

UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos



A BEHAVIOURAL ANALYSIS OF SHARED MOBILITY'S IMPACT ON CAR DEPENDENCY

DOCTORAL THESIS

Submitted for the degree of Doctor by:

María Vega Gonzalo

Ingeniera Industrial
Máster Universitario en Ingeniería en Tecnologías Industriales

Madrid, 2025



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Doctoral Degree in Civil Engineering Systems

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“Forget the damned motor car and build the cities for lovers and friends.”

– Lewis Mumford

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Abstract

Private cars play a pivotal role in urban mobility systems of cities worldwide, offering an extremely convenient option to cover households' mobility needs and shaping infrastructure, daily habits and perceptions. However, growing awareness of the negative impact of excessive use of this mode of transport on the quality of life in urban areas, and the urgent need to decarbonize the transport sector are driving the shift towards more sustainable mobility. City governments are implementing measures to reduce car demand in urban areas — such as low emission zones or parking regulations — while encouraging a shift towards more sustainable modes by improving public transport services, expanding cycle lanes or introducing shared mobility options. In this respect, some authors even argue that the car-centric transport system is in decline. In this transition, shared mobility, understood as a new mobility concept that decouples ownership from the use of a wide range of services, has the potential to play an important role by replacing private car ownership.

In accordance with this hypothesis, the potential influence of the ongoing expansion of shared mobility on car dependency has been examined using the perceived need to own a car in the future as a proxy. This overarching objective was accomplished through the analysis of extensive survey data using different types of discrete choice modelling techniques. First, a preliminary analysis provided an up-to-date overview of current trends in car ownership and car use and laid the groundwork for the subsequent studies included in the thesis. Second, the potential impact of shared mobility on car dependency in the mid-term was explored considering both the perception of shared mobility's users and the general population in Spanish urban areas. The behavioural approach adopted in these studies allows to understand the impact that socioeconomic characteristics, subjective attitudes and travel behaviour towards conventional and shared modes have on the individual's perceived need to own a private car in the mid-term. Moreover, spatial considerations regarding the place of residence or the built environment have been introduced to account for the effect of the geographical context on the interrelations between shared mobility and car dependency.

The studies carried out enabled the identification of travel profiles that are more strongly associated with a greater potential for shared mobility services to reduce car dependency. The results make clear that the use of shared mobility is associated with lower car dependency.

Additionally, this association is particularly strong among those that include more than one shared mobility service in their daily mobility habits. It is especially interesting to note that the adoption of shared cars or mopeds by car dependent individuals significantly increases their likelihood of considering that a private car will not be necessary. As for the socio-economic profiles, it is observed that teleworkers and high-income individuals with low car ownership levels are more likely to believe that living without a car would be feasible. The spatial analysis showed that the potential of shared mobility to reduce car dependency extends to municipalities located in the sub-urban ring, even though shared mobility is not yet available in most of these areas. Nevertheless, the results suggested that complementing the expansion of shared mobility with sustainable urban development would enhance the reduction effect. These findings resulted in policy recommendations on how to leverage shared mobility to reduce car dependency in urban areas and advance towards more sustainable urban mobility systems.

Resumen

El automóvil privado desempeña un papel fundamental en los sistemas de movilidad urbana de las ciudades de todo el mundo, ofreciendo una opción extremadamente cómoda para cubrir las necesidades de movilidad de los hogares y condicionando el desarrollo de infraestructuras, los hábitos cotidianos y las percepciones de los individuos. Sin embargo, la creciente concienciación sobre el impacto negativo del uso excesivo de este medio de transporte en la calidad de vida de las zonas urbanas, así como la urgente necesidad de descarbonizar el transporte están impulsando el cambio hacia una movilidad más sostenible. Los gobiernos municipales están aplicando medidas para reducir el uso del coche -como zonas de bajas emisiones o normas de aparcamiento-, al tiempo que fomentan el cambio hacia modos más sostenibles -mejorando los servicios de transporte público, ampliando los carriles bici o introduciendo opciones de movilidad compartida-. En este sentido, algunos autores sostienen que el sistema de transporte centrado en el automóvil está en declive. En esta transición, la movilidad compartida, entendida como un nuevo concepto de movilidad que desvincula la propiedad del uso para una amplia gama de modos, tiene el potencial de desempeñar un papel importante sustituyendo al coche privado.

De acuerdo con esta hipótesis, se ha examinado la posible influencia de la actual expansión de la movilidad compartida en la dependencia del automóvil, utilizando como variable instrumental la necesidad percibida de poseer un coche en el futuro. Este objetivo se ha logrado mediante el análisis de datos de encuesta utilizando distintos modelos de elección discreta. En primer lugar, se ha realizado un análisis preliminar que ofrece una visión actualizada de las tendencias en la propiedad y el uso del automóvil en las ciudades europeas y sienta las bases para los estudios posteriores. En segundo lugar, se ha explorado el impacto que la movilidad compartida puede tener en la dependencia del coche a medio plazo en las principales ciudades españolas, considerando tanto a usuarios de movilidad compartida como a la población general. El enfoque conductual adoptado en estos estudios permite comprender el impacto que las características socioeconómicas, las actitudes subjetivas y las decisiones sobre movilidad tienen en la necesidad percibida del individuo de poseer un coche privado a medio plazo. Además, se han introducido consideraciones espaciales relativas al

lugar de residencia para dar cuenta del efecto del contexto geográfico en las interrelaciones entre movilidad compartida y dependencia del coche.

Los estudios realizados permitieron identificar los perfiles de viaje más fuertemente asociados con un mayor potencial de los servicios de movilidad compartida para reducir la dependencia del coche. Los resultados dejan claro que el uso de la movilidad compartida se asocia a una menor dependencia del coche. Además, esta asociación es particularmente fuerte entre aquellos que incluyen más de un servicio de movilidad compartida en sus hábitos diarios de movilidad. En cuanto a los perfiles socioeconómicos, se observa que los teletrabajadores y las personas con altos ingresos y bajos niveles de propiedad de automóviles son más propensos a creer que vivir sin coche sería factible. El análisis espacial mostró que el potencial de la movilidad compartida para reducir la dependencia del coche se extiende a los municipios situados en el anillo suburbano, a pesar de que la movilidad compartida aún no está disponible en la mayoría de estas zonas. No obstante, los resultados muestran que complementar la expansión de la movilidad compartida con un desarrollo urbano sostenible potenciaría el efecto reductor. A partir de estas conclusiones se ha propuesto una serie de recomendaciones sobre cómo instrumentalizar la movilidad compartida para reducir la dependencia del automóvil y avanzar hacia sistemas de movilidad urbana más sostenibles.

