiment is explained. A methodological section on modelling approach used to analyse the data collected follows. Finally, the results of the survey as well as of the mixed logit model used in the study are outlined before a concluding section summarising the main outcomes of the chapter.

4.1 STUDY DESIGN AND DATA SET

As AVs are not yet available on the market, SP experiment was used to obtain information about future parking preferences. This section discusses the design of the SP experiment. A questionnaire was developed consisting of four parts[2]:

1. Questions regarding the mobility habits and preferences of respondents prior to COVD-19 pandemic
2. Socioeconomic and sociodemographic questions, to gain insight into characteristics of the respondent, such as gender, age, employment, highest obtained education level, income level, household size.
3. Attitudinal statements, used to measure lifestyle traits that could influence preferences for various parking strategies. This part of the questionnaire included a series of 18 statements, for which the respondent would indicate her/his level of agreement using six-point Likert items. Based on a priori hypothesis and previous studies on AV acceptance, the statements included attitudes towards: i) environment, ii) innovation, iii) AV acceptance, iv) sustainable car free cities. For each of the expected latent variables, between 4 and 5 statements were provided to obtain a better understanding of behavioural attitudes.
4. Six choice sets to gain insights into the preferred parking alternatives of individuals. The respondents were first presented with the textual description of each of the parking concepts, and then with a series of six scenarios such as that shown in Figure 4.1, with the values changing in each alternative. The four possible parking alternatives included are:
    a. Parking in a dedicated area. In this parking strategy the vehicle drops off its user and parks in a dedicated garage area on the outskirts of the city or central business district, where land demand and efficiency are not of highest importance.
    b. Parking nearby in a city centre. In this parking strategy the vehicle drops off its user and starts looking for an available parking spot nearby, relocating if there is a limit on the permitted duration of parking. Such parking was expected to be more costly in comparison to the remaining alternatives, as per assumed higher land demand and utilisation in the area.
    c. Sending the vehicle back home. In this parking strategy the vehicle drops off its user and returns home, to serve other household members or wait for the principal user's request.
    d. Cruising. Finally, in this parking strategy the vehicle drops off its user and start driving in nearby locations until called again.

[2] A copy of the one of the survey could be accessed under the following link

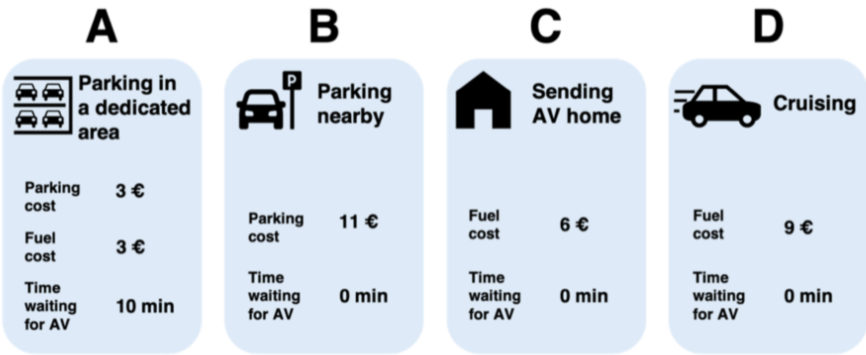

FIGURE 4.1 EXAMPLE OF CHOICE SET PRESENTED TO THE RESPONDENT

The SP experiment was designed using a qualitative approach based on variables obtained from a series of focus groups. During focus groups conducted in Q2 and Q3 of 2020, respondents were asked about the variables affecting the parking choice in the era of AVs. The decision variables identified during the focus groups included: total parking cost, environmental impact and waiting time for the AV to arrive. More details on the focus group proceedings could be found in a forthcoming paper. Therefore, the respondent was confronted with choice of the most suitable strategy based on parking costs, fuel costs (used as an environmental proxy) and waiting time for the AV to arrive.

To maximise information obtained from each choice set, the SP experiment was created as an Bayesian efficient design using the Ngene software (ChoiceMetrics, 2012; Ibeas et al., 2014; Rose and Bliemer, 2009). An efficient design requires to run a pilot of the survey to obtain more accurate and precise prior parameters calibrating a MNL. The priors were obtained through estimations using data collected in the pilot phase with 35 respondents. Despite the small sample, all relevant priors resulted statistically significant and of the expected range and sign. The efficient design resulted in 12 scenarios, divided into two blocks of 6 choice sets presented to the respondent.

The attributes levels were chosen using the estimated costs of driving the AV provided by Litman (Litman, 2020a). Moreover, the attributes levels were designed to reflect the assumed functioning of the parking strategies and expected parking policies:

- There is a possible delay in arrival of AV, due to late request or unforeseen events, if the vehicle is further away (parked in a dedicated spot or sent home). Hence the user could be required to wait for the vehicle. If the vehicle is nearby the waiting time is marginal and not applicable to the given scenario.
- Fee for parking in the dedicated parking area on the outskirts of the city is lower than that in the central areas nearby.

- Cruising should not be the cheapest option, as it's expected that there will be dedicated parking policies to reduce the empty miles travelled. Nevertheless, to reduce the complexity of the survey, the cost increase is reflected in the raise of fuel price.

The final used attribute levels are presented in the following Table 4.1:

TABLE 4.1 SP EXPERIMENT ATTRIBUTES AND THEIR LEVELS

	Parking in a dedicated area (A)	Parking nearby (B)	Sending AV home (C)	Cruising (D)
Parking costs	0€ ǀ 3€ ǀ 6€	7€ ǀ 11€ ǀ 15€	0 €	0 €
Fuel costs	1€ ǀ 3€ ǀ 5€	0 €	6€ ǀ 8€ ǀ 10€	5€ ǀ 9€ ǀ 13€
Waiting time	0 min ǀ 5 min ǀ 10 min	0 min	0 min ǀ 5 min ǀ 10 min	0 min

4.2 THEORETICAL AND MODELLING FRAMEWORK

4.2.1 OBTAINING LATENT VARIABLES

As previously mentioned, the respondents were asked to indicate their level of agreement with a series of attitudinal statements. Confirmatory Factor Analysis (CFA) (Brown, 2015) was used to obtain the attitudinal variables, incorporated into latent variables which are in turn represented in the utility functions of the MNL. The factors were extracted using the principal factor extraction method with a Varimax rotation to yield orthogonal, interpretable results (Efthymiou et al., 2013b). Bartlett's test of sphericity ($p = 0.000$) and the Kaiser-Meyer-Olkin measure (KMO = 0.82) were used to confirm the adequacy of data for factor analysis (Hair, 2009). The root mean square error of approximation (RMSEA) for the CFA model also indicates an appropriate model fit at 0.078 (Tyrinopoulos and Antoniou, 2012).

The four obtained latent variables are a result of the CFA and supporting literature analysis:

1. Environmental concern, which expresses the degree to which an individual could favour more environmentally friendly option while making a decision.
2. Innovativeness, which indicates whether an individual could belong in the innovator or early adopters' group, being more likely to accept market novelties and opt for less conventional choices.
3. AV acceptance, which reflets whether an individual is likely to trust AVs to be safe and reliable and capable of reaching the destinations without supervision.
4. Support for sustainable car-free cities, which reflects whether an individual supports promoting public transport, walking, and cycling and limiting the number of cars and parking areas in inner cities.

4.2.2 Latent variable mixed logit

Random utility theory has been the most used approach to predict and understand the discrete choice in transportation. The theory implies that an individual (n) assesses each of the available options based on the perceived utility of each alternative, and makes the choice that maximises the utility (Ortúzar and Willumsen, 2011). The utility (U) is composed of a deterministic part – a vector of the explanatory variables as well the attributes of the alternative as the socioeconomic characteristics (X_{in}) of the individual – and of a stochastic component – an error term (ε) that accounts for all variables unknown or omitted by the modeler. As an additive linearity is assumed, the utility of alternative i can be expressed as follows (Ortúzar and Willumsen, 2011):

$$U_{in} = \beta X_{in} + \varepsilon_{in}$$

Where β is the vector of parameters to be estimated.

There is a variety of discrete choice model specifications depending on the assumptions concerning the error term. In the frequently used MNL, it is assumed that the random residuals follow a Gumbel distribution and are independent and identically distributed (Ortúzar and Willumsen, 2011). Therefore, the MNL does not allow to account for the panel data (result of more than one choice per respondent) and omits the heterogeneity of the studied population. To cope with those restrictions a Mixed Logit with latent variables (LVs) was used in this study (Yáñez et al., 2010). This model specification allows to relax the assumption that model parameters are the same for all respondents, as well as the assumption of no correlation across observations given by one respondent (panel data). The utility function of the ML with LVs is represented as follows (Yáñez et al., 2010):

$$U_{in} = \sum_k \theta_{in} X_{inkt} + \sum_l \beta_{il} \eta_{inlt} + \varepsilon_{int}$$

Where θ_{in} and β_{il} are parameters to be estimated, associated respectively with the tangible attributes and the LVs. The *t* represents the multiple-choice situations, which one respondent *n* is confronted with.

All estimations were performed using the PandasBiogeme software (Bierlaire, 2020), within the iterative procedure, in which variables reported as insignificant in the decision making were omitted. In early simulations a plethora of socioeconomic and sociodemographic characteristics was used (gender, age, income). They were however omitted in the final version of the model to better showcase the impact of lifestyle traits, often correlated with a sociodemographic profile of an individual. The considered utility functions consisted of socioeconomic characteristics, latent variables, alternative attributes (waiting time, parking cost and fuel cost) and the alternative specific constants (ASC). Moreover, for the attributes of the alternatives (waiting time and costs) the alternative specific coefficients and generic ones were considered. In the end the generic representation was chosen as per its higher significance and comparable value results between the alternatives.

The perception of alternative attributes, such as waiting time or cost, often varies across population, therefore those parameters were introduced as random in the model. Two distributions were tested for the random parameters – typically used normal distribution and triangular distribution. The triangular distribution was tested as it allows to capture the non-symmetrical nature of societal preferences, more in line with the waiting time and cost attributes (Hess et al., 2005). The comparison of the model was made based on the percentage of population exhibiting the expected negative sign of the parameters, the likelihood ratio test and the Akaike information criterion (Kolarova et al., 2019). Those comparisons showed that triangular distribution yielded better results. For this reason, in the final model a triangular distribution for the random time and costs coefficient was chosen.

4.3 Results

4.3.1 Survey sample

The final version of the SP experiment was distributed to the respondents, using EU survey (the online survey management tool of the European Commission), between April and May 2021. The survey was disseminated online through social media platforms and through personal connections of the authors. The targeted respondents of the survey were European citizens. A total of 160 individuals completed the survey, each answering 6 choice experiments, leading to a total of 960 choice replications. The sample size of the survey is above the required sample size for the efficient design (S-estimate at 112.25).

The sample obtained via internet survey distribution has a decent distribution in terms of socio-demographic characteristics (Figure 4.2). Given the overall focus of the survey on the active population group, the young individuals could be underrepresented, while the highly educated individuals are overrepresented, as the survey was also distributed among colleagues of authors.

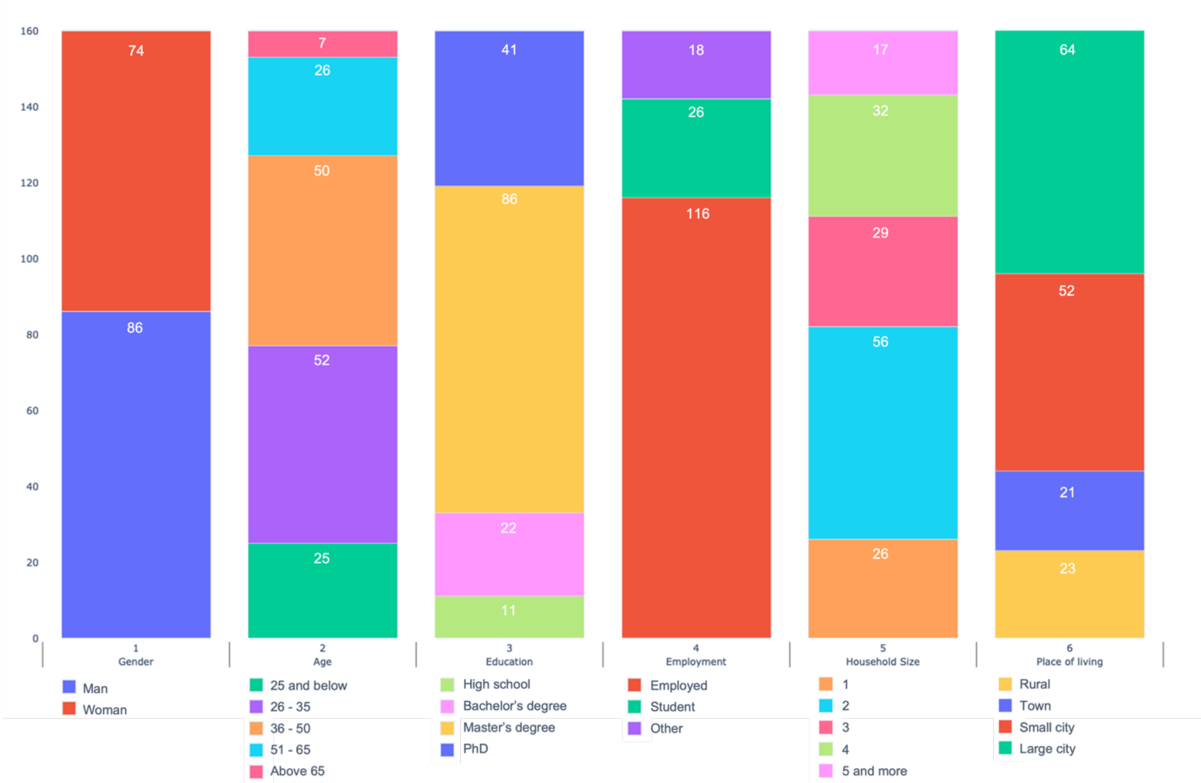

FIGURE 4.2 SOCIODEMOGRAPHIC CHARACTERISTICS OF THE SAMPLE

The latent variables reflecting the attitudes of the respondents were found to be influential over the choice decision. Table 4.2 presents the CFA loadings as well as the sources of each statement. The statements provided were based, whenever possible, on statements previously used and found to be effective in the literature.