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Abbreviations and Acronyms

CATI	Computer-Assisted Telephonic Interview
CAWI	Computer-Assisted Web Interview
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
EFA	Exploratory Factor Analysis
FUA	Functional Urban Area
GHG	Green House Gas
GFI	Goodness-of-fit Index
GSEM	Generalised Structural Equations Models
LEZ	Low Emission Zones
MaaS	Mobility as a Services
OR	Odds Ratio
PA	Path Analysis
RMSEA	Root Mean Square Error of Approximation
SEM	Structural Equations Model
SP	Scientific Publication
SRMR	Standardized Root Mean Square Residual
TDM	Travel Demand Management
TOD	Transit Oriented Development
TLI	Tucker Lewis Index
UPM	Universidad Politécnica de Madrid
UVARs	Urban Vehicle Access Regulations

1. Introduction

This introductory chapter aims to motivate the research topic (Section 1.1) justifying its importance for the development of a more sustainable urban mobility system. Additionally, it enumerates the scientific contributions that have been elaborated throughout this thesis (Section 1.2) and describes the structure of the present document (Section 1.3).

1.1. Research Motivation

The increasing urgency to tackle the climate crisis and mitigate global warming has underscored the need for governments worldwide to drastically reduce GHG emissions. In this social, economic and technological transition to sustainability, urban transport is set to play a key role. Overall, the transport sector accounts for around a quarter of the total emissions in Europe (EEA, 2017). Of this, about 23% comes from urban transport (European Commission, 2021). Far from decreasing, transport demand in the urban context is expected to keep growing in the coming years, fuelled mainly by population growth and the increased trend of urban sprawl (ITF, 2023).

Against this backdrop, it becomes clear that a transformation of the transport sector to drastically reduce its dependence on fossil fuels is unavoidable. As a consequence, ambitious decarbonisation goals have been set that will inevitably require a radical transformation of transport systems, practices and infrastructure in urban areas (European Commission, 2023; ITF, 2021a). At the same time, it is crucial to guarantee the fulfilment of transportation's social functions. The green transition should be achieved while ensuring that citizens of all socio-economic backgrounds have equal access to employment, education, health and leisure opportunities. The complexity of solving these issues confronts local and regional institutions with unprecedented challenges in policy making, but also with a valuable opportunity to create more liveable, accessible and resilient cities. Seizing this opportunity requires a rethinking the central role that private cars currently play in the development of transport infrastructure, the organisation of public space and the construction of daily practices.

In fact, apart from the generation of GHG emissions, the use and ownership of private cars in urban areas have associated a considerable list of negative externalities, namely traffic congestion, road accidents, noise and air pollution (Gössling & Choi, 2015) and the occupation of large fractions of space both when circulating and when parked (Gössling et al., 2016; Hérán & Ravalet, 2008). On the other hand, they offer a convenient option to make door-to-door trips, as well as chained trips, to carry on daily tasks, such as doing groceries or driving children or vulnerable individuals. In low density areas with limited public transport supply, the competitiveness of the private car increases even further, making it the only virtually available mode of transport to carry out daily activities. This convenience, together with the strong mobility culture that conceives car ownership and use as a basic right, poses great challenges for urban planners when trying to convince citizens to relinquish private cars. This challenge can only be overcome through a combination of "push" and "pull" policies that increase the costs of using the private car while offering convenient and realistic alternatives to cover individuals' mobility needs. While "push" policies, such as vehicle restrictions, parking

regulations or congestion charging, are highly effective in reducing car demand, they need to be combined with "pull" measures, such as the promotion of public transport and active transport modes or the provision of shared mobility services, to mitigate the impact that coercive policies can have on accessibility (Gärling & Schuitema, 2007).

In addition to the measures traditionally available to planners (e.g. urban pricing, public transport supply, etc.), the last few years have seen the emergence of shared services as a valuable tool in the effort to reduce excessive private car ownership and use, both in and around urban areas, if properly regulated. Shared mobility comprises those transport services that can be accessed in a short-term basis and on-demand through the utilisation of mobile applications and without the intervention of any intermediary (Invers, 2022). In this thesis, the term shared mobility refers to those services that only provide access to vehicles (namely, bike-sharing, scooter-sharing, moped-sharing and car-sharing). Therefore, those that include the driver, such as ride-hailing or car-pooling, have been excluded.

The added value of shared mobility services lies in the flexibility they offer both for users and transport planners, while featuring some characteristics that can make them more socially and environmentally sustainable than private cars. For travellers, these services can be extremely convenient to carry out trips for which public transport would not be a very convenient option, such as carrying goods, driving children or reducing travel times in specific situations (e.g., arriving to an airport or travelling to work-related appointments). In addition, the wide variety of shared vehicles that can be currently found in many cities allows travellers to choose a convenient mode for most purposes and situations, while removing the economic burden of owning any of them. As for the planners, shared mobility allows to increase accessibility in areas where population density is too low to justify the investment that expanding the public transport network would entail (UITP, 2023). From the point of view of environmental considerations, these services are observed to have a lower carbon footprint than private cars. In fact, the International Transport Forum estimates that, under the scenario of a strong regulation, a widespread adoption of shared mobility services could reduce CO₂ transport related emissions between 30% and 60% by 2050 (ITF, 2019b). This reduction derives primarily from an increase in vehicle utilisation rates and the provision of access to vehicles that are generally fully electric. Beyond the direct impact in emissions, shared mobility services entail a series of indirect benefits that would make cities healthier and more liveable. For instance, the decrease in vehicle fleets would reduce the amount of urban space dedicated to parking, allowing to allocate more space to active modes and green areas. In addition, the use of electric vehicles, which constitute a big part of shared fleets, would reduce air and noise pollution (Shaheen et al., 1998). However, in its current state, shared mobility

faces several challenges that must be addressed before it can achieve a net positive contribution to sustainability. In general terms, it has been often mentioned that it mainly acts as substitute of public transport and active modes, leading to an increase in the total GHG emissions (see e.g. Cervero et al., 2007 or Papu Carrone et al., 2020). In addition, the short lifespan of many vehicles, the need to rebalance the fleets and swap the batteries entails a high volume of life-cycle emissions that often cancels the positive effect that they could have on the decarbonisation of urban transport (see e.g. Schelte et al., 2021 or Felipe-Falgas et al., 2022).

Nevertheless, it has been often pointed out that harnessing the benefits of shared mobility and mitigating some its adverse effects depends largely on these services contributing to a reduction in car ownership levels (Cervero et al., 2007; Vejchodská et al., 2023). In this regard, a considerable number of previous contributions (see e.g. Kim et al., 2019; Jain et al., 2021; Hausteine, 2021) have proven that the usage of car-sharing has the capacity to reduce the number of cars owned by households. However, car-sharing is by far not the most widely available service in most cities, neither the most frequently adopted and for many purposes is not the most efficient one in terms of energy consumption and space occupation. Although car-sharing improves the utilisation rates of existing vehicles, the full potential of shared mobility to bring a positive effect to the sustainability of urban mobility lies in the provision of access to a wide range of vehicles. In a context of wider expansion of shared mobility, usage could be disentangled from ownership and individuals would be able to easily choose the most convenient service for each occasion in terms of pricing, purpose and personal preferences.

Despite the potential benefits of such a scenario, the current reality falls short in terms of the availability and accessibility of shared mobility. Adoption rates remain relatively low and its usage is predominantly concentrated among privileged groups, particularly educated, high-income males (see e.g. Aguilera-García et al., 2022; Reck & Axhausen, 2021). This is presumably due to the high fares with respect to public transport (Butler et al., 2021), the technological barrier of needing to download and use a digital application (Chahine et al., 2024), safety concerns (Filipe Teixeira et al., 2023) or the reluctance of car users to change mobility habits (Sohn & Yun, 2009). Similarly, the spatial availability of shared mobility is in most cases rather unequal. The supply is often confined within the core cities of metropolitan areas or even within the central districts of those cities, where the supply of public transport is wide and the high mix of land uses ensures good access to opportunities. This distribution leads to the occupation of public space in areas where it is already scarce and an increased probability of substituting active modes or public transport (Jiao & Wang, 2021; Qiao & Yeh, 2023).

Provided this current stage of development, it becomes clear that the elaboration of suitable frameworks that remove these barriers and ensure an equitable access to shared mobility is indispensable to harness the potential of shared mobility as a competitive and more sustainable alternative to private car ownership at a large scale. In this endeavour, two key objectives should be achieved. The first is to consolidate the shared mobility ecosystem, understood as a set of services that are widely available, to ensure that individuals can access the mode that best suits their purpose and needs for each trip. Second, to extend shared mobility fleets to the outer rings of metropolitan areas, as these services are a cost-effective solution to improve accessibility in low-density areas with scarce public transport services, where car dependency is more acute. In order to analyse the impact of shared mobility on car dependency in such scenarios, this work focuses on car dependency in the medium term, i.e. the perspective of needing a car in the future, which may provide a more insightful view than other variables such as actual or empirical changes in car ownership and use.

In the context of the rapid expansion of shared mobility services and the growing need to reduce excessive car reliance in urban areas and their surroundings, the motivation of this thesis is to explore how the achievement of the above-mentioned objectives would affect car dependency. For this purpose, a behavioural modelling approach has been adopted in order to achieve a deep understanding of the decision-making processes that would underly individual's choices and preferences regarding private cars if a realistic and convenient alternative was available. This work aims to provide insights regarding the impact of shared mobility on car dependency, that can inform the deployment of transport policies that pave the way for a sustainable, equitable and efficient implementation of shared mobility.

1.2. Scientific output

The main body of this thesis has resulted in the development of three Scientific Publications (SP), all of them already published in peer-reviewed and indexed journals.

1. **SP1** Vega-Gonzalo, M., Gomez, J., & Christidis, P. (2023). How has COVID-19 changed private car use in European urban areas? An analysis of the effect of socio-economic characteristics and mobility habits. *Transportation Research Part A: policy and practice*, 2, 103679. <https://doi.org/10.1016/j.tra.2023.103679> [2023 JCR Journal Impact Factor: 6.3; Q1 Transportation, Q1 Economics, Q1 Transportation Science & Technology].

2. **SP2.** Vega-Gonzalo, M., Gomez, J., Christidis, P., & Vassallo, J. M. (2024). The role of shared mobility in reducing perceived private car dependency. *Transportation Research Part D: Transport and Environment*, 126, 104023. <https://doi.org/10.1016/j.trd.2023.104023> [2023 JCR Journal Impact Factor: 7.4; Q1 Transportation, Q1 Environmental Studies, Q1 Transportation Science & Technology].
3. **SP3** Vega-Gonzalo, M., Aguilera-García, Á., Gomez, J., & Vassallo, J. M. (2024). Analysing individuals' use of moped-sharing and their perception about future private car dependency. *Cities*, 146, 104741. <https://doi.org/10.1016/j.cities.2023.104741> [2023 JCR Journal Impact Factor: 6.0; Q1 Urban Studies].

During the development of the research, a number of complementary publications have been produced. While they do not form part of the thesis per se, the research activities carried out in the context of these publications have allowed the exploration of underlying issues and led to a deeper understanding of the emerging dynamics in urban mobility.

- Vega-Gonzalo, M., Aguilera-García, Á., Gomez, J., & Vassallo, J. M. (2024). Traditional taxi, e-hailing or ride-hailing? A GSEM approach to exploring service adoption patterns. *Transportation*, 1-40. <https://doi.org/10.1007/s11116-022-10356-y> [2023 JCR Journal Impact Factor: 3.5; Q1 Civil Engineering, Q2 Transportation, Q2 Transportation Science & Technology].
- Vega-Gonzalo, M., Christidis, P., & Gomez, J. (2023). Car Ownership and Post-COVID Urban Mobility across European Cities. *Transportation Research Procedia*, 69, 305-312. <https://doi.org/10.1016/j.trpro.2023.02.176>
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1.3. Structure of the document

This thesis has been formatted in accordance with the standards outlined by the Universidad Politécnica de Madrid (UPM) for doctoral theses presented in the form of a compilation of scientific publications. It should be acknowledged that there may be minor overlaps between the scientific outputs (SPs) and certain chapters of this document. The structure of the thesis

has been graphically represented in Figure 1-1, including the name of the chapters and the role they play in the overall work that has been done within this doctoral thesis.

Chapter 1 includes the introduction to the topic that is addressed in this work and explains the rationale behind the choice of this topic. In this first chapter, the scientific publications that have resulted from the doctoral project are also enumerated.

Chapter 2 provides a summary of the policy context in which this thesis has been developed. Specifically, it provides some reflections on what is understood as car dependency through this work, based on the contributions of previous research. In addition, it reviews the urban transport policies that are aimed at reducing car dependency and presents the main impacts that shared mobility has been observed to have in urban mobility systems.

Chapter 3 compiles the existing research works that have previously studied the determinants of car ownership and use and the impact that shared mobility services have been observed to have in these travel choices.

Chapter 4 jointly considers all the information that has been gathered in the first three chapters to propose the research questions that capture the contributions that this work intends to make. Thereafter, a series of research objectives have been enumerated aiming to identify which specific impacts of shared mobility on car dependency should be analysed to provide sound answers to the research questions. Finally, the assumptions and hypotheses on which this thesis rests have been explained.

Chapter 5 presents the specific context in which the phenomenon under study has been analysed, justifying the choice of the case studies and explaining the characteristics that are relevant to understand and interpret the results that will be later obtained for each study.