TABLE 4.2 RESULTS OF CFA FOR EACH OF THE PROPOSED LATENT VARIABLES

	Source	Loading
Environmental concern		
I am concerned about global warming	Atasoy, Glerum and Bierlaire (2013)	0.86
I am willing to spend a bit more money to buy a product that is more environmentally friendly	Haboucha, Ishaq and Shiftan, (2017)	0.82
I would be willing to change my behaviour based solely on the concern for the environment	Adapted from Haboucha, Ishaq and Shiftan, (2017)	0.87
I often worry about the effects of pollution on myself and those close to me	Ewing and Sarigöllü, (2000)	0.79
Innovativeness		
I try new products before my friends and neighbours	Roehrich (2004)	0.86
I know more than others on the latest new products	Roehrich (2004)	0.81
If a new product gives me more comfort than my current product, I would not hesitate to buy it	Vandecasteele (2010)	0.75
If innovation is more functional, then I usually buy it	Vandecasteele (2010)	0.79
I tend to follow trends	Adapted from Roehrich (2004)	0.64
Initial AV acceptance		
I would be comfortable with autonomous vehicle being in control of driving	Adapted from (*Expectations and concerns of connected and automated driving*, 2020)	0.90
I expect autonomous vehicles to be safe	Nastjuk *et al*. (2020)	0.86
Overall, I would trust an autonomous vehicle to get me safely to my destination	Nastjuk *et al*. (2020)	0.94
I would not have concerns about the security and data privacy of autonomous vehicles	Nastjuk *et al*. (2020)	0.66
Support for sustainable car-free cities		
Cities, in general, should have more green areas	Created for this study	0.71
Cities should strive to make neighbourhoods walkable and cyclable	Nilsson and Küller (2000)	0.84
I support efforts to create car-free inner cities	Kaiser, Fuhrer and Wölfing (1999)	0.89
I support raising parking fees in cities	Kaiser, Fuhrer and Wölfing (1999)	0.82
Parking areas in cities should be reduced and used for other communal purposes	Nilsson and Küller (2000)	0.87

4.3.2 ESTIMATED MODEL COEFFICIENTS

The estimation results of the final model are presented in the following Table 4.3. For each of the parameters, estimated coefficients (β) and standard deviations (η) of random parameters, the t-value is given. T-value is a value used in a t-test - a statistical measure of the reliability of the estimates typically used to validate the discrete choice estimations (Ortúzar and Willumsen, 2011). Moreover, number of observations, log-likelihood at convergence and the ρ^2 index are shown below the estimated parameters. Overall, all the estimated parameters are found to be significant with the t-student test and of correct, expected sign and value.

TABLE 4.3 RESULTS OF MIXED LOGIT WITH LATENT VARIABLES ESTIMATION

Coefficient	Estimated value	t value
$ASC_{PARKING\ IN\ A\ DEDICATED\ AREA}$	-1.31	-3.86
$ASC_{PARKING\ NEARBY}$	fixed	fixed
$ASC_{SENDING\ AV\ HOME}$	fixed	fixed
$ASC_{CRUISING}$	-3.06	-5.82
Environmental $concern_{PARKING\ IN\ A\ DEDICATED\ AREA}$	fixed	fixed
Environmental $concern_{PARKING\ NEARBY}$	fixed	fixed
Environmental $concern_{SENDING\ AV\ HOME}$	-0.76	-2.25
Environmental $concern_{CRUISING}$	-0.80	-2.46
$Innovativeness_{PARKING\ IN\ A\ DEDICATED\ AREA}$	fixed	fixed
$Innovativeness_{PARKING\ NEARBY}$	fixed	fixed
$Innovativeness_{SENDING\ AV\ HOME}$	fixed	fixed
$Innovativeness_{CRUISING}$	2.60	4.11
AV $acceptance_{PARKING\ IN\ A\ DEDICATED\ AREA}$	-1.06	-2.70
AV $acceptance_{PARKING\ NEARBY}$	-1.13	-3.18
AV $acceptance_{SENDING\ AV\ HOME}$	fixed	fixed
AV $acceptance_{CRUISING}$	fixed	fixed
Preference of car-free $cities_{PARKING\ IN\ A\ DEDICATED\ AREA}$	2.35	5.83
Preference of car-free $cities_{PARKING\ NEARBY}$	fixed	fixed
Preference of car-free $cities_{SENDING\ AV\ HOME}$	fixed	fixed
Preference of car-free $cities_{CRUISING}$	fixed	fixed
Total parking costs (mean)	-0.52	-12.07
Total parking costs (η)	0.34	8.67
Waiting time (mean)	-0.141	-7.44
Waiting time (η)	0.143	6.85
Model fit		
Log-likelihood (0)	-1259.64	
Log-likelihood (final)	-903.20	
$\rho 2$	0.273	
Akaike information criterion	1827.84	
Estimated parameters	12	
Observations	960	

The results indicate that the lifestyle traits and preferences, reflected through the latent variables, could have impact on future decision-making concerning parking a private AV. When presented with the choice of parking, those who already put their trust in the future AV technology, are less likely to choose the nowadays conventional options of parking nearby (β=-1.13) or of parking in a dedicated area (β=-1.06). On the contrary they do not seem discouraged from choosing the unconventional approach, namely sending the vehicle back home or allowing it to cruise. It could mean that once the AV technology is commercially available and widely used, it would inevitably gain more trusts with potential users, who in time could find themselves preferring to leverage those novel parking strategies that allow maximization of personal convenience.

Moreover, the inner innovativeness of an individual could also impact their decision making concerning the future parking options. The estimated ML indicates that more innovative individuals, who are comfortable with technological novelties, could have a preference towards allowing the vehicle to cruise (β=2.6) – an option not currently available. This could prove to be especially dangerous, as it could increase the number of empty VMT and lead to even higher congestion than today. Therefore, it is important to find policies that would discourage users from choosing this parking strategy. Drawing conclusions form this study, policy makers on regional and national levels, could issue an informative campaign that would primarily target those who tend to easily adopt new technology (early adopters).

Unsurprisingly, those more concerned about the environment are less likely to allow their vehicle to cruise while waiting for them (β=-0.76), or to send their vehicle back home (β=-0.8), as due to increased fuel (electricity) consumption it could prove harmful for the environment. Moreover, individuals who already nowadays support creation of sustainable car-free cities, are drawn to the option of sending the vehicle to the dedicated area on the outskirts of a city (β=2.35).

While AVs will highly revolutionise the transport industry and heavily impact future urban planning and land use, people social attitudes will influence the way in which AVs will be adopted in tomorrow's cities and how they will contribute to the sustainability of urban area. Therefore, whilst the massive deployment of AVs may still be a long way ahead, it is important to already encourage sustainable attitudes towards mobility in order to mitigate the risk of future negative externalities related to the uptake of self-driving cars.

Lastly, the cost of parking and waiting time for the AV also impact the decision between various parking strategies. Therefore, it is already important nowadays to reflect on the proper distribution of the areas in which AV parking centres could be located. The cost and location of those parking zones should be optimised to avoid an increase in VMT, secure more efficient use of space in urban areas and encourage individuals to use them more often, than the other parking strategies that could prove to be less sustainable for cities in the long run. Those aspects are investigated in more detail in the following subchapter.

4.3.3 Price elasticity studies of proposed parking strategies

The results of the model were further used to provide insights for policymakers regarding decision making on the future parking policies to support sustainable usage of AVs. For that we present an average probability of choice of a given parking strategy under a variety of price and waiting time assumptions. In this section of the study those results are further described and presented, along policy implications.

Parking cost is certainly one of the most crucial factors while choosing a way to park your vehicle. Therefore, an analysis of change in parking choices in response to variation of pricing of the proposed scenarios, was made. In all the analysis the response to increase/decrease of a given parking strategy is analysed as a reference cost to the remaining parking strategies. In the essence the non-analysed parking strategies have a fixed cost – with the two non-analysed scenarios having the same parking cost, whereas parking nearby is twice as expensive as the reference parking scenario. Four following pricing elasticity studies were performed: cruising (Figure 4.3a), sending the vehicle home (Figure 4.3b), parking in a dedicated area (Figure 4.3c) and sending the vehicle home and cruising (Figure 4.3d)

The pricing elasticity of cruising shows that probability of choosing the cruising options increases with lowering of the price, and when the cruising costs are marginal it becomes the most probable option, with probability of choice at 0.43. Nevertheless, even though the cost of cruising option is marginal for individual than the sending AV home or parking in a dedicated area, the option does not dominate the probability. Notably, once the cost of cruising is almost as expensive as parking the vehicle nearby (75% of cost) the probability of choosing cruising is lower than that of choosing the traditional parking nearby option.

Moreover, the pricing elasticity of both cruising and sending the vehicle home (Figure 4.3d) yields similar results, showing that sending the vehicle back home would be the preferred scenario, if the costs of the two strategies were equally low (probability of choice 0.72 vs. 0.11). These results indicate that the average individual is still not comfortable with allowing the vehicle to drive on its own without the supervision and would prefer more conventional strategies or sending the vehicle home to be used by other household members.

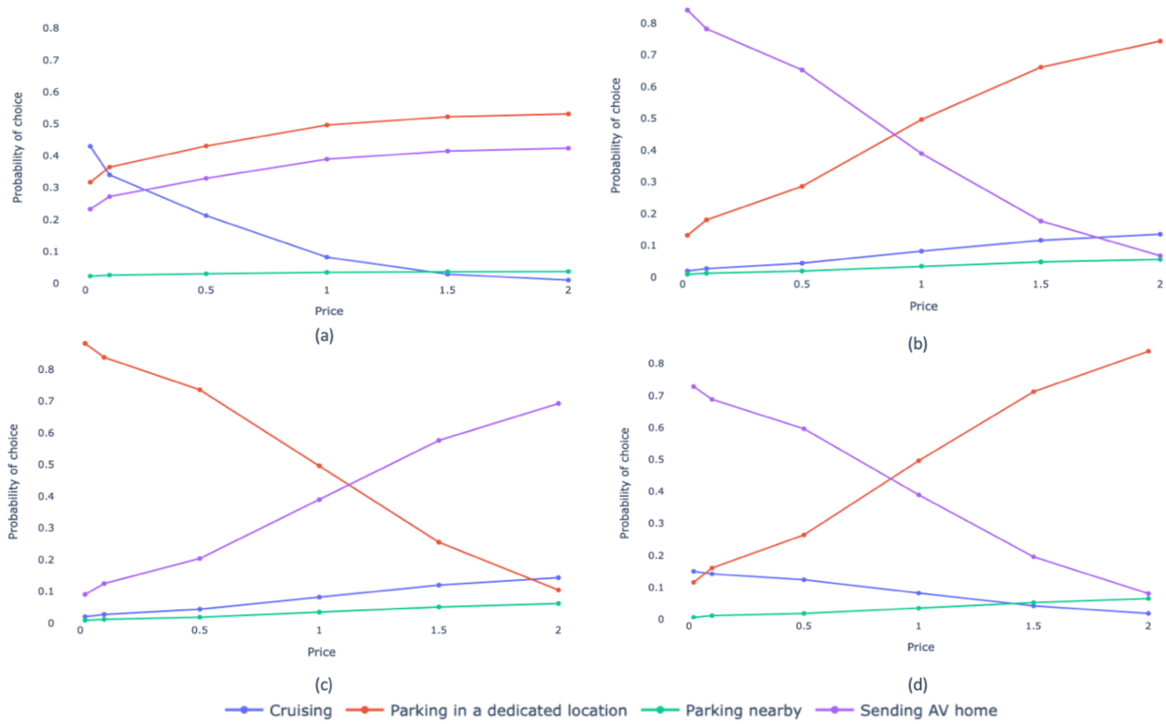

FIGURE 4.3 PRICE ELASTICITY OF THE 4 PARKING STRATEGIES. CHART (A) REFERS TO CRUISING, CHART (B) TO SENDING THE VEHICLE HOME, CHART (C) TO PARKING IN A DEDICATED LOCATION, AND CHART (D) TO SENDING VEHICLE HOME AND CRUISING

The response to price fluctuations of sending the vehicle home (Figure 4.3b) show that when the costs of sending the vehicle home and parking it in a dedicated area are equal, the probability of sending the vehicle home is lower than that of an alternative (0.39 vs 0.5). In turn, once sending the vehicle home, becomes cheaper than any other alternative the probability of choosing it skyrockets, coming with almost a certain choice (0.85) when the cost of sending the vehicle home would be marginal. This could prove to be a struggle for regional policy makers, who would need to find a way to make both cruising and sending the vehicle home costs more comparable with parking costs.

Once the cost of sending the vehicle home increases the probability of choice swiftly decreases, with parking the vehicle in a dedicated area proving to be the most probable choice (0.74 vs. 0.07). Nevertheless, the price elasticity of sending the vehicle to a dedicated area (Figure 4.3c) shows that there are certain individuals who would prefer to send the vehicle home despite higher costs. The analysis shows that once the cost of parking the vehicle in a dedicated are marginal the probability of choosing this strategy is 0.88, with 0.09 probability of sending the vehicle home. This marginal tendency to send the vehicle back home could be explained by the fact, that some users might want to make the vehicle available to other household members.

Moreover, with the price of sending the vehicle home twice as high as cruising and parking in a dedicated area, therefore equal to that of parking nearby, sending the vehicle home is still preferred than parking it close by. This could signal a shift in mentality and a support for lowering the number of parking spaces in central locations as the vehicles turns autonomous, confirming the current theories that majority of central parking locations could be removed and used for other purposes, without a major drawback from car dependant population.

4.3.4 Waiting time elasticity studies of proposed parking strategies

Nowadays, an important factor while deciding on the parking location is the access time required from the vehicle to the destination. As the AVs would be able to drop their passengers right in front of their destinations, access/egress time would be non-existent. Nevertheless, if the passenger doesn't notify the vehicle well in advance about the desired leaving time, or in case of unforeseen events, the user might end up waiting for the vehicle to arrive. Since, time is a sensitive issue while chosing the parking strategy, the waiting time elasticities were also analysed in the further two scenarios.