Chapter 6 describes the materials and methods that have been employed to answer the research questions. Firstly, it encompasses the description of the data that has been used for this research. And second, it indicates the modelling frameworks that have been implemented taking into account the research goals as well as the specific characteristics of each of the available datasets.

Chapter 7 includes the first scientific publication that conforms this thesis, which provides an updated overview of the recent trends in the determinants of car ownership and use that have been occurring in European cities.

Chapter 8 collects the second and third scientific publications that have been developed as part of the thesis. They constitute the main contribution of this research, since they focus on

the impact that the availability of shared mobility services would have on the perceived need to own a car in the future.

Chapter 9 discusses the main findings obtained in the scientific publications from Chapters 7 and 8, analyses them together to obtain more general results, answer concisely the research questions and discuss the research hypotheses.

Chapter 10 outlines the main contributions of this thesis and proposes a series of policy recommendations on the basis of the results explained in Chapter 9. These recommendations focus on how to regulate shared mobility services in a smarter way and how they might be combined with other policy tools to harness its full potential and reduce car dependency. Finally, the main limitations of this thesis are identified and consequently, further avenues for future works that could extend the contributions of this research are suggested.

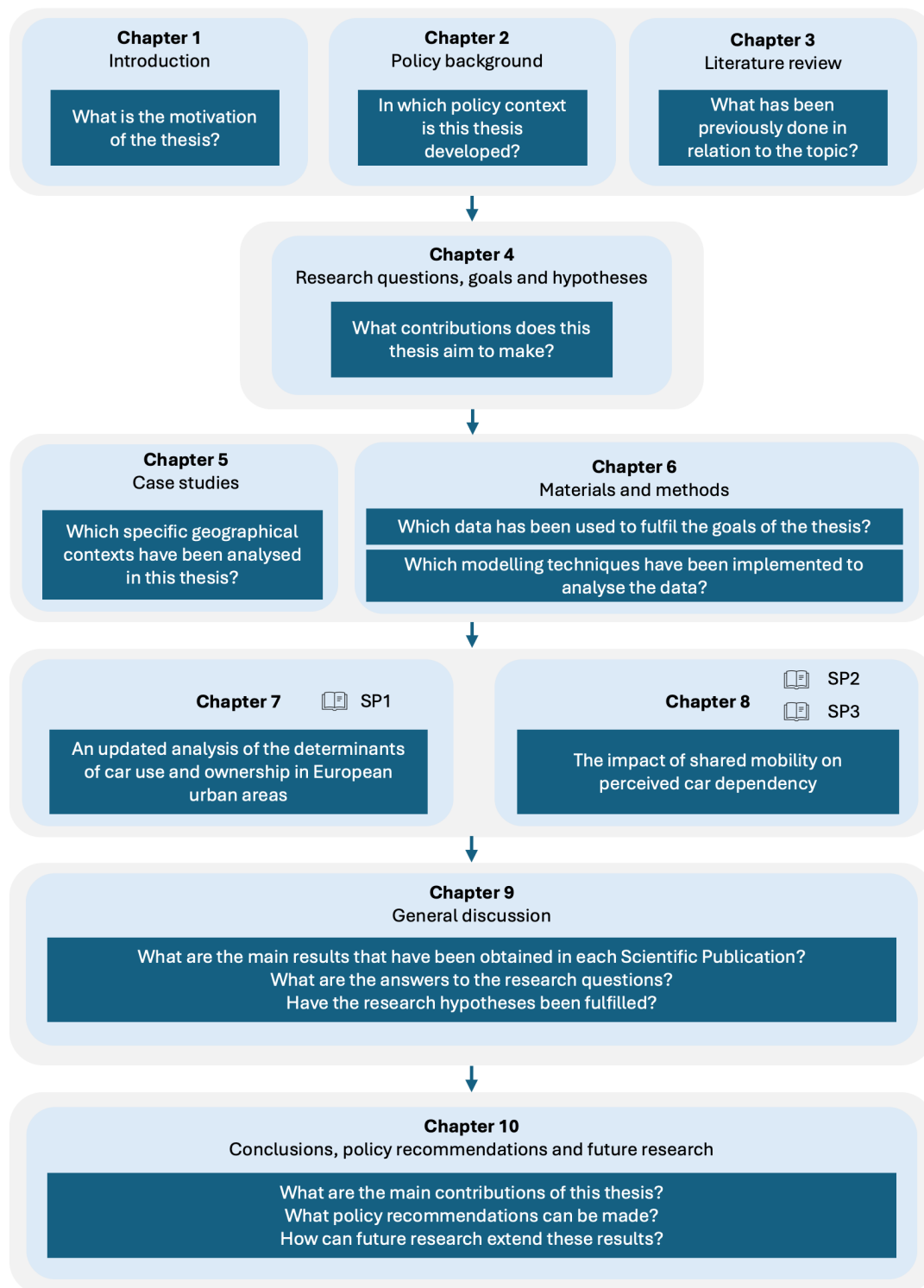


Figure 1-1: Structure of this thesis

2. Policy background

This chapter provides background information on the societal and policy context in which this thesis is developed. First, a brief review of the existing approaches to the conceptualisation of car dependency is presented (Section 2.1). Second, a classification of the existing policies to mitigate car dependency is elaborated (Section 2.2) and the impacts (both positive and negative) of the deployment of shared mobility in urban areas and its surroundings are discussed (Section 2.3).

2.1. What is car dependency?

Despite the relatively common use of the concept of car dependency in transport planning (Basu & Ferreira, 2021; Cullinane & Cullinane, 2003; Lagrell & Gil Solá, 2021), its complexity and multidimensionality have made it difficult for the scientific community to reach an agreement on its definition (Behren et al., 2018; Kenworthy & Laube, 1999; Langer et al., 2023). Several authors have proposed conceptualisations that consider different aspects of the excessive reliance on private cars, conforming a body of work whose analysis provides valuable information to better understand what car dependency is.

A first group of works understands car dependency as a technical regime composed of many different layers: individual characteristics, beliefs and perceptions, infrastructure, etc. For instance, according to Lucas & Jones (2008) car dependency is a system that re-enforces itself over time. On the first place, wealth and land use patterns that offer little accessibility by public transport or active modes drives the decision to purchase a car. As a consequence, the accessibility of the household is broadened, leading to the development of car-based lifestyles. As more households go through this process, car-centred infrastructures and urban planning expand, decreasing the accessibility by other modes and making the car increasingly convenient, which ultimately results in rising motorisation rates at the population level and the consolidation of the car dependent regime. In a similar trend, Mattioli et al., (2016) propose a framework, which distinguishes three layers of dependency, an upper layer, comprising the dependency induced by the characteristics of the space, the culture or the society; an intermediate layer, which captures circumstantial car dependency due to the characteristics of the trip or the activity that is to be fulfilled; and a micro-level, in which the choices, habits and perceptions of the individuals are the cause of dependency. Additional examples of this holistic understanding of car dependency can be found in Urry (2004) or Goodwin (1995).

Despite the relevance of this first approach, the complexity of capturing all the dimensions of car dependency would hinder the empirical analysis of this problem. For this reason, car dependency is often assimilated to observable choices or indicators that allow to capture some of the dimensions that have been defined by more holistic frameworks. In this regard, the most common approach directly associates car dependency with car ownership and use, either at the individual (Asgari & Jin, 2023; Van Eenoo, Fransen et al., 2022) or at the city level (Newman & Kenworthy, 1989; McIntosh et al., 2014). A second group of contributions focus on the spatial context as the ultimate determinant of car dependency, understanding that the dependence arises when the private car is the only available alternative to reach opportunities. This is the case of the research works by Wiersma et al. (2017), who analyse

the impact of improving accessibility by public transport on car dependency; Belton Chevallier et al. (2018), who focus on the mobility of low-income household living in car dependent areas or Langer et al. (2023), who propose a quantitative measure for car dependency considering accessibility to opportunities as well as motorisation rates. A last group of works addresses the subjective dimension of car dependency, finding that the reliance on cars is often motivated by the perceptions of the individuals in terms of the emotional attachment to cars (Steg, 2005), the difficulties to change daily habits (Zhao, 2011) or social practices that deem cars as the default mode (Lucas, 2009).

Taking these approaches into account, this work argues that the perceived need to own a car to carry out daily activities can be seen as the ultimate consequence of car dependency. Thus, it builds on the studies that consider car ownership as the best proxy for this concept. Further justifications of the methodological approach used to measure car dependency can be found in Section 6.2.

2.2. Strategies to mitigate car dependency

As exposed in the previous section, car dependency entails a large list of negative impacts at the social and environmental level (ITF, 2021b) but also for individuals, since excessive reliance on private car mobility can lead to high costs, both in terms of time and money (Miner et al., 2024). However, despite the challenges that reducing the excessive reliance on private cars poses for both transport planners and citizens, the rapid growth of urban areas, the climate crisis and the increasing awareness regarding the impact of private motorized transport on public health have turned this endeavour into a priority. This transition requires a complete set of actions and pathways that allow to drastically reduce emissions. These actions should include both technological solutions, that make vehicles more efficient (such as electrification); and behavioural measures – also known as Travel Demand Management (TDM) measures –, that aim to reduce the utility of car use, increasing it for more sustainable modes. Given the behavioural approach to the problem of car dependency that is adopted in this thesis, a review of the existing TDM measures targeting car use has been elaborated hereafter.

There are several approaches to classify TDM measures. One of the most common ones is the division between push and pull methods (Kuss & Nicholas, 2022). While the first type corresponds to policies that penalize the use of the private car (coercive), the second type aims to increase the appeal of more sustainable alternative modes with the objective of inducing a modal shift (non-coercive). Despite the high effectiveness of push measures, they usually have low public acceptability and are difficult to implement and maintain over political

cycles. However, the impact of non-coercive policies has been observed to be modest when not combined with “harder” policies (Gärling & Schuitema, 2007).

An alternative classification could be the one proposed by Carran-Fletcher et al. (2020), which considers five groups of measures:

1. **Improvement of alternative transport options:** they include measures such as the **improvement of public transport**, either by extending the network (Hahn et al., 2023), improving reliability or reducing travel times (Bhatta & Drennan, 2003; Sharav et al., 2017); the **deployment of shared mobility services and its integration with public transport** (Bertolini & le Clercq, 2003; Kong et al., 2020) or the **promotion of active modes** by developing suitable infrastructure (bike lanes and pedestrian areas) (Agarwal et al., 2020; Brownrigg-Gleeson et al., 2023) or providing easy access to bikes through bike-sharing programs (Fishman et al., 2014; Narayanan et al., 2023).
2. **Urban Vehicle Access Regulations (UVARs):** they can be mostly identified with push measures given that they aim to reduce the convenience of the private car with respect to other modes. It entails the creation of physical areas where the circulation and/or parking of cars is restricted or subjected to the payment of a fee. This is the case of **Low and Zero Emission Zones**, where only electric vehicles or low-emission internal combustion vehicles are allowed to enter; or **on-street parking regulations**, which reduce available parking spaces, limit the parking time or set a time fee for parking (Gonzalez et al., 2022; Tarriño-Ortiz et al., 2022). Other pricing schemes such as static or dynamic road pricing or Tradable Mobility Credits schemes would also fall into this category (Pattinson et al., 2022; Provoost et al., 2023; Viegas, 2001).
3. **Land use planning and development:** this type of policies focuses on ensuring that the built environment in which individuals conduct their daily activities encourages the use of sustainable modes of transport and minimizes the need to own and use personal cars (Aumann et al., 2023). Notwithstanding the high potential of sustainable urban development, it poses big challenges in terms of deployment, as they require big investments and long-term planning (Wachter et al., 2024). Some examples of this kind of policies include: i) **Transit Oriented Development (TOD)**, that proposes to organize urban space around transit nodes in order to ensure people's accessibility (Ibraeva et al., 2020); ii) **urban densification**, that aims to build more compact cities and limit urban sprawl (Eggimann et al., 2021); iii) **land-use mix policies**, whose goal is to ensure that daily activities can be conducted in the proximity of the place of residence by ensuring that space is allocated to a balanced mix of different land uses (Zhang & Zhao, 2017) or iv) **complete streets**, which encourages the use of alternative modes by ensuring safe

spaces for them to circulate and reducing the public space dedicated to motorized transport (Hui et al., 2018).

4. **Outreach and education campaigns:** this type of policy aims to modify individual's behaviour through communication campaigns to raise awareness about the importance of shifting away from the private car to other modes due to health benefits, reduced costs, less environmental footprint, etc. (Zhou et al., 2020).

It is noteworthy that many of these measures are mostly targeted at reducing car use. However, it has been previously observed that increasing the barriers to car use and offering feasible alternatives is likely to ultimately lead to a reduction in car ownership (Gonzalez et al., 2021; Yang et al., 2022).

This work focuses on shared mobility because it offers policymakers a highly flexible tool to enhance accessibility and serves as one of the most competitive alternatives to private vehicle ownership. In this context, shared mobility can be viewed as part of a broader set of measures aimed at improving alternatives to private cars, both as independent modes of transport and as feeders for public transit. Nevertheless, I argue that the potential for positive contributions of shared mobility goes beyond this aspect, as it constitutes an enabler for the development of sustainable land use planning and urban development and as a mitigator of the impact that coercive measures might have on accessibility. In the next section, I elaborate on this idea of shared mobility as a transversal tool to achieve a more sustainable urban mobility and as enabler of the remaining TDM measures.