When the vehicle is parked nearby or it is cruising, it is assumed to be close to the user and therefore the waiting time is marginal and assumed to be equal to zero. Therefore, the user must wait for the vehicle only if it is sent to park on the outskirts of the city or if it is sent back home. To perform the elasticity studies concerning the waiting time, it is assumed that the cost of parking the vehicle in a dedicated area, sending it home or cruising costs the same, whereas parking nearby is twice as expensive, similarly to the pricing elasticity analysis. To perform the waiting time elasticity study, an exemplary set of waiting times was chosen (0 min, 2min, 5min 10min, 20 min and 30 min). The time stretches to 30 minutes to represent a case in which a dedicated parking area is on the outskirts of a spread-out city, in which in case of a road blockage the driving time to the central (user's) location could be substantial.

In the first waiting time elasticity study, the effect of waiting time is introduced only in case of parking in the dedicated area (Figure 4.4a). In this assumed scenario the home of the user could be near the central location, while the distance of dedicated parking area from the central location is investigated. In the second waiting time elasticity study (Figure 4.4b), the waiting time is introduced for both sending the vehicle home as well as sending it to park in a dedicated area. This scenario reflects the parking decision of an individual living on the outskirts of the city. The results show that while the waiting time for an AV is marginal, parking in a dedicated area is the most probable choice (0.49). However, once the waiting time increases, even slightly (2min) users living next to central areas would likely to send the vehicle home instead of sending it to a dedicated parking lot. Whereas, the users whose home is further away, would prefer to send the vehicle to a dedicated spot as long as the waiting time is not substantial and does not exceed 15 minutes, after which cruising becomes the most probable choice. This again proves, that while the attitudes of the individuals nowadays, point towards the urban sustainable parking choice, it could change if the parking locations are not convenient enough to secure the desired waiting time.

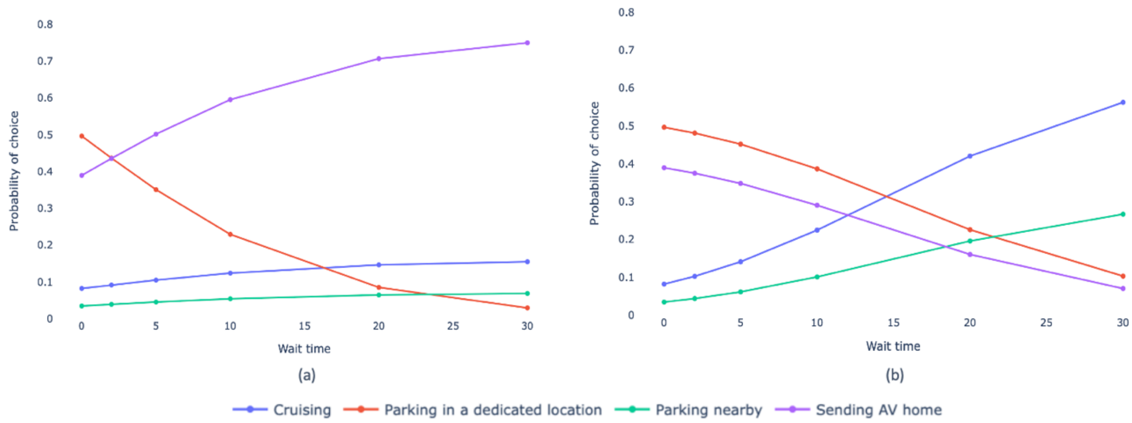

FIGURE 4.4 Waiting time elasticity of the 2 parking strategies. Chart (a) refers to parking in a dedicated area, chart (b) to parking in a dedicated area and sending the vehicle home

4.4 Policy recommendations for future parking strategies for privately owned AVs

The results suggest, that for now, there is a high preference for parking in dedicated areas in the outskirts of the city. Nevertheless, as the users gain trust in the AVs or are part of the early adopters' group, they show higher preference towards unconventional parking strategies – cruising and sending the vehicle home. Moreover, the study shows that those with higher regard for the environment and with a preference for car-free cities are more likely to choose a sustainable parking outside of the city centre. As the lifestyle traits represented through the latent variables were found significant, the continuation of current and future educational campaigns could be used to build on the sustainable lifestyle attributes of the population. Specifically, it is important to target educational campaign at those with high intake of technological novelties, while at the same time developing the environmentally and urbanely cautious social attitudes.

The study also focused on the impact of pricing policy and required wait time on the eventual choice of parking. It has been found, through the mixed logit model, that while price and wait time are considered differently by various individuals in the population, adopting the right parking policy could lead to a sustainable uptake of AVs. Those findings include:

- Once the AVs are deployed, the central parking lots could indeed be heavily limited, without the negative pull back from car dependant users. This study shows that those users will no longer prefer to park their vehicle in a central area once cheaper and convenient alternatives are in place.
- There is currently a lack of acceptance towards allowing the vehicle to cruise. This fact could be leveraged by policy makers, who might intervene and take measures that will limit

the cruising option, before it becomes widely adopted. This way, the pull back from the private AV users would not be as strong, as in a hypothetical scenario in which the users are used to this convenient and, if not regulated, cheap parking strategy.

- If not regulated, the cruising costs and the costs of sending the vehicle home would be marginal compared to a paid parking area. Under this scenario, a majority of people would decide to send their vehicle home, which could increase the negative externalities coming from rise in empty vehicle miles travelled. A solution could be twofold either by increasing the cost of cruising/sending the vehicle home by setting prices for vehicles that enter and cruise around central locations (for which vehicles entering from city parking areas would be exempt), or by sufficiently lowering the price of parking in the desired by city government's locations.
- Increasing wait time significantly reduces the probability of choice of the dedicated parking area on the outskirts of the city. For individuals with homes close by the destination locations, this would mean sending the vehicle home, which could prove to be useful for policy makers through lowering the demand for parking spots. Whereas individuals with home further away from destination locations, might opt for other unsustainable solution - cruising. This would suggest the need to keep some of the parking areas not far away from central locations available nowadays. Exemplary, park and ride facilities, could be redesigned and serve AVs in the future, while the on-street parking lots in the central areas could be reused in more sustainable manner.
- Moreover, with time as AVs gain trust and allowing the vehicle to cruise becomes common and perceived as normal, the waiting time for the vehicle could be required to be even shorter, if the cost of cruising is not regulated by the city policy makers.
- Despite the applied parking policy, there would always be individuals who would send vehicles back to their home locations, so they can serve other household members.

4.5 Chapter summary

Introduction of AVs on the market will certainly revolutionise transportation in urban areas. One of the driving choices that is expected to be particularly affected by AVs is parking. Previous studies have tried to identify the new possible strategies enabled by AVs. However so far there has not been any attempt to measure people attitudes towards it. This study has tried to untangle the future preferences for parking strategy to shed light on a topic that can be particularly relevant for policy makers, urban planners, and transport modellers.

The effects that the current lifestyle traits have on the parking choice are quantified through the mixed logit model with latent variables, which accounts for panel data. Four latent variables were found to significantly impact the decision about the preferred parking option: environmental concern, innovativeness, AV acceptance and preference for car-free cities. The results suggest, that for now, there is a high preference for parking in dedicated areas in the outskirts of the city. Nevertheless, as the users gain trust in the AVs or are part of the early adopters' group, they show higher preference towards unconventional parking strategies – cruising and sending the vehicle home. Moreover, the study shows that those with higher regard for the environment and with a preference for car-free cities are more likely to choose a sustainable parking outside of the city centre. As the lifestyle traits represented through the latent variables were found significant in the decision-making process, the continuation of current and future educational campaigns could be used to build on the sustainable lifestyle attributes of the population. Specifically, it is important to target educational campaign at those with high intake of technological novelties, while at the same time developing the environmentally and urbanely cautious social attitudes.

Nevertheless, it is still widely unknown how the future of parking will unfold. It is also important to note that it will highly depend on the extent to which vehicle ownership rate changes, as we will not debate on the parking of our vehicle if we instead opt for the system of SAVs. Notwithstanding, despite many limitations of forecasting with SP experiments this study proves to be the first step in closing the research gap concerning parking preferences of the future.

5. Investigating the environmental and societal impact of Last-mile delivery by automated droids

The developed NMS are not only user-centred but could also be used for delivery of parcels especially in the last-mile delivery. This Chapter aims to lay out a MCDA framework altered for sustainability assessment of innovation in the last mile delivery and apply it to real case study. The framework was adapted to investigate and assess the conflicting needs of the system stakeholders. The authors hope that it could be used by regional policymakers and service providers, as decision making support tool for planning and development of future, carbon neutral transport system. Moreover, the study includes an application of the framework to the last-mile delivery system of the Ispra site of the Joint Research Centre (JRC) of the European Commission in Italy. As previously mentioned in Chapter 2, the impact of some of the NMS used for last-mile delivery services have been previously investigated. Nevertheless, the sustainability of last-mile delivery droids has been a topic scarcely investigated by researchers. Therefore, the case study lays out and assesses six alternatives of handling the postal services: i) currently used Euro 4 light commercial vehicle (LCV), ii) Euro 6 LCV, iii) electric LCV, iv) delivery droid (robot) coupled with Euro 4 LCV, v) delivery droid coupled with a depot station and vi) delivery droid coupled with eLCV. The assessment is one of the first studies to investigate automated delivery droids, which could become a frequent addition to the urban landscape in the near future.

The analysis is structured as follows, first, the steps required for the assessment support framework and implementation methodology are given. Then in the following subchapter, results of the analysis concerning last mile delivery system are presented, with discussion and policy impact and summary as subsequent subchapters.

5.1 Sustainability assessment framework

The framework was developed based on the relevant literature briefly outlined in Chapter 2. However, additional material from other fields was also used to structure the four step methodology, so that the assessment reflects a comprehensive last-mile delivery assessment (Mansourianfar and Haghshenas, 2018; Santoyo-Castelazo and Azapagic, 2014). To reflect the importance of quality of the last-mile delivery solutions, the operational assessment was added alongside the traditional three sustainability pillars assessment (economic, environmental and social). Additionally, the used indices and objectives were aligned to fit the last-mile delivery scope. The choice of the indices drew from the general economic indices used for the project assessment, previous sustainability and environmental assessments performed in the field, as highlighted in Chapter 2, and additional indices agreed with experts responsible for the postal delivery at the case study location. The authors believe that the set of indices presented in the study could prove to be a good starting point for the last-mile delivery assessments and could thus be the basis for future studies in the field.

This section further presents the following steps of the proposed assessment framework, in sub-sections 5.1.1, 5.1.2, 5.1.3 and 5.1.4 (Figure 5.1).

1. Choice of last mile delivery solutions to consider
2. Development of operational strategies for the analysed options
3. Selection and specifications of operational, financial, environmental and social indicators to be used for measuring the sustainability of each option
4. Creation of prioritisation scenarios (considering the needs of a variety of involved stakeholders) with integration in the MCDA framework

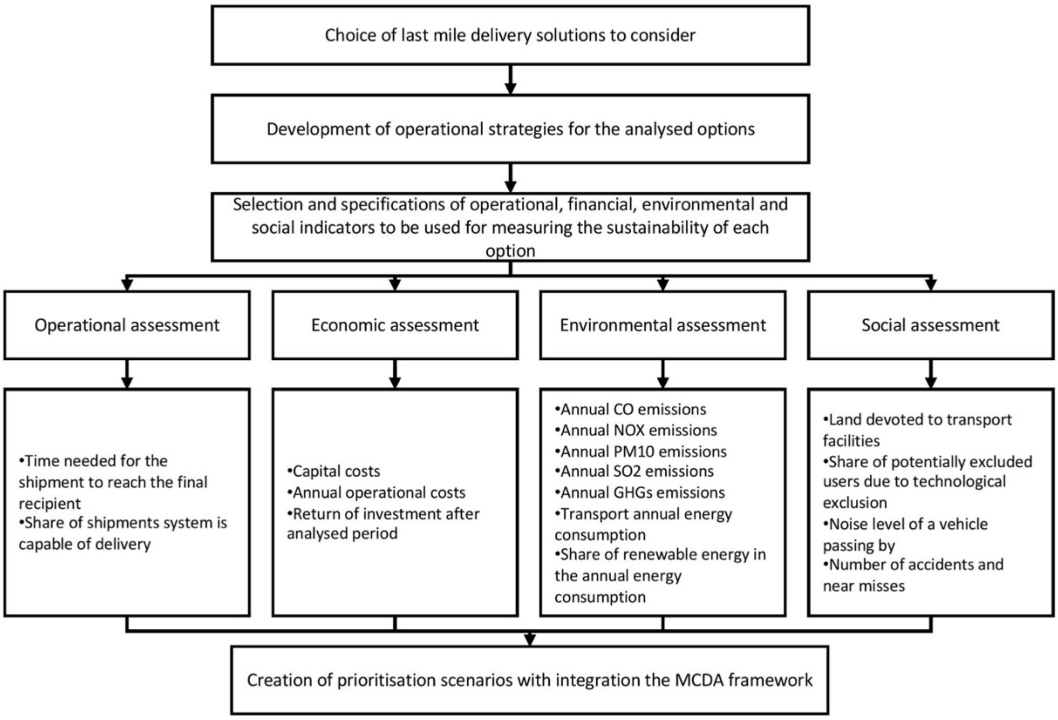

FIGURE 5.1 SUSTAINABILITY ASSESSMENT FRAMEWORK

5.1.1 CHOICE OF LAST MILE DELIVERY SOLUTIONS

The first step of the sustainability assessment framework is aimed at identifying last mile delivery solutions that could be applied within an analysed system, taking into account the specific characteristics of potential end-users as well as the considered region. Upon the selection of technologies, vehicle attributes such as load capacity, energy source, emissivity, price, rolling coefficient, drag coefficient, size and weight need to be identified to proceed with the analysis.

5.1.2 Development of operational strategies for the analysed options

Implementation of new technologies is often (but not necessarily) linked to entirely new operational scenarios. Therefore, a careful development and examination of the implementation strategy of each of the considered new solutions is needed. It is vital to define the locations of the warehouses or depot station, potential delivery routes and timings, limitations connected to the regulatory vehicle requirements in the region, as well as the manner in which the delivery services are ordered. Moreover, as the delivery solutions become more compact, those considerations should include the delivery limitations tied to as well finite load capacity.

If one of the solutions considered is not capable to carry the entire postal services, the solution could be disregarded in further analysis. Alternatively, a new operational strategy could be developed in which the limited solution is assisted by another last mile delivery method.

5.1.3 Selection of sustainability indicators

To perform a sustainability assessment four analysis dimensions were chosen. The selection of sustainability dimensions, was based upon the three traditional pillars of sustainability – economic, environmental and social (Basiago, 1998) with an additional operational dimension. For each of the dimensions, a set of objectives was created to match the aims and directions found in global and regional mobility policies and trends. Thereafter, for each objective, an adequate indicator (or set of indicators) was defined, based on the findings of previous research on the sustainability of last mile delivery and relevant policy evaluation criteria.