2.3. The impact of shared mobility on urban mobility

Although shared mobility services appeared decades ago with the emergence of bike-sharing, the widespread adoption of smartphones and the consequent development of digital platforms triggered a very rapid expansion that has continued since the 2010s. Initially, this expansion was clearly dominated by ride-hailing services, but now, nearly all types of personal vehicles suitable for urban use — such as cars and vans, mopeds, e-scooters and bikes — are available in shared formats in most big and medium cities worldwide (Fluctuo, 2023b).

Unlike conventional modes, such as public transport (mainly managed by public transport authorities) or private cars (owned by individuals), the operational model of shared mobility services is rather novel to transport planners. In fact, apart from the deployment of bike-sharing services by some local governments, in most cases the fleets are owned and operated by private companies, whose ultimate goal is not only to provide sustainable mobility options but also to generate economic benefit (Cohen & Kietzmann, 2014). For this reason, shared mobility services constitute an agent in the urban mobility ecosystems that should be

adequately regulated to mitigate the associated negative externalities, moving towards policy frameworks that enhance their beneficial effects. This sub-section provides a summary of the overall positive and negative impacts of shared mobility within urban mobility systems.

Positive impacts

The primary contribution of shared mobility to the sustainability of urban transport systems lies in its potential role as facilitator for the deployment of some policies outlined in Section 2.2. Figure 2-1 shows schematically the interrelations of shared mobility with the three first measures from the Carran-Fletcher et al. (2020) classification, which were considered as those with which shared mobility can interact.

First, in the case of the UVARs that limit the use of cars in certain areas or increase the costs of using them, shared vehicles provide a valuable low-emission alternative to access these areas in case of necessity (de Buen Kalman, 2021). The environmental and social impacts of using shared mobility services in central and dense areas are considerably smaller than those of the private car. Given that shared fleets tend to be fully electric and newer than private vehicles, their use sharply reduce noise and air pollution levels in urban areas. Furthermore, the smaller size of shared vehicles and their higher utilisation rates lead to a lower occupancy of public space. In this regard, shared mobility has the role of mitigating the impact that UVARs and pricing strategies can have on accessibility within urban centres (Ding et al., 2023; Tarriño-Ortiz et al., 2022).

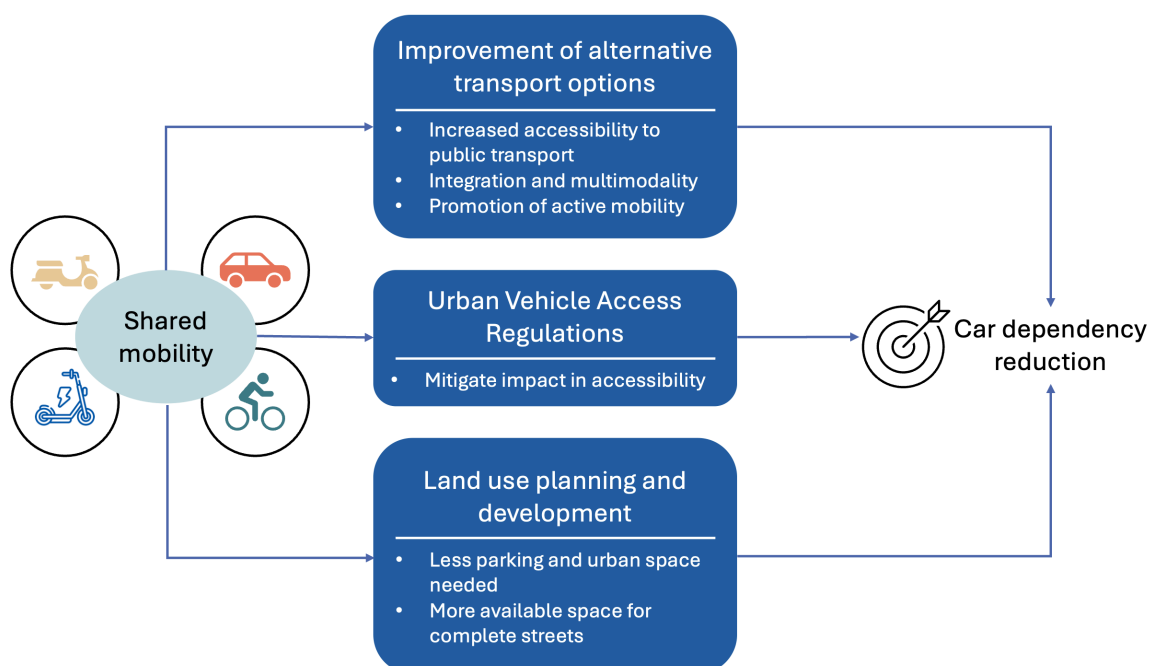


Figure 2-1: Conceptual outline of the impact of shared mobility services in urban mobility

Regarding non-coercive policies, properly regulated shared services can act as enablers for their implementation. For instance, shared mobility could connect low-density areas where public transport demand is not enough to justify the expansion of the network, increasing the accessibility to public transport (Bi et al., 2021; Rotaris & Danielis, 2018). However, low population densities are likely to result in low turnover rates, making these areas less attractive for private operators to deploy their fleets. For this reason, unravelling this essential function of shared mobility requires developing Private-Public Partnerships and trip subsidizing (Zuniga-Garcia et al., 2022).

In a similar trend, shared mobility is a key element in the development of multimodal mobility systems. First, as mentioned before, it provides access to a wide variety of different vehicles that can cover multiple purposes. This means that users can combine them with public transport and private active modes in a flexible and convenient way depending on the purpose they would need to fulfil. Second, the fact that shared services are based on digital applications facilitates the integration of information with other modes in Mobility as a Service (MaaS) platforms or other kinds of trip-planners (Arias-Molinares & Carlos García-Palomares, 2020; Matyas & Kamargianni, 2019). Third, the spatial adaptability of shared services, as they are predominantly free-floating and the installation of docking stations is relatively inexpensive, facilitates straightforward physical integration within mobility hubs (Geurs et al., 2024; Horjus et al., 2022).

Furthermore, reducing the size of vehicle fleets and increasing vehicle utilisation rates could reduce the public space dedicated to parked and circulating cars (Crozet, 2020; Glotz-Richter, 2016). These spaces could then be re-designed to improve accessibility through active modes by incorporating better biking and walking infrastructures. In the same fashion, higher utilisation rates could potentially lead to lower levels of life cycle emissions of vehicles (Amatuni et al., 2020; Morfeldt & Johansson, 2022). However, this does not seem to be occurring due to the short life span of most shared vehicles (Arbeláez Vélez, 2023).