A set of illustrative objectives and indicators to consider is proposed in the remaining part of the subchapter. Depending on the aim and characteristics of the analysed system, those objectives and indicators could vary. Nevertheless, it is crucial in each of the further sustainability assessments to consider all of the proposed dimensions and aim to capture the direct and indirect impact of the system transformation.

A summary of the chosen dimensions, objectives and indicators is presented in Table 5.1.

TABLE 5.1 DIMENSIONS, OBJECTIVES AND INDICATORS USED IN THE ASSESSMENT SUPPORT FRAMEWORK

Dimension	Objective	Indicator
Operational	Quality of service	Time needed for the shipment to reach the final recipient
		Share of door-to-door deliveries
Economic	Economic productivity	Capital costs
		Annual operational costs
		Return of investment after analysed period
Environmental	Air pollution prevention	Annual CO emissions
		Annual NOX emissions
		Annual PM10 emissions
		Annual SO_2 emissions
	Climate stability	Annual GHG emissions
	Energy efficiency	Transport annual energy consumption
		Share of renewable energy in the annual energy consumption
Social	Community development	Land devoted to transport facilities
		Employment turnover
	Equity	Share of potentially excluded users due to technological exclusion
	Noise minimalization	Noise level of a vehicle passing by
	Safety and security	Number of accidents and near misses

Operational dimension

The main operational objective is the quality of the service, the evaluation of which is made through two indicators – the time of delivery and the coverage of delivery demand. The time of delivery is the time passed from registration of shipment at the postal office to its delivery to the final recipient. The coverage of the delivery demand is the share of parcels and letters that the solution is capable of delivering in a door-to-door manner. The second indicator was chosen as compact last mile delivery solutions could have a limited cargo space and load capacity and would not be able to carry all parcels.

Economic dimension

Three economic indicators are used to measure economic productivity objective: capital costs, total annual operational costs and return of investment after five years. Capital costs are the costs of obtaining the fleet of new last mile delivery solutions. The annual operational costs comprise maintenance costs, insurance costs and fuel/electricity consumption costs. The annual operational costs were chosen as an indicator, as it was found important by the expert responsible for the postal services in the location of the case study. As explained, minimising an annual outgoing cashflow is an important factor of financial sustainability of an organisation. This is especially the case of organisations founded with public means, which often have a rigorous budget.

The last indicator represents the share of the investments cost returned after five years, due to savings on operational costs, as compared to the expenditures tight to the currently used system. The indicator was chosen to reflect the profitability of investment in innovative systems, which might be more cost-consuming at first, but secure lower operational costs.

Environmental dimension

The analysis includes three environmental objectives chosen according to the global and regional goals and strategies to enhance quality of life in urban areas and achieve carbon neutral and efficient transport systems: air pollution prevention, climate stability and energy efficiency.

The environmental indicators that reflect the air pollution prevention objective are total annual emissions of Carbon Monoxide (CO), Nitrogen Oxides (NOx), Particulate Matter (PM), and Sulphur Oxidise (SO_x) which according to epidemiological studies are the most important air pollutants in cities (Friedrich and Quinet, 2011) and were used as indices in previous environmental assessments of last mile delivery (Marujo et al., 2018; Navarro et al., 2016; Verlinde et al., 2014). Additionally, annual GHG emissions are an environmental indicator representing the climate stability objective. This reflects the struggle of multiple regional and national governing bodies, to achieve carbon neutrality of transport and prevent rapid progression of climate crisis.

The energy efficiency is also a crucial objective that both private and public sector are struggling to enhance. It is reflected through remaining two environmental indices – total annual energy consumption and share of renewable energy in the total energy consumed.

Social dimension

Lastly, there are four objectives reflecting social sustainability, in line with global and regional policies that aim for a sustainable and inclusive future in dense urban areas. These objectives are: community development, equity, noise minimisation, as well as safety and security.

The community development is often an important goal of local governments, reflected in the analysis with land devoted to transport facilities and the employment turnover indicators. The transport's need of urban space usage (such delivery bays or loading zones) is increasing. With, most urban areas struggling with an imbalance between the loading zone supply and the demands of freight transport operations (Chen et al., 2018), which causes variety of parking issues such as double-parking of freight vehicles which park illegally on street. This makes bottlenecks and therefore leads to increase congestion and increasing emissions (Iwan et al., 2018). With the sprawl of urban areas contributing to the negative transport externalities, it is vital to reclaim the land dedicated to transport facilities in the centres as well as on the outskirts of cities. The reclaimed areas could be used to propagate community development, with Barcelona's superblock serving as a perfect example (Braubach et al., 2017; '"Superblocks" free up to 92% of public space in Barcelona', n.d.). Community development could also be determined by the employment turnover indicator, as studies suggest that communities with higher share of unemployed workers, could suffer from higher crime and violence rates, as well as poorer health of individuals and worse academic performance of children (Jenkins, 1982; Nichols et al., n.d.).

Equity as an objective is included, as some of the newly introduced last-mile delivery solutions could require the end-user to operate smart phones applications. Implementation of such solutions could lead to further marginalisation of digitally excluded, which should be accounted for before their deployment.

Noise minimisation is an objective considered as it has been a concern of numerous regional governments. Long-term exposure to environmental noise, could be particularly harmful, with estimates it causes 12 000 premature deaths and contributes to 48 000 new cases of ischaemic heart disease per year in the European territory (European Environment Agency, 2020).

Finally, safety and security of road traffic is a major concern of all national and regional governing bodies and their citizens. This concern could be amplified by the close presence of new technology, for which trust has not been sufficiently built in the society.

5.1.4 Definition of prioritisation scenarios

The final, fourth, step of the assessment framework allows to compare the solutions, using the MCDA. MCDA is often used to assess numerous, possibly conflicting, criteria in a structured manner. The ordered and controlled assessment that accounts for all previously set objectives is especially important with system changes that involve numerous stakeholders with opposing views. There are numerous MCDA methods to evaluate a system and any of those could be used in the assessment support framework. Multi-attribute value theory (MAVT) has been selected, as one of the most widely used methodologies. MAVT constitutes from determining partial value functions based on established weight for each criterion to capture the global value function in a following manner (Azapagic and Perdan, 2005).

$$V(s) = \sum_{i=1}^{I} w_i u(s)$$

Where:

$V(s)$ is a global value function, representing the total obtained score for an analysed last mile delivery solution s

w_i is a weight of importance for sustainability indicator i

$u(s)$ is a value function, determined through ranking, reflecting the performance of solution s on indicator i. In the ranking value the lesser value is assigned to the most desirable outcome and the highest value to the solution that performs the worst in a given indicator.

I is the total number of indicators

The last mile delivery is a system that involves and impacts a variety of stakeholders realising different vision and aiming for diverse objectives. Therefore, the assessment of the systematic change should not only consider and evaluate the previously mentioned sustainability indicators, but also try to measure the value that each of the indicators could bring to a given stakeholder. With that in mind, four assessment scenarios were created to evaluate each of the last mile delivery solutions from a stakeholder perspective in a MCDA. The developed scenarios and considered weights were designed to represent the main stakeholders of the last-mile delivery systems and their priorities and needs. Apart from understanding the perspective of each of the stakeholder group the four prioritisation scenarios served as a sensitivity analysis, allowing to measure the impact of weight change on the final outcomes of the assessment.

The definition of prioritisation scenarios, results in identification of weights (w) used in the sustainability assessment. The steps to obtain the prioritisation scenario, require the understanding of strategic aims of the decision maker or stakeholder. Once the priorities in terms of analysed dimensions are understood, the weights could be obtained in the following manner:

1. A constant sum (100) is assigned to all the dimensions of the analysis - *operational, economic, environmental and social* (e.g. in the first scenario they are assigned equally giving each dimension a 25 point importance).
2. Within each of the four dimensions, the corresponding weight is distributed equally for each of the corresponding objectives (e.g. within the environmental dimension, the three objectives – *air pollution prevention, climate stability and energy efficiency* – are assigned 8,33 point each).
3. The weights within each objective are distributed equally among the corresponding indicators (e.g. within the energy efficiency objective, the two indices – *transport annual energy consumption and share of renewable energy in the annual energy consumption,* are assigned both 4,165 points).

The first scenario was developed to assess the relatively most optimal setup in which all the dimensions have the same importance. The scenario was created as a base and to support stakeholders whose intentions and priorities could be different than those presented in the remaining scenarios.

The second scenario, reflects the focus of a national or multi-national policy maker, such as EC. The strive for environmentally sustainable future with clean and efficient energy and transport sectors has been a clear mission of the EC, as well as similar regulatory bodies, through programmes such as The European Green Deal, Horizon 2020, Horizon Europe or Concerto. Therefore, this scenario highlights the importance of environmental sustainability by assuming the environmental dimension to be thrice as important as each of the remaining dimensions.

The third scenario highlights the significance of finance and operational effectiveness which would be of highest importance for a last mile delivery service provider. Therefore, the economic and operational dimensions are assumed to be of equal importance and twice as important as an environmental and social dimension.

The fourth scenario looks from the perspective of a city government or other regional governing body, which aims to increase the quality of life for citizens within a given area. Those stakeholders would strive to implement solutions brining the biggest value in the environmental and social dimensions, aiming to reduce air and noise pollution and create collaborative, inclusive and safe environment. Therefore, in the fourth scenario, environmental and social dimensions are twice as important as the financial and operational one. Moreover, safety and equity would be important decision-making factors for governments valuing the safety and inclusivity of implemented solutions. Therefore, those objectives are valued as twice as important as the remaining objectives in the social dimension.

The final weight assigned to each indicator in all scenarios is presented in Table 5.2.

TABLE 5.2 INDICATOR IMPORTANCE WEIGHTS FOR EACH OF THE ANALYSED SCENARIOS

Dimension	Objective	Indicator	Weight S1	Weight S2	Weight S3	Weight S4
Operational	Quality of service	Time needed for the shipment to reach the final recipient	12,50	10	16,67	8,33
		Share of door-to-door deliveries	12,50	10	16,67	8,33
Economic	Economic productivity	Capital costs	8,33	6,67	11,11	5,56
		Annual operational costs	8,33	6,67	11,11	5,56
		Return of investment after analysed period	8,33	6,67	11,11	5,56
Environmental	Air pollution prevention	Annual CO emissions	2,08	3,33	1,39	2,78
		Annual NOX emissions	2,08	3,33	1,39	2,78
		Annual PM10 emissions	2,08	3,33	1,39	2,78
		Annual SO2 emissions	2,08	3,33	1,39	2,78
	Climate stability	Annual GHG emissions	8,33	13,33	5,56	11,11
	Energy efficiency	Transport annual energy consumption	4,17	6,67	2,78	5,56
		Share of renewable energy in the annual energy consumption	4,17	6,67	2,78	5,56
Social	Community development	Land devoted to transport facilities	6,25	5	4,17	5,56
	Equity	Share of potentially excluded users due to digital exclusion	6,25	5	4,17	11,11
	Noise minimisation	Noise level of a vehicle passing by	6,25	5	4,17	5,56
	Safety and security	Number of accidents and near misses	6,25	5	4,17	11,11

5.2 Case study: The Joint Research Centre's Ispra site

The case study analysis is set on JRC Ispra site. The JRC is the EC's science and knowledge service, providing independent scientific research to support policymaking, with its biggest site located in Ispra - a town in northern Italy. The setting was chosen, as the site could stand for micro urban environment with its size (167 ha), population (almost 2700 employees), infrastructure (36 km of roads connecting 230 buildings) and the demand for external and internal postal services[3].

The map of the JRC Ispra site is presented on following Figure 5.2.

[3] JRC webpage is available under following address: https://ec.europa.eu/jrc/en

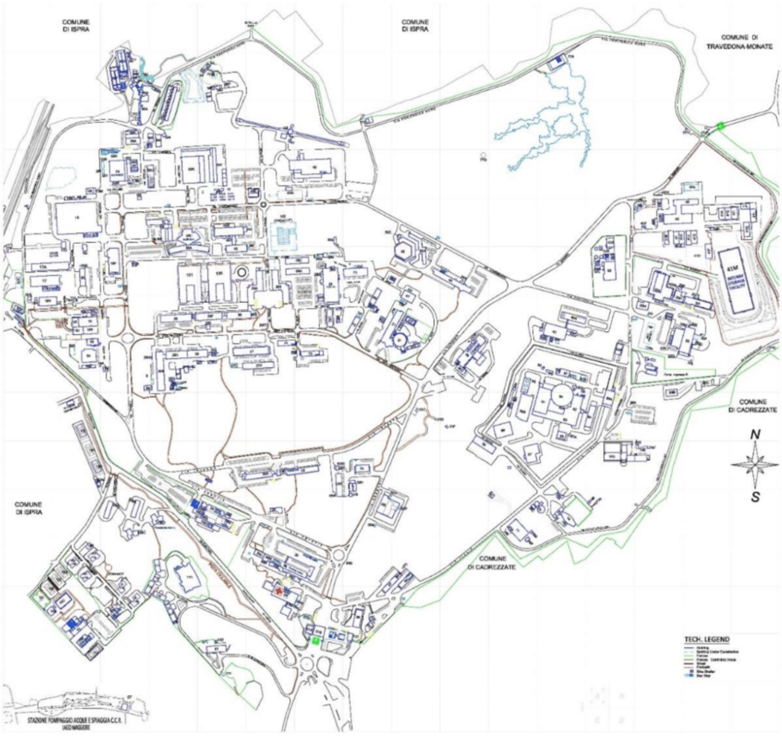

FIGURE 5.2 MAP OF THE JRC ISPRA SITE - SETTING OF THE ANALYSIS

The postal services on site serve as representation of last mile delivery system – the Italian post as well as courier services deliver mail and parcels to post office found on site. Thereafter, the incoming mail is delivered, and the outgoing mail is taken from each building on site (approx. 600 incoming and 300 outgoing deliveries per week). Additionally, to the external mail services, internal deliveries of goods and letters between buildings on site are handled every day (approx. 75 deliveries per week).

The demand for postal services was created as an exemplary week of all postal services carried out at the JRC Ispra site. The information on the number of parcels processed by various postal services was obtained during the interviews with the service responsible. The input from the interviews indicated that some services of the JRC obtain and send mail daily, involving some specific buildings of the JRC Ispra site. Therefore, to create the demand, it was assumed that the delivery services would serve those buildings every day. While the rest of the employees are equally likely to obtain a parcel within a given day. Following this assumption, the demand for the parcels was obtained using a Monte Carlo sampling (5000 draws) from a probability distribution obtained using the number of employees per building. The obtained weekly sample is not significantly different from the distribution of people per building (Z-test =1,176), and therefore is assumed to be an adequate representation of the sample.

5.2.1 Choice of last mile delivery solutions

For the purpose of the assessment, six types of delivery solutions are considered, with the first three being a traditional choice for last mile delivery: LCVs. In particular, three types of LCVs were considered: Euro 4 LCV with gasoline engine from 2006 (the vehicle that currently handles the postal delivery), a new 2020 Euro 6 vehicle with gasoline engine (the LCV with the highest number of new vehicle registrations in the country of setting) and a 2020 eLCV.

The three LCV-based services are compared with an automated last mile delivery service operated by delivery droids. The not yet widely implemented solution is considered as there was already an initial acceptance of the technology by the employees of the institution. An initial acceptance check was performed in the mobility survey distributed at the JRC in October 2020. A fraction of the questionnaire was dedicated to the future of mobility at the site, and out of the 25% of staff that filled in the survey, 60% of employees declared willingness to use last mile delivery droids for lunch delivery as well as private or work-related postal services. As the JRC is wheelchair accessible, the droid based system would be able to carry deliveries to all individuals in all buildings located onsite. However, as the last mile delivery droid is not capable of covering the entire shipment demand due to its relatively small cargo space and maximum load capacity, it needed to be coupled with other delivery system. Three types of solutions were considered to assist the droid system, namely:

- eLCV for the majority of deliveries and droid handling special singular requests.
- Euro 4 LCV that currently handles deliveries on the analysed setting only for parcels which do not fit in the droid.
- Depot station, so that the recipients pick up the parcels that cannot be delivered with droids.

The vehicle specific information used for the purpose of the analysis is presented in the following Table 5.3.

TABLE 5.3 VEHICLE SPECIFIC CHARACTERISTICS

VEHICLE	EURO 4 LCV	EURO 6 LCV	ELCV	DELIVERY DROID
Energy source	Gasoline	Gasoline	Electricity	Electricity
Production year	2006	2020	2020	2020
Mass [kg]	2 330	3 000	2 300	40
Cargo space dimensions (L X W X H) [CM]	310 x 142 x 190	305 x 198 x 195	186 x 114 x 113	42 x 38 x 31
Maximum load capacity [kg]	1 500	1 500	715	10
Price (euro per one vehicle)	NA	32 000	38 000	4 550

5.2.2 Development of operational strategies for the analysed options

Currently, the postal services are carried out with an LCV which visits all buildings on site every day to deliver both the external and internal mail as well as potentially pick up the outgoing external and internal deliveries. Furthermore, the LCV makes an additional delivery route, to deliver parcels to their recipients.

The same operational strategy is assumed to remain for all LCVs considered in the analysis. The routes that the LCV follows were assumed to be the shortest (in terms of driving time) possible, found with the traveling salesman optimisation method. The distances and travel times between each building were obtained using the google distance API and latitude and longitude of each building.

The combination of eLCV with last-mile delivery droid results in a new operational strategy, for which, it is assumed that the eLCV makes two routes. During the first drive, all postal and courier letters are delivered to their recipients, and all parcel deliveries during the second drive. Similarly, to previous operational strategies, it is assumed the driver follows the shortest path between the buildings that have an awaiting shipment. Complementary, the outgoing and internal mail is handled by the last-mile delivery droid. Therefore, the eLCV visits only buildings for which there is an intended delivery on a given day, as it is not required to visit all dwellings, to check if there is a pending internal or outgoing mail to collect. The droid is charged overnight and stored in the post office at the JRC site, from which it starts and in which it ends all its trips. The internal mail is handled with singular trips of the droid upon a request from the sender. The droid makes the trip from the post office to the sender and immediately after to the recipient of the mail and back to the post office. Similarly, the outgoing mail is also handled as singular request with the droid starting the trip in the post office, picking up the mail at the working place of an individual creating the request and coming back to the post office. It is assumed that, for each singular request, the droid chooses to follow the shortest path (in terms of distance), using the walking pathways and accessing buildings. As the exact distance of delivery route was impossible to determine, the distance is assumed to be equal to walking distance from door to door of each building (obtained analogously to driving distance) with additional 100 meters of internal building delivery.

The results, presented further in chapter 5, indicate that one droid is sufficient to account for all daily demand for internal and outgoing mail. While, in the strategies in which the droids are coupled with a Euro 4 LCV or with the depot station the droids also deliver post and courier mail, raising the number of required droids to 3. In said strategies the droids deliver post mail and courier mail separately (due to different timing of deliveries). The route that the droid takes to deliver the post and courier mail is determined using the traveling salesman problem, using the walking distance between buildings. If the route is too long to be handled with one droid on one charge, the delivery is handled by two droids. The parcels to be carried by each droid are determined using the previously encoded clusters of buildings, which allow to direct the parcels with nearby destination together. Moreover, the droids handle the internal and outgoing mail by singular trips upon request, similarly to what was described in the previous operational strategy.

While the droids are coupled with a Euro 4 LCV, the vehicle is used only to handle the incoming parcels, which cannot be delivered by the droid due to cargo space limitation. The LCV delivers the parcels each day, taking the shortest route. Similarly, when the droid is coupled with the depot station the parcels that are not suitable for the droid to deliver are placed in a depot station, located at the post office. It is assumed that the recipients are informed about awaiting parcel and pick it up coming from their main office building, to which they return, once the parcel is picked up.

5.2.3 Selection of sustainability indicators

This subchapter presents the key assumptions and estimation techniques to obtain the indicator values used in the analysis.

Operational dimension

The time of delivery is estimated based on the operational strategies developed in the previous point. Therefore, for all the LCVs as the operational strategy does not change from the current one, the delivery time remains the same and is equal to 2-3 days. With the introduction of the last mile delivery droids, the delivery time shortens to same or next day delivery, as the droid is able to immediately handle the singular internal and outgoing requests.

Moreover, when the delivery droid is coupled with the depot station, parcels that do not fit into the droid are assumed to be picked up at the depot station. The share of parcels that would not fit into the droid was obtained during interviews with postal services employees and estimated at 5% of the total number of parcel shipments.

Economic dimension

The capital costs of obtaining the last mile delivery solutions, were obtained from their manufacturers. There is no capital cost of obtaining a Euro 4 LCV as it is already available on site.

For the annual operational costs (comprised of maintenance costs, insurance costs and fuel/electricity consumption costs), the electricity/fuel consumption costs for all vehicles are calculated according to the average electricity/fuel price in Italy in 2020. The maintenance as well as insurance costs for the Euro 4 LCV are assumed to be equal to the current costs borne by the JRC for those services. Those costs for Euro 6 and eLCVs are assumed to be equal to maintenance and insurance costs of vehicles of the same class, which are a part of fleet of JRC service vehicles.

The maintenance and insurance cost of the last mile drone are assumed to be 5%[4] of the capital costs of the fleet. The same assumption is made for the depot station.

The return of investment (ROI) indicator was estimated knowing the capital costs and the annual operational costs, after an assumed five-year period. The period was chosen as evaluation period for costs assessment at the analysed institution – the JRC. ROI was calculated in the following manner. To obtain the results, the annual savings were discounted over the inflation.

$$\text{ROI} = \frac{Cost\ savings}{Cost\ of\ investment} \cdot 100\% \qquad 2$$

Environmental dimension

To estimate the remaining environmental indicators, first the energy consumption of all last mile delivery solutions needed to be obtained. Total energy consumption of the combustion engine LCVs was calculated as the fuel consumption of everyday drive between all man-present buildings on site, using the green driving tool (European Commission, 2021). Green driving tool is a detailed vehicle simulation platform, developed internally at the EC and made available to the public to support environmentally aware decision making. The tool calculates fuel consumption, cost of journey and GHG emissions of combustion-engine vehicles, based on specific vehicle configuration and journey information.

The fuel consumption of cars, used to pick up parcels at the depot station (used in the strategy of droid system coupled with a depot station) is calculated based on the assumed fleet distribution of the JRC population in a comparable manner, based on expert knowledge of the site's population and launched mobility survey for the site's employees. The fleet was assumed to constitute of Euro 6 vehicles produced between 2017 and 2019. Further information known about the fleet is the distribution to vehicle segments according to green driving tool classification (30% of segment A vehicles, 40% of segment C vehicles and 30% of segment E vehicles) and the engine type of the vehicle (30% of gasoline fuelled vehicles, 65% of diesel combustion engines and 5% of EVs).

The electricity consumption of eLCV and the last mile delivery droid was calculated using vehicle dynamics, according to the following equation (Lebeau et al., 2015):

$$E_{ij} = \frac{d_{ij}}{3600 \cdot \eta} \cdot \left(m \cdot g \cdot (\omega \cdot \cos\varphi + \sin\varphi) + 0.0386 \cdot \left(\rho \cdot \sigma \cdot \mu \cdot \vartheta_{ij}^{2}\right) + m \cdot \frac{d\vartheta}{dt} \right) \qquad 3$$

Where:

- E_{ij} is the electricity consumed by the engine (kWh)

[4] Average vehicle maintenance and insurance cost as a share of vehicle price given by the American Automobile Association (The American Automobile Association, 2019).

- d_{ij} distance of the drive (km)
- η is the efficiency of the vehicle
- m is a mass of the vehicle (kg)
- g is gravitational acceleration
- ω is a vehicle rolling coefficient. Assumed to be the coefficient of car tire on asphalt for LCV and car tire on cobblestone for the last mile delivery droid)
- φ is a road gradient angle (deg)
- ρ is air density
- σ is the drag coefficient of the vehicle (with the delivery droid assumed to be a cuboid)
- μ is the cross section of the vehicle (m^2)
- ϑ is the speed of the vehicle ($\frac{km}{h}$) (assumed to be the maximal driving speed allowed onsite for the eLCV and 6 $\frac{km}{h}$ for the delivery droid - a speed of the droid on pavements given by its manufacturer)

The electric solutions could consume energy coming from sustainable renewable sources, which is represented by the share of renewable energy consumed indicator. The indicator is calculated as a share of renewable electricity consumed in total energy consumption, according to the Italian energy mix for 2019 (International Energy Agency, 2021).

The total emissions of the combustion-engine LCVs were obtained using COPERT, a vehicle activity-based emission calculation model developed by the European Environmental Agency (Ntziachristos and Samaras, 2020). Whereas the emissions of eLCV and the last mile delivery droid were calculated according to the emissivity of Italian grid given by the national Italian institute of environmental protection (*Istituto Superiore per la Protezione e la Ricerca Ambientale*) (Istituto Superiore per la Protezione e la Ricerca Ambientale, 2019).

Social dimension

The assessed social indicators include: land devoted to transport facilities, employment turnover, share of potentially excluded users due to digital exclusion, noise level of a vehicle passing by and number of accidents and near misses. To conduct the case study, all of those were thoroughly assessed with all the analysed operational strategies for last mile delivery.

The land currently devoted to last mile delivery services is a parking spot of the LCV. The amount of land dedicated to transport would not change if other LCVs were the prospective solution, whereas in case of delivery droids the vehicle would require a smaller space (operation room for charging and storing). Also, the depot station would require an additional land to stand on. The amount of land required by those solutions was given by their manufacturers.

The employment turnover indicator is omitted in the analysis as it would be constant in all analysed scenarios due to particular characteristics of systematic change. Upon discussing with departments responsible for shipment delivery at the considered setting, it has been agreed that implementation of automated delivery with delivery droid would result neither in additional hires nor in layoffs. The reason being, the wider and diverse responsibilities of staff in charge of delivery services. Additionally, one of the employees could undergo additional training to handle the droid day to day operation and maintenance.

Equity is measured as a share of potentially excluded customers. The LCVs that currently deliver mail on the JRC site do not require an external device to operate, while the last mile delivery droid and the depot station could be more difficult to operate by those digitally excluded. The share of those potentially marginalised is not estimated but, rather acknowledged as an additional difficulty for digitally excluded.

The objective of noise minimisation is measured through a noise pollution indicator as the pass by noise caused by the vehicle. The noise levels of LCVs are obtained from legislative requirements and experimental research (European Parliament, 2014; Miloradović et al., 2017; Ministry of Infrastructure and the Environment, 2015), whereas the noise level of the last mile delivery droid is said to be negligible, as per information obtained from its producer, and is therefore equal to environmental noise.

Safety and security of road traffic is a major concern, especially in presence of delivery droids which would frequent the pavements typically reserved for walkers and is therefore an important objective. It is measured as the total number of near misses and accidents involving the LCV fleet of the analysed JRC (0) for all LCV vehicles. The safety of the droid is marked as not determined as to lack of available experiment-proven information or conducted risk assessment of the droid.

5.2.4 Definition of prioritisation scenarios

Safety and security of road traffic is a major concern, especially in presence of delivery droids which would frequent the pavements typically reserved for walkers and is therefore an important objective. It is measured as the total number of near misses and accidents involving the LCV fleet of the analysed JRC (0) for all LCV vehicles. The safety of the droid is marked as not determined as to lack of available experiment-proven information or conducted risk assessment of the droid.

5.3 Results

For the sustainability assessment of last mile delivery, the results of each indicator needed to be obtained. The results suggest that droid-based system coupled with a Euro 4 LCV outperforms other solutions on the economic dimensions. While a combination of eLCV with supplementary droid is the most environmentally friendly option. Both of those options also secure the highest quality of delivery, whereas eLCV was found to be the most socially sustainable option.

On the operational dimension, the best results are yielded by the combination of eLCV and delivery droid and the delivery droid-based system coupled with a Euro 4 LCV. As, delivery droid allows for an instant pick up of outgoing mail and delivery of internal shipments, which otherwise would have to wait for the next routine drive of an LCV. Moreover, the supporting LCVs secure the door-to-door delivery of the parcels which do not fulfil criteria of a small delivery droid.