Finally, shared mobility, particularly bike-sharing, offers local institutions an exceptionally efficient tool to guarantee access to active modes of transportation. Disentangling the ownership and use of bikes provides extensive incentives for their adoption. This is especially relevant in cases in which electric bikes are a much more convenient option than conventional bikes, given the high prices of the former. For instance, in cities where the natural barriers hinder the use of traditional bikes, the low-cost access to e-bikes can encourage individuals to adopt this mode (Julio & Monzon, 2022). Additionally, it has been observed that, as e-bikes allow for longer and faster trips, they are considerably more likely to substitute the private car than mechanical bikes (Campbell et al., 2016; Zhou et al., 2023).

Negative impacts

Notwithstanding the great potential of shared mobility services to make urban mobility more sustainable and efficient, they can also result in unintended adverse effects. The most frequently observed ones are the following:

- **Substitution of public transport and walking:** one of the main unwanted impacts of shared services is the substitution effect they often have with respect to public transport and walking (Firnkorn & Müller, 2012; Papu Carrone et al., 2020). These services can only make a net positive contribution to the sustainability of urban transport if they replace the most environmentally damaging modes. Otherwise, their deployment is likely to lead to an increase in total mileage travelled and consequent emissions (Cervero et al., 2007).
- **Equity impacts:** research works analysing the drivers for the adoption of shared mobility services and the frequency of their use have pointed out that they are mainly used by high-income, well-educated individuals (Alemi et al., 2018; Reck & Axhausen, 2021). These findings hint towards a gap in the access to these modes, probably due to their higher prices compared to public transport and the fact that their use require a certain level of acquaintance with technology (Golub et al., 2019; Qian & Jaller, 2020). Additionally, there is also a component of spatial inequality in the access to these services, since their supply is mostly concentrated in the city centre, where the provision of public transport is already sufficient. However, in lower density areas, where public transport is scarcer and the added value of shared services would be higher, the supply is in general limited (Bach et al., 2023; Duran-Rodas et al., 2020).
- **Safety concerns:** new vehicles such as e-scooters or e-bikes can circulate at higher speeds than pedestrians but not as fast as cars or motorbikes. Thus, their introduction poses challenges in terms of road space distribution. First, it has been observed that sharing the road space with traditional motorized vehicles leads to an increase in the number of accidents. Additionally, the lack of regulation of these services or the difficulties to enforcing them lead to low helmet use or driving at excessive speeds (Carnicé, 2023; Stigson et al., 2021). This issue is particularly pressing, as it is one of the main reasons why cities around the world, including Paris, Barcelona and Madrid, are progressively banning shared e-scooters (Le Monde, 2024).
- **Bad parking practices and excessive occupation of public space:** specially in the case of shared micromobility under no regulation, users tend to park the vehicles in unsuitable places, such as sidewalks or bike lanes (McGurk, 2024; Taylor, 2023). This practice

hampers pedestrian traffic, especially in the case of disabled individuals and influences negatively the public opinion towards shared mobility.

- **Fleets' re-balancing and operational challenges:** A general characteristic of shared mobility services is the spatial imbalance between the areas where most trips are generated and where they are attracted. To solve this problem, operators need to move vehicles around to ensure their availability throughout the service area. Similarly, battery swapping has to be done manually. Both activities are often carried out using combustion engine vans, which often have to travel a considerable number of kilometres, resulting in a volume of emissions that has been observed to account for up to 50% of the life cycle emissions of the shared vehicles (see e.g, Schelte et al., 2021 or Felipe-Falgas et al., 2022).

3. Literature review

This chapter summarizes the literature review that has been conducted to identify which research gaps need to be fulfilled in the scientific knowledge. Furthermore, this review establishes the basis for the later evaluation of the results that have been obtained during the thesis. Sections 3.1 and 3.2 provide an overview of the main results yielded by the extensive body of contributions that have previously analysed the determinants of car ownership and use. Thereafter, a detailed examination of the existing works dealing with the determinants of shared mobility adoption and usage is provided (Section 3.3). Finally, Sections 3.4 and 3.5 present the previous research that has studied the impact of shared mobility on car ownership and car use, respectively.

3.1. Determinants of car ownership

Car ownership and usage are inherently intertwined, as the frequency of car use is invariably influenced and limited by the number of cars accessible to an individual. Nevertheless, much of the existing literature concentrates on either car ownership or car usage choices. In the realm of research analysing car usage, car ownership is often regarded solely as an explanatory factor for travel behaviour (Buehler, 2011; He & Thøgersen, 2017; Nolan, 2010). Conversely, a smaller subset of studies has developed various modelling frameworks to disentangle the explanatory impacts of car ownership and travel behaviour. These frameworks consider car ownership as endogenous to socio-economic and environmental characteristics while treating it as exogenous to car usage (Ben-Akiva & Lerman, 1974; Ding et al., 2018; Van Acker & Witlox, 2010). Both approaches yield comparable findings regarding the influence of car ownership on car usage: households with more cars tend to rely on them more frequently and cover longer distances (Dieleman et al., 2016; Van Acker & Witlox, 2010).

Previous works dealing with car ownership have shown that socio-demographic factors significantly influence motorisation rates. Income emerges as a pivotal determinant, with wealthier households typically possessing a greater number of cars (Cornut & Madre, 2017; Nolan, 2010; Potoglou & Kanaroglou, 2008). Similarly, highly qualified individuals often receive higher salaries and consequently tend to own more cars (Chu, 2002; Zhang et al., 2014). Household composition, including age and number of members, also influences car ownership patterns. These factors are inevitably intertwined with life-cycle effects (marriage, having kids, retirement, etc.), which in turn influence changes in car ownership. For instance, Dargay (2001) noted a distinct increase in car ownership among young adults in the UK, followed by a decline as the household head reaches retirement age and children leave home. This decline in car ownership among older adults, along with the positive correlation between the number of adults in the household and the number of cars owned, has been supported by several contributions such as Cornut (2016) for the Paris region and Matas & Raymond (2008) for Spain.

Regarding the structure of the household, the presence of children appears to increase the likelihood of car ownership (Clark et al., 2016; Dieleman et al., 2016; Oakil et al., 2016). Moreover, subjective attitudes have been observed to be determinant of car ownership decisions (Soza-Parra & Cats, 2023). In particular, aspects such as social norms (to what extent the individual perceives that having a car is an accepted and widespread practice in society), the social status attached to private cars, the perceived convenience of the private car or the level of environmental consciousness, have been observed to be important determinants of car ownership (Belgiawan et al., 2014; He & Thøgersen, 2017; Heinonen et al., 2021).