The financial aspects of the analysis are somewhat different. The simulation of weekly delivery of analysed parcel demand with six analysed delivery strategies has allowed to determine the required number of droids needed to cover the demand during the 8 working hours. The assessment was made by plotting the time required for the deliveries and state of charge of the droid. The obtained results suggest that three delivery droids would be needed to handle all delivery services at the JRC, and one droid would be enough to handle outgoing and internal mail as a complement to an eLCV.

The outcomes suggest that with the current market prices, the lower operational costs of delivery droid-based system coupled with the Euro 4 LCV would cover 67% of investment after five years. High return of investment, due to saving in operational costs is also secured with the droid based system combined with a depot station (41%). Additionally, those results indicate that 25% of eLCV investment would be covered after this period and 23% for the best quality of operation system – combination of an eLCV with a delivery droid. Investment in a Euro 6 LCV brings the lowest return, as the fuel costs of this vehicle result in higher operational costs. Which proves that, in presence of developing technology, capital costs should not be a decisive criterion, and in the long run the environmentally unsustainable option could also become a financial anchor.

The environmental dimension is closely related to the total energy consumption of each system, which was obtained because of weekly delivery system simulation. The total energy consumed by the delivery droid is significantly smaller than the consumption of other systems, even though the vehicle covers greater distance. The distance covered by everyday drive and parcel delivery by LCVs is equal to 12 754 km annually, whilst the three delivery droids would have to collectively cover more than twice as much (27 782 km) due to dispersed delivery strategy. Moreover, to deliver the parcels which the droid cannot carry, the Euro 4 LCV would have to drive 1 284 km annually. Interestingly, the number of kilometres covered by cars when recipients pick up their parcels at the depot station is almost three times higher due to disaggregated approach. A combination of both strategies – postal, courier and parcel shipments delivered with eLCV and the internal and outgoing mail handled by the droid, results in a lowering of travelled kilometres to 22 094 km per annum. More importantly, it cuts in half the distance covered with an LCV (6 210 km), significantly contributing to reduction in all emissions while maintaining a full demand coverage.

Annual emissions depend on the type of energy consumed, with cleaner energy source – electricity providing better results. Therefore, investment in delivery droids and the eLCV is the most positive from the environmental standpoint, with singular eLCV being a close second in terms of air quality but lagging in climate neutrality objective due to GHG emissivity of the Italian grid. Moreover, the coupling of delivery droid system with other solution, also yields positive environmental results, decreasing emissions.

Implementation of the droid with the Euro 4 LCV, drastically decreases emissions, and allows to achieve moderately good results in the air quality objective. Coupling the droid with the depot station, results in the final recipient's car usage to pick the parcel from the post office and bring it back to their building. Nevertheless, even with higher millage covered by cars, the GHG emissions are lower than those caused by the Euro 4 LCV. That is because the fleet driven by the JRC employees is newer and subject to higher emission norm standards.

Annual emission of SO_x is the only environmental indicator which gives better results with a fully LCV solution – Euro 6 LCV. It is because of high emissivity of an Italian electricity system, however with a reasonable assumption that Italian energy system will continue the sustainable transformation to renewable energy sources, all the electricity emissions would inevitably decrease.

The results obtained for the social dimension objectives and indicators, point that an eLCV would be the most socially sustainable solution, as per the guaranteed equity of the system, lower harmful noise pollution and proven safety of the LCV based system. Nevertheless, once the delivery droid is tested and established to be safe and with adequate digital education, the droid based solutions could outperform the eLCV, due to the low motor noises and possibly lower spatial demand.

The analysis of results for each indicator did not allow to determine which of the proposed solution is the most optimal, as per contradictory outcomes on the criterion, objective and dimension level. Hence, the need to take the further steps of the assessment support framework. The detailed outcomes of the analysis for each indicator and each delivery solution are presented in Table 5.4. The table representing the ranking results of each solution (Table 5.5) is following along with the detailed explanation of how the ranks were obtained.

TABLE 5.4 INDICATOR RESULTS FOR EACH DELIVERY SOLUTION

Dimension	Objective	Indicator	Euro 4 LCV	Euro 6 LCV	eLCV	eLCV + last mile delivery droid	Last mile delivery droid + Euro 4 LCV	Last mile delivery droid + depot station
Operational	Quality of service	Time needed for the shipment to reach the final recipient	2-3 days	2-3 days	2-3 days	0-1 day	0-1 day	0-1 day
		Share of door-to-door deliveries	100%	100%	100%	100%	100%	95%
Economic	Economic productivity	Capital costs [€]	-	32 000	38 000	42 535	13 605	23 605
		First year operational costs [€]	2 834	1 645	822	817	927	834
		Return of investment after analysed period	0%	18%	25%	23%	67%	41%
Environmental	Air pollution prevention	Annual CO emissions [g]	309,50	132,81	0,22	0,12	0,58	0,69
		Annual NOX emissions [g]	419,31	259,43	0,52	0,29	21,62	51
		Annual PM10 emissions [g]	132,09	8,03	0,007	0,004	13,30	42,46
		Annual SO_x emissions [g]	2,06	1,94	48,17	26,88	9,84	10,05
	Climate stability	Annual GHG emissions [g]	2 544 244	2 394 075	1 146 159	639 492	480 975	409 989
	Energy efficiency	Transport annual energy consumption [kWh]	8 604	8 093	2 373	1 324	1 331	1 216
		Share of renewable energy in the annual energy consumption	0%	0%	33%	33%	12%	13%
Social	Community development	Land devoted to transport facilities [m2]	20	20	20	30	30	10
	Equity	Share of potentially excluded users due to technological exclusion	No	No	No	Yes	Yes	Yes
	Noise minimisation	Noise level of a vehicle passing by [db]	74	74	70	66	65	66
	Safety and security	Number of accidents and near misses	0	0	0	ND	ND	ND

TABLE 5.5 RANKING RESULTS FOR EACH DELIVERY SOLUTION

Dimension	Objective	Indicator	Euro 4 LCV	Euro 6 LCV	eLCV	eLCV + droid	Droid + Euro 4 LCV	Droid + depot station
Operational	Quality of service	Time needed for the shipment to reach the final recipient	6	6	6	1	1	1
		Share of door-to-door deliveries	1	1	1	1	1	6
Economic	Economic productivity	Capital costs [€]	1	4	5	6	2	3
		First year operational costs [€]	6	5	2	1	4	3
		Return of investment after analysed period	1	6	4	5	2	3
Environmental	Air pollution prevention	Annual CO emissions [g]	5	6	2	1	3	4
		Annual NOX emissions [g]	6	5	2	1	3	4
		Annual PM10 emissions [g]	6	3	2	1	4	5
		Annual SO_x emissions [g]	2	1	6	4	3	5
	Climate stability	Annual GHG emissions [g]	6	5	4	2	3	1
Social	Energy efficiency	Transport annual energy consumption [kWh]	6	5	4	2	3	1
		Share of renewable energy in the annual energy consumption	6	6	1	1	4	3
	Community development	Land devoted to transport facilities [m2]	4	4	4	6	6	1
	Equity	Share of potentially excluded users due to technological exclusion	1	1	1	6	6	6
	Noise minimisation	Noise level of a vehicle passing by [db]	6	6	5	4	1	2
	Safety and security	Number of accidents and near misses	1	1	1	6	6	6

For the ranking, the smallest value is assigned to the most desirable outcome whereas the highest value is assigned to the solution that performs the worst in each indicator. Moreover, to penalize the worst performing delivery solutions and reward the best performing ones, the ranking is kept always between 1 and 6 (e.g. if there is just one differentiative result, as in the share of door-to-door deliveries, the best performing solutions will all be ranked as 1 while the worst performing ones will be ranked 6).

The results depicting the performance of the analysed delivery solutions within each prioritisation scenario are obtained using the ranking results presented in Table 5.5 and chosen weights presented in Table 5.2 according to the equation given in section 5.1.4. These results are described in more detail in the following sections, and graphically represented on Figures 5.3 to 5.6.

5.3.1 Scenario 1

S1 reflected a case in which all the dimensions are equally valuable. The results of the analysis indicate that overall, a system using last mile delivery droid supported by the readily available Euro 4 vehicle is the most suitable option in this scenario. While this option is economically and environmentally satisfactory, the further marginalisation of digitally excluded and unknown safety implications are the main drawbacks. Nevertheless, as the JRC population uses digital services in their work, the equity issue would not pose a major constraint.

Secondly, the second-best performing solution could be used – the combination of eLCV with the delivery droid, which while initially cost intensive is more profitable in the long term than a Euro 6 LCV, and less energy-consuming than a singular eLCV. Provided testing and safety assurance of the solution it would further outperform the LCV based options.

The droid-based system coupled with a depot station, is also a well performing option, nevertheless, it would require additional capital costs, and could be troublesome to the population, as the delivered parcels could be too heavy or too difficult to carry by some individuals. Investment in eLCV, either supported by the droid or not, is also preferred to the combustion engine LCVs. There is a clear difference in performance between the combustion engines and electric motor solutions, mostly because of the negative environmental impact but also because of the high operational costs. Pointing, to the fact that investment in the combustion-engine LCVs should not be considered.

The detailed results of S1 performance, with three best preforming scenarios highlighted, are presented hereunder on Figure 5.3. The horizontal axis on the figure represents the total score obtained by each of the analysed solution, with the highest score, being least favourable according to the sustainability assessment framework.

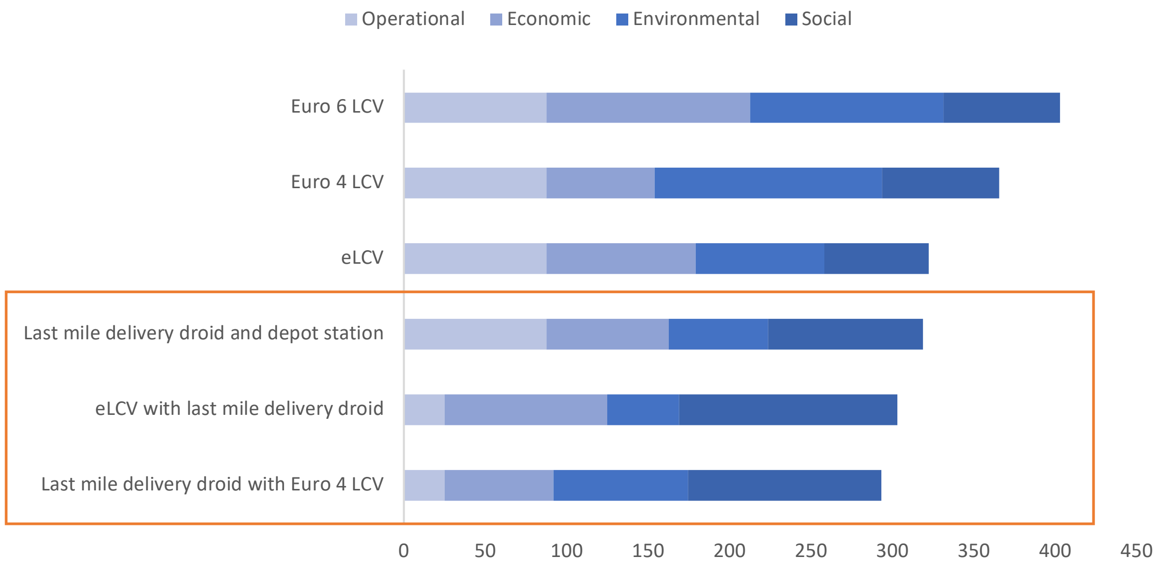

FIGURE 5.3 RESULTS OF SUSTAINABILITY ASSESSMENT FOR SCENARIO 1

5.3.2 Scenario 2

In S2, emphasis was put on the environmental performance of the solutions, which could reflect the desires of national or multinational governing body, which needs to fulfil the set environmental targets. It is no surprise that the best performing solution in this case is the eLCV coupled with the delivery droid, which is the fully electric solution, resulting in good air quality, low total energy consumption and the highest share of renewable energy. Moreover, the environmental and operational advantage of a droid and eLCV outperforms the economic benefits of singular eLCV investment and the tested safety of the system.

The second-best performing solution is the one with the lowest carbon footprint – the coupling of delivery droids with the depot station. The small and efficient electric motors of the droids result in low electricity consumption, while the new fleet of vehicles used by the JRC employees does not bump the emissivity of the system much higher. The environmental performance of both those strategies would be higher if the vehicles that accompany the droids, would be electric, which was not considered due to high total capital costs of such solution. Nevertheless, with time, the Euro 4 LCV could be substituted with eLCV, and the car fleet of JRC employees would also be transitioning towards a more sustainable one.

Unsurprisingly, the fuel absorbing Euro 4 vehicle is the least desired solution, mostly due to its major negative environmental impact. Nevertheless, the importance of environmental factors does not justify an investment in a Euro 6 LCV, due to the miserable performing economic dimension, and marginal environmental advancement compared to other options. The further support for this scenario could be built with accompanying regional policies restricting the entry of combustion engine vehicles to city centres and residential locations. Such change would result in lower operational performance of combustion engine LCVs, due to inability to deliver the entire shipment demand.

The detailed results of S2 performance are 3 resented hereunder on Figure 5.4, analogously to S1 representation.

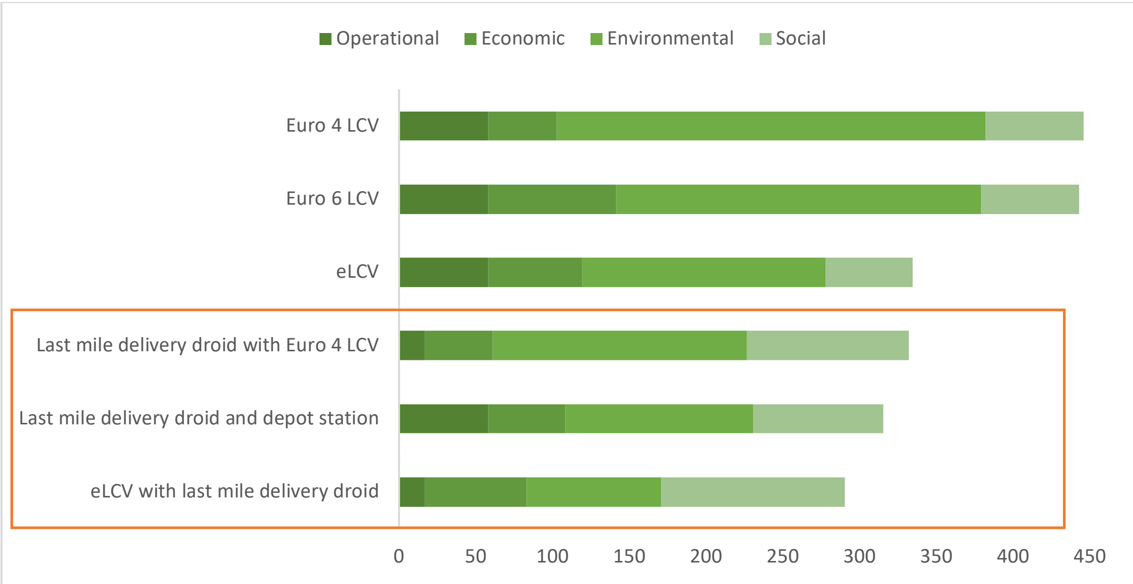

FIGURE 5.4 Results of sustainability assessment for Scenario 2

5.3.3 Scenario 3

The S3 reflected the approach of the private last mile delivery service provider. It was assumed that a private body, which is profit oriented would focus on the economic and operational dimensions of the solutions, highlighting the importance of the full delivery coverage.