Moreover, the number of cars that households decide to own is clearly influenced by the built environment and the spatial characteristics of the individual's surroundings. In fact, it has been observed that more diversified land use patterns (Li & Zhao, 2017), employment density (Ding & Cao, 2019), less parking availability (Jiang et al., 2017) and population density around the place of residence (Ding et al., 2018) decrease the number of cars owned by the household. Similarly, accessibility to public transportation (Mulalic & Rouwendal, 2020; Zhang et al., 2017) and proximity to the city centre (Ding & Cao, 2019; Cao et al., 2019) tend to correlate with lower car ownership levels. The characteristics of the city are also observed to play a non-negligible role in the number of cars in the household.

Finally, a limited number of studies have compared the extent to which the characteristics of the city could affect individuals' car ownership decisions, presumably due to the fact that gathering disaggregated data from several cities for comparison purposes can be an arduous task. In fact, to the best of the author's knowledge, only two previous research works have carried out such analysis, both of which have focused primarily on comparing the effect of the built environment. Berrill et al. (2024) homogenized travel surveys from nineteen European cities to explore how the effect of urban form on car ownership may change across those cities. In the same fashion, Yin & Sun (2018) used information from 3,500 individuals living across Chinese cities to analyse how the correlations between the built environment and car ownership decisions vary between urban areas.

3.2. Determinants of car use

In general terms, the factors that affect car ownership are also correlated with car use. However, the direction of these effects is not always the same. Higher income, employment and education levels are linked to a higher demand of the private car (Jiang et al., 2017; Schwanen et al., 2004; Shen et al., 2016). Regarding household size and structure, it has been noted that having more children increases car use (Dargay & Hanly, 2007; Kim & Ulfarsson, 2008). Nevertheless, the studies analysing the effect of household size have yielded some uncertain results (Ding et al., 2018; Yang et al., 2021). Research on the relationship between age and car use has produced two theories. Some studies indicate that car use peaks among middle-aged adults and then declines (Shen et al., 2016; Yang et al., 2021), whereas others suggest a consistently positive effect of age on car use (Nolan, 2010; van Acker & Witlox, 2010). In the current context of widespread adoption of teleworking practices, previous studies that have investigated the effect of teleworking practices on car use are particularly interesting. Early research indicated a slight but significant decrease in the number of trips and vehicle-kilometres driven due to telecommuting (Choo et al., 2005; Koenig et al., 1996).

However, more recent studies show that while commuting trips may decrease, there is a shift towards other types of trips, such as longer weekend travel or more fragmented journeys (e.g., Kim et al., 2015 for Washington, de Abreu e Silva & Melo, 2017 for the UK or Obeid et al., 2024 for the US). Finally, in the same trend the relationships between subjective attitudes and car use are rather similar to those observed for car ownership (Soza-Parra & Cats, 2023). Social norms (Donald et al., 2014), affective link with private cars (Lois & López-Sáez, 2009) or the awareness of the social and environmental consequences of car use (Abrahamse et al., 2009) are key factors in explaining the decision to use the private car.

Regarding the relationship between the built environment and car use, the results of previous studies generally point to effects similar to those observed for car ownership (Chen et al., 2008; de Abreu e Silva et al., 2012). However, some researchers suggest that its impact on car use is primarily indirect, mediated through changes in car ownership levels (Cao et al., 2007; Ding et al., 2018; van Acker & Witlox, 2010). Reasonably, longer commuting distances are positively correlated with car use (de Abreu e Silva et al., 2012; Ding et al., 2014, 2017). At the city level, high car accessibility, urban sprawl and low land-use mix are observed to increase car use (García-Palomares, 2010; Yang, 2008).

3.3. Determinants of shared mobility adoption and use

The rapid expansion of shared mobility services in many cities worldwide has been accompanied by a rapid evolution of the scientific literature devoted to understanding the factors that influence the adoption and use of these services. This section of the literature review focuses on those works whose goal was to identify which characteristics of the individual and its built environment determine the adoption and use of shared mobility services. In this regard, it should be highlighted that this section does not aim to provide an exhaustive revision of the existing works analysing the socio-economic characteristics of shared mobility users, but rather to describe the main trends that have been observed. This is useful to subsequently understand and properly interpret the potential interrelationships between car ownership and shared mobility use.

The shared mobility ecosystem presents a remarkable diversity, as it encompasses various types of shared vehicles that can be rented, as well as differing service characteristics such as free-floating, station-based, one-way and round-trip options. However, the socio-economic profiles and travel behaviours of users across these different services appear to be fairly homogeneous (Blazanin et al., 2022; Mouratidis, 2022). Hereafter, this review focuses on the factors driving the adoption and usage of those types of services available in Europe, namely car-sharing, moped-scooter-sharing, bike-sharing and kick-scooter-sharing.

In fact, all shared mobility services are mainly used by young to middle-aged males (see e.g. Adnan et al., 2019 for bike-sharing; Laa & Leth, 2020 for kick-scooter sharing; Gilibert & Weymar, 2022 for moped-sharing; and Hjorteset & Böcker, 2020 for car-sharing). In general terms, higher levels of income and education are associated with higher adoption rates and frequency of use (see e.g. Blazanin et al., 2022 for e-scooter sharing; Reck & Axhausen, 2021 for bike-sharing; Vega-Gonzalo et al., 2024 for moped-scooter-sharing; and Efthymiou & Antoniou, 2016 for car-sharing).

A second group of explanatory factors that have been observed to strongly affect the decision to use shared mobility services are subjective preferences. These psychological constructs need to be included in the analyses through the construction of latent variables that measure individual attitudes. For instance, environmental awareness has generally been found to positively influence the adoption and use of bike-sharing (Blazanin et al., 2022), e-scooter-sharing (Eccarius & Lu, 2020) and moped-scooter-sharing (Van Veldhoven et al., 2022). In the case of car-sharing, the effect of eco-friendly attitudes remains unclear (Efthymiou & Antoniou, 2016; Hjorteset & Böcker, 2020). Furthermore, the capacity or willingness to incorporate the use of technology in daily life activities also seems to play an important role (Acheampong & Siiba, 2020; Alemi et al., 2018), which is reasonable given that most shared mobility services need to be used through mobile applications. Users' willingness to participate in the sharing economy has also been found to influence patterns of shared mobility usage (Aguilera-García et al., 2022; Gomez et al., 2021). Finally, it is worthy highlighting that risk aversion and safety concerns seem to affect negatively the adoption of shared micromobility (see Blazanin et al., 2022 for kick-scooter-sharing; and Julio & Monzon, 2022 for bike-sharing).

The effect of the spatial context on the demand for shared mobility services has received considerable attention in the academic literature (Arias-Molinares et al., 2021; Jin et al., 2023; Mateo-Babiano et al., 2016). However, most research works dealing with this topic have opted for analyzing macro demand data that does not provide information on the place of residence of the individual. In fact, the number of contributions