The last mile delivery droid-based system assisted by Euro 4 LCV for parcel delivery is the preferred option for the last mile delivery provider. Investment in the droids secures better operational performance by shortening the delivery time for the shipments. Moreover, the investment is not capital-consuming compared to the purchase of a new LCV and brings significant savings due to lower operational costs (67% of the investment will be covered by those savings after 5 years).

The second preferred solution is the coupling of eLCV with delivery droid, which, even though cost intensive at the beginning, enhances the operational quality of the service provider by shortening the delivery time, similarly to the best option. This solution also guarantees the lowest operational costs, resulting in significant savings for the investor.

Coupling the droid based system with the depot station is not the preferred option, as it does not provide the door-to-door delivery, which in case of heavy parcels could be problematic for the users, and therefore lowers the quality of the service.

Investment in the eLCV is not considered as preferred solution in this scenario even though it secures annual operational savings, as it is cost intensive and does not secure a better quality of the service for the users. Investment in the Euro 6 vehicle is also not supported, because of similar reasons and further marginalised because of poor environmental performance.

Moreover, keeping only the Euro 4 LCV is also not encouraged, despite the lack of investment. Which proves that, if private companies are even marginally concerned about the societal and environmental implications of their actions, service providers could turn towards innovation. Investments in developing start-ups could prove profitable, while satisfying the growing needs of consumers.

The detailed results of S3 performance are presented hereunder on Figure 5.5, in an analogical manner to previous results presentation.

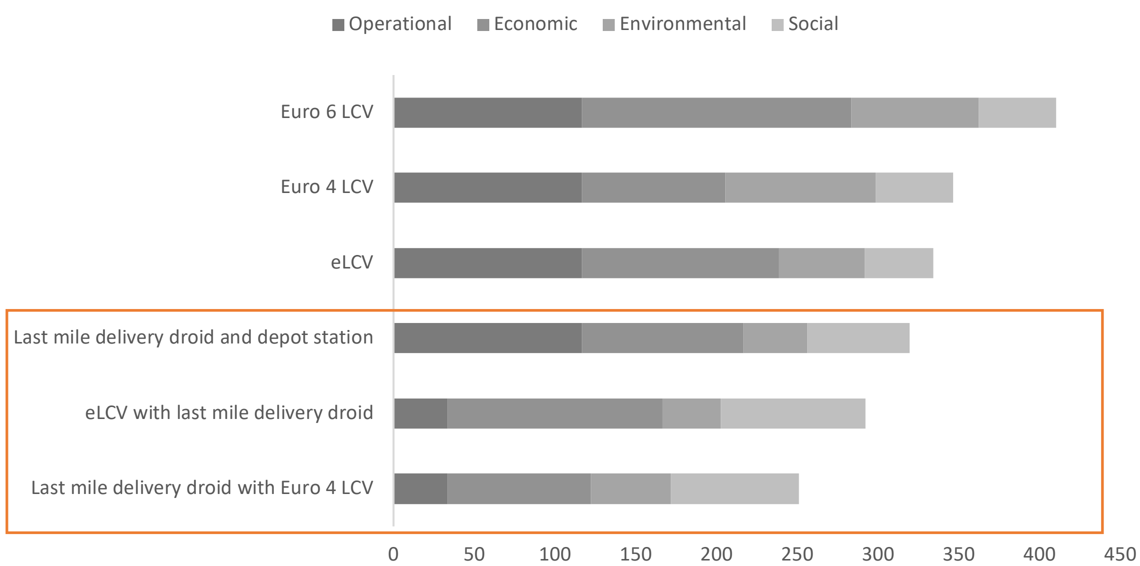

FIGURE 5.5 Results of sustainability assessment for Scenario 3

5.3.4 Scenario 4

The S4 underlines the importance of social and environmental sustainability and could reflect the objectives of a regional governing body aiming to enhance the quality of life in its area. The objectives that have the highest impact on the analysis are social equity, safety, air pollution prevention and climate stability.

The results of this scenario highlight the need to investigate and confirm the safety of the last mile delivery droid. As opposed to all previous scenarios, the droid based strategies are not identified as the best solution in this case, because of the lack of risk assessment. Nevertheless, as the last mile delivery droid-based strategies are more environmentally sustainable, once the safety of the droid is assured, those results could change. If so, the second most preferred option is the eLCV coupled with the delivery droids. This option secures the best environmental performance, decreases the traffic noise and provides good quality service to the consumers. The third preferred option of coupling the droid with the depot station, additionally results in lower land demand for transport services which could be preferred in dense urban areas.

Due to their highly negative impact on the environment and low societal added value, the combustion engine LCVs are again the lowest performing solutions, with an increasingly visible difference in the obtained total result.

The detailed results of S4 overall score performance are presented hereunder on Figure 5.6.

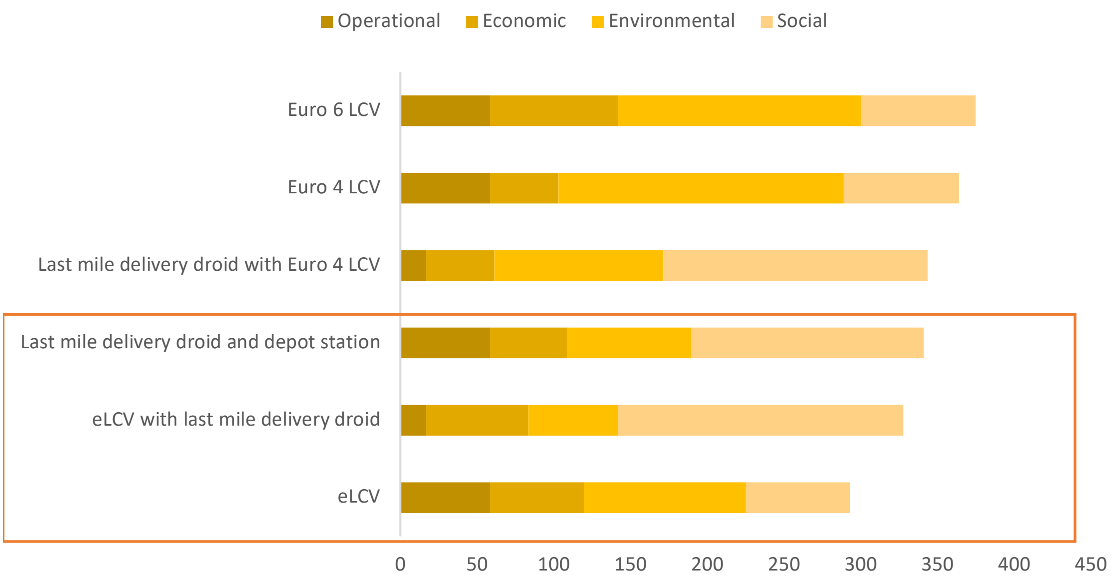

FIGURE 5.6 RESULTS OF SUSTAINABILITY ASSESSMENT FOR SCENARIO 4

5.4 Policy recommendations for implementation of last-mile delivery droids

With a recent ambitious declaration of EC's objective to cut 90% of transport GHG emissions by 2050 (European Commission, 2019), there is a more pressing need to seek carbon neutral transport solutions also in the last mile delivery systems. Therefore, all stakeholders involved in the system creation should consider the environmental implications of the freight delivery, and transport policies should direct profit seeking companies to consider electric low-carbon technologies. Indeed, this analysis has proved that, even with a marginal consideration of social and environmental factors in S3 and heavy contribution of operational and economic dimensions, the carbon-intensive combustion engine LCVs did not prove to outperform the electric innovations.

Hence the importance of regional, national, and European policymakers to focus on transferring the responsibility for the implications of negative externalities on their creators. For instance, regional policymakers could restrict combustion engine freight vehicles from entering city centres, forcing the companies to invest in or even develop more sustainable alternatives. Furthermore, the European policymakers could opt to subsidise local delivery providers who support sustainable innovation or penalise those with outdated fleets, which contribute to climate crisis and air pollution in urban areas. According to the Green Deal sustainable and smart mobility strategy, fees for road usage could also be implemented (European Commission, 2019). Those types of actions result in further penalisation of combustion engine and preference towards sustainable innovation.

Among the solutions proposed in this analysis, eLCVs are already an established and tested option, yet with a significant potential for further development and implementation by delivery companies. In particular, the high capital costs of the eLCVs at present constitute a barrier for delivery providers. Furthermore, the proposed alternative delivery droid-based systems could further reduce the electricity consumption and following emissions, while lowering the investment cost. Nevertheless, the system that is based on delivery droids also has its shortcomings, namely the limited cargo space and low maximum weight of the parcel, unproven safety record and the plausible marginalisation of digitally excluded.

To secure the full demand coverage, the droid should be coupled with an alternative solution. In this study, we analysed the combination of droid based systems with Euro 4 LCV and the depot station. Both of those solutions provided good results, with cost-efficient droid based system coupled with already available LCV for marginal number of deliveries preferred. That is because of guaranteed full door to door service, and significant emissions and energy consumption reduction. Nevertheless, Euro 4 LCV in time should be decommissioned and replaced by a more sustainable solution.

Alternatively, the delivery droid could be coupled with depot stations, at which the packages which do not fulfil the droid criteria could be stored waiting for the pick up by their final recipient. It is crucial to highlight the importance of land needed for transport services indicator. The reduction of land dedicated for transport services is a desirable outcome for cities as the reclaimed land could be used for community development, enhancing the quality of life of the citizens and proposing new social activities. Moreover, where possible, the land could be used for residential purposes, possibly reducing the urban sprawl, further contributing to the air quality improvements. This solution, however, could prove to be unsustainable if individuals coming to collect the shipment would use unsustainable transport solutions. Therefore, droid based delivery systems coupled with depot stations could be implemented in dense urban areas in which there is a pressing need to reduce land devoted to transport. In those types of spaces, provided that the depot station is nearby, it is also more likely that individuals would opt to walk to pick up shipments.

Nevertheless, before those vehicles are allowed to roam on our pavements, the safety of those solutions needs to be established. For that purpose, the droid should firstly be implemented on testing grounds, preferably within living labs, in which participants are already using innovation. Guaranteed safety of the droid would significantly improve the scores it obtained in this analysis, confirming its sustainable status.

Moreover, the implementation of droid-based services could result in further exclusion of those digitally impaired. As an advanced society, we should not aim for further marginalisation of those digitally excluded, either by change or by choice, and, while implementing the solution of tomorrow, always consider the digital capabilities of the entire population. Therefore, whilst implementing the droid delivery systems, some form of analogue delivery should always be possible. The living labs could be used to co-create the delivery droid application and booking system with digitally excluded. Such activity could result in provision of a solution more accessible to all.

5.5 Chapter summary

This work followed an MCDA framework for the sustainability assessment of innovation in last mile delivery. The framework was applied to the mail and parcel delivery system of the JRC Ispra site (Italy). The proposed sustainability assessment framework is considered a suitable decision-making support tool for the deployment of future, carbon neutral transport systems.

The obtained results illustrate the complexity and challenges faced by the planners and policymakers designing future transportation, in which multiple stakeholders with various preferences and priorities intertwine with significant externalities that the system is responsible for. The results point out that there is no fit for all solution, but a string of conflicting needs and criteria, hence trade-offs and compromises are necessary.

It has been demonstrated that, for a stakeholder valuing all sustainability and operational dimensions equally, the implementation of last mile delivery droids coupled with currently available LCV would be the preferred system. It is also a very cost-efficient system, resulting in fast return of investment due to operational savings, and would be therefore the preferred option for delivery service providers, who value the economic and operational dimensions.

Moreover, the eLCV assisted by a delivery droid was the preferred option for all environmentally concerned, because of the efficient electric motors and clean energy source. When considering social criteria, the marginalisation of digitally excluded coupled with safety uncertainties related to untested delivery droids, point to a different implementation direction, identifying the eLCV again as the most sustainable option.

The results indicate that the implementation of the delivery droid system can have a positive impact on the environment, whilst improving the quality of services by shortening the delivery times. Nevertheless, due to compact size of those solutions, they should always be implemented with utmost caution for the type of delivered shipments. The limited cargo space of the droid often indicated the need to couple the system with an assisting technology for larger parcels and for those not willing or not capable of using the droids.

6. Synthesis of Results, Summary of Impacts and Policy Implications

This chapter presents the findings of this PhD research in a concise manner. Further, it demonstrates how these findings could assist policy makers in preparing a sustainable transport agenda for the years ahead. These discussions could help governments and other stakeholders develop a realistic insight into the potential of emerging technologies in resolving urban transport issues.

6.1 Synthesis of results

This section summarises the main findings of this dissertation. The key discoveries of this work are outlined as follows:

SAV related findings

- SAVs have been long awaited and are often referred to as the solution to achieve low carbon transportation and to limit climate crisis. Yet, user behaviors must be carefully considered when designing those services and the policies they should be subjected to in order to limit unintended consequences, such as the environmental rebound effect.
- The rebound effect could be lowered if the car owners are encouraged to use SAV-based services.
- The negative environmental rebound could be minimised by an optimal fleet size. Such fleet size should facilitate that users willing to switch from private modes towards shared rides do so, while those opting for sustainable modes remain using them.
- The highest environmental rebound effect was caused by the generation of new demand, caused by users willing to participate in more activities that they used to before the introduction of SAVs technology.

AVs parking related findings

- For now, there is a high stated preference for parking in dedicated areas in the outskirts of the city. Nevertheless, as the users gain trust in the AVs or are part of the early adopters' group, they show higher stated preference towards unconventional parking strategies – cruising and sending the vehicle home.
- Those with higher regard for the environment and with a preference for car-free cities are more likely to choose parking outside of the city centre, which would support policies of car free central areas.

- Despite the applied parking policy, there would always be individuals who would send vehicles back to their home locations, so they can serve other household members.

Last-mile delivery droid related findings

- The implementation of the delivery droid system can have a positive impact on the environment, whilst improving the quality of services by shortening the delivery times. Nevertheless, due to compact size of those solutions, they should always be implemented with utmost caution for the type of delivered shipments. The limited cargo space of the droid often indicated the need to couple the system with an assisting technology for larger parcels and for those not willing or not capable of using the droids.
- The analysis has proved that, even with a marginal consideration of social and environmental factors and heavy contribution of operational and economic dimensions, the carbon-intensive combustion engine LCVs did not prove to outperform the electric innovations.
- For a stakeholder valuing all sustainability and operational dimensions equally, the implementation of last mile delivery droids coupled with currently available LCV would be the preferred system. It is also a very cost-efficient system, resulting in fast return of investment due to operational savings, and would be therefore the preferred option for delivery service providers, who value the economic and operational dimensions.
- The eLCV assisted by a delivery droid was the preferred option for all environmentally concerned, because of the efficient electric motors and clean energy source.
- The marginalisation of digitally excluded coupled with safety uncertainties related to untested delivery droids, point to a different implementation direction, identifying the eLCV again as the most sustainable option.

6.2 Synthesis of Policy Insights

The findings of this research can also benefit governments and help policy makers come up with more thoughtful and realistic decisions. These policy insights can be outlined as follows:

SAV Policies

- The local, national, and transnational authorities should raise awareness of the sustainable mobility and the impact of individual's transportation choices. Those campaigns could help refrain sustainable modes users from shifting towards comfortable SAV services.

- The number of SAV vehicles should be capped and determined by the local authorities striving towards greener urban mobility. The number of vehicles should be high enough to secure a seamless service that could support ridesharing, and encourage those currently using private cars, but not high enough to provide a go to solution for those who currently use active modes.
- The pricing policy/fleet design of the SAV based service, should aim to discourage short trips, which are currently often made with active modes. This would secure a more sustainable uptake of the service limiting the environmental rebound effect.
- The regulators should focus on limiting a creation of new transport demand, which highly contributes to the environmental rebound effect. That would mean that planning the transport policies should be heavily coupled with land-use as the new generated demand is connected to leisure and shopping activities.
- The regulators should try to achieve a similar level of service for the shopping and leisure activities in different urban areas, as the introduction of SAV-based service could lead to acceptance of longer trips in exchange of a better service further away, contributing to environmental rebound effect.
- SAVs should be introduced in a way which supports sharing of trips. The regulators should react in time to make sure that the service providers to not develop a low-cost automated taxi, that would maximise the profits of the provider. Alternatively, the public transport in cities could be entirely switched for autonomous demand responsive transport, as the usage of PT is limited with the introduction of the SAV-based service.

AV Policies

- Current and future educational campaigns could be used to build on the sustainable lifestyle attributes of the population. Specifically, it is important to target educational campaign at those with high intake of technological novelties, while at the same time developing the environmentally and urbanely cautious social attitudes.
- Once the AVs are deployed, the central parking lots could indeed be heavily limited, without the negative pull back from car dependant users. This study shows that those users will no longer prefer to park their vehicle in a central area once cheaper and convenient alternatives are in place.
- There is currently a lack of acceptance towards allowing the vehicle to cruise. This fact could be leveraged by policy makers, who might intervene and take measures that will limit the cruising option, before it becomes widely adopted. This way, the pull back from the

private AV users would not be as strong, as in a hypothetical scenario in which the users are used to this convenient and, if not regulated, cheap parking strategy.

- If not regulated, the cruising costs and the costs of sending the vehicle home would be marginal compared to a paid parking area. Under such assumption majority of people would decide to send their vehicle home, which could increase the negative externalities coming from rise in empty vehicle miles travelled. A solution could be twofold either by increasing the cost of cruising/sending the vehicle home by setting prices for vehicles that enter and cruise around central locations (for which vehicles entering from city parking areas would be exempt), or by sufficiently lowering the price of parking in the desired by city government's locations.
- With time as AVs gain trust and allowing the vehicle to cruise becomes common and perceived as normal, the waiting time for the vehicle could be required to be even shorter, if the cost of cruising is not regulated by the city policy makers.
- Increasing wait time significantly reduces the probability of choice of the dedicated parking area on the outskirts of the city. For individuals with homes close by the destination locations, this would mean sending the vehicle home, which could prove to be useful for policy makers through lowering the demand for parking spots. Whereas individuals with home further away from destination locations, might opt for other unsustainable solution - cruising. This would suggest the need to keep some of the parking areas not far away from central locations available nowadays. Exemplary, park and ride facilities, could be redesigned and serve AVs in the future, while the on-street parking lots in the central areas could be reused in more sustainable manner.

Last-mile delivery droid policies

- The results of the study illustrate the complexity and challenges faced by the planners and policymakers designing future transportation, in which multiple stakeholders with various preferences and priorities intertwine with significant externalities that the system is responsible for. The results point out that there is no fit for all solution, but a string of conflicting needs and criteria, hence trade-offs and compromises are necessary.
- Regional, national, and European policymakers should focus on transferring the responsibility for the implications of negative externalities on their creators. For instance, regional policymakers could restrict combustion engine freight vehicles from entering city centres, forcing the companies to invest in or even develop more sustainable alternatives. Furthermore, the European policymakers could opt to subsidise local delivery providers

who support sustainable innovation or penalise those with outdated fleets, which contribute to climate crisis and air pollution in urban areas.

- The reduction of land dedicated for transport services is a desirable outcome for cities as the reclaimed land could be used for community development, enhancing the quality of life of the citizens and proposing new social activities. Moreover, where possible, the land could be used for residential purposes, possibly reducing the urban sprawl, further contributing to the air quality improvements.
- Droid based delivery systems coupled with depot stations could be implemented in dense urban areas in which there is a pressing need to reduce land devoted to transport. In those types of spaces, provided that the depot station is nearby, it is also more likely that individuals would opt to walk to pick up shipments.
- Before last-mile delivery droids are allowed to roam on our pavements, the safety of those solutions needs to be established. For that purpose, the droid should firstly be implemented on testing grounds, preferably within living labs, in which participants are already using innovation. Guaranteed safety of the droid would significantly improve the scores it obtained in this analysis, confirming its sustainable status.
- Moreover, the implementation of droid-based services could result in further exclusion of those digitally impaired. As an advanced society, we should not aim for further marginalisation of those digitally excluded, either by change or by choice, and, while implementing the solution of tomorrow, always consider the digital capabilities of the entire population. Therefore, whilst implementing the droid delivery systems, some form of analogue delivery should always be possible. The living labs could be used to co-create the delivery droid application and booking system with digitally excluded. Such activity could result in provision of a solution more accessible to all.

7. Conclusions and further research

This research investigated impact of new mobility services on transport and related externalities. The study commenced by reviewing the current NMS related studies, exploring the methods utilised in literature and reporting the results obtained by previous researchers. The literature review provided evidence that further studies are needed to better assess the environmental and societal impact of the automated vehicles, especially private and shared autonomous vehicles and last-mile delivery droids.

The environmental impact of SAVs investigated how triggered behavioural changes could mitigate the initial benefits of SAVs deployment be it in terms of climate crisis or air quality. This rebound effect was obtained using an activity-based demand estimation connected with a traffic microsimulation platform. The demand estimation was obtained in a simulation platform SimMobility, while the traffic simulation was made with Aimsun Next software. The study was made for a city of Santander in Spain, which could be viewed as a representative of a general mid-sized European city. The microsimulation of traffic allowed to use the environmental and battery consumption models, from which the estimated environmental rebound effect was obtained.

The results of the study show that the deployment of a SAV based service could be environmentally beneficial due to fleet electrification and sharing of rides. Nevertheless, behavioural changes could indeed lead to a significant rebound effect. The maximum obtained rebound effect resulted in 42% higher CO_2 emissions as compared to a scenario in which the SAVs are introduced but no behaviour changes linked to perceived lower value of in-vehicle time were introduced. For the NO_X and PM emissions the maximal rebound effect leads to 36% and 49% emissions increase respectively. The behavioural change that caused the highest rebound effect in all the scenarios was the participation of analysed individuals to a higher number of non-mandatory activities.

It is clear that the solemn introduction of the SAVs is not a solution for the transport related externalities, as previously hoped. Instead, the SAV based services should be carefully designed, co-created by service providers, authorities, and their users to ensure its substantial uptake. While modelling can help anticipating users' reactions, large-scale experiments and cocreation are also needed to achieve the sustainable urban mobility, without triggering further negative externalities. Additional measures could also be taken to further lower the environmental rebound effect, exemplary, the application used to order SAV rides could be integrated with other mobility services to suggest a greener alternative whenever it would offer a quality of service comparable to SAVs. Such solution could limit the number of users opting out from active modes towards SAV- based service. Moreover, the environmental rebound effect could be lowered if cities were to follow the 15-minute city trend, which aims to secure all required services in a proximity to the residential area. If this was the case the citizens would not use the SAV fleet and chose active modes preferred for short trips.

As the AVs are expected to be electric measures in energy management and development could also heavily contribute to the sustainable uptake of SAVs. For instance, the environmental rebound effect could be fully decreased by a transition to zero emission electricity grid. Moreover, a proper charging strategy for the SAV fleet would be needed to make sure that the vehicles do not destabilise the electricity grid, as well as regain their cost-effectiveness by consuming cheaper electricity in off-peak hours. Furthermore, with optimisation of electricity demand data, demand for SAV based services and their charging patterns, SAV vehicles could also serve as energy balancing asset, by adapting to a vehicle to grid charging pattern. In such case the batteries of the vehicles could be aggregated into a bigger electrical load to ensure the stability of the grid instead of negatively impacting it.

Further implications of the NMS were investigated for privately owned AVs. While privately owned AVs will highly revolutionise the transport industry and heavily impact future urban planning and land use, it's the people's social attitudes that will influence the way in which AVs will be adopted in tomorrow's cities and how they will contribute to the sustainability of urban area. One of the driving choices expected to be particularly affected by AVs is parking. This research aimed to provide empirical evidence on the preferences of parking in the future, once new parking strategies, enabled by vehicle automation, emerge. In particular the thesis presented the results of a stated preference survey in which respondents were confronted with four parking strategies: i) on-street parking nearby ii) dedicated parking area on the outskirts of the city iii) cruising and iv) sending AV back home. The results of the survey were analysed through a mixed logit with latent variables.

Four latent variables were found to significantly impact the decision about the preferred parking option: environmental concern, innovativeness, AV acceptance and preference for car-free cities. The results suggest, that for now, there is a high preference for parking in dedicated areas in the outskirts of the city. Nevertheless, as the users gain trust in the AVs or are part of the early adopters' group, they show higher preference towards unconventional parking strategies – cruising and sending the vehicle home. Moreover, the study shows that those with higher regard for the environment and with a preference for car-free cities are more likely to choose a sustainable parking outside of the city centre.

The impact of last-mile delivery droids was investigated using a tailor-made MCDA framework for the sustainability assessment of innovation in last mile delivery. The methodology integrated multi criteria decision making analysis, sustainability pillars and scenario analysis to best reflect the conflicting needs of stakeholders involved in the last mile delivery system. The case study provides an application of the framework to the delivery system of the Joint Research Centre of the European Commission where six alternative solutions were analysed and compared: i) the existing service using a manually-driven Euro 4 light commercial vehicle (LCV); ii) the same service using a Euro 6 LCV; iii) the same service using an electric LCV (eLCV); iv) a service composed by an automated delivery droid (robot) coupled with a Euro 4 LCV; v) a service with the delivery droid coupled with a depot station; and vi) a service with the delivery droid coupled with the eLCV.

The obtained results illustrate the complexity and challenges faced by the planners and policymakers designing future last-mile delivery, in which multiple stakeholders with various preferences and priorities intertwine with significant externalities that the system is responsible for. The results point out that there is no fit for all solution, but a string of conflicting needs and criteria, hence trade-offs and compromises are necessary. Nevertheless, low-capital investment in delivery droids could lead to significant savings on the operational costs, whilst improving the environmental performance of the system. However, there are potential social sustainability shortcomings in terms of safety and equity.

Further section 7.1 discusses the possible future research directions previously described research and, respectively.

7.1 Future directions

1. Even though, this study provided first estimation of the environmental rebound effect of SAVs further analysis could provide a better understanding of SAVs deployment in presence of various transport policies. Further research could consider simulating dedicated platooning lanes, superblocks, car restricted zones or tradable credits schemes used for mobility management. Comparison of scenarios of plausible policy developments in a given area would be of utmost importance to policymakers that often struggle to identify the effect of their policies in the light of innovation deployment.
2. Moreover, before giving precise policy recommendations for SAVs deployment it is important to deepen the research performed in this thesis. An adequate follow-up study should analyse a variety of SAV services designs, differentiating the capacity of the vehicles as well as the possibility to order a personal, unshared ride.
3. The study investigating the environmental rebound effect of SAVs should be recreated both in a densely populated congested area as well as loosely populated rural area. Such studies could deepen the knowledge about the environmental rebound effect, and lead to different results because of high congestion in urban areas and longer distances in rural areas.

4. The results from the mixed logit model concerning the future parking strategies of privately owned AVs could be fed into the traffic microsimulation platform. In that case not only the environmental rebound effect could be investigated in terms of privately owned AVs, but also the impact of empty rides of privately owned AVs on the congestion in a city.
5. In terms of last-mile delivery it is important to investigate whether the usage of delivery droids would be sustainable throughout the entire lifecycle, using the cradle to grave approach. Therefore, as a next step complementing this research, a thorough LCA of the solution would be needed. This would considerably strengthen the sustainability assessment of last-mile delivery services, especially when several droids would be needed.
6. Before the delivery droids are allowed to freely roam on pavements of our cities, viable safety tests must be performed along with digital education and co-creation with those users unwillingly excluded by technology.

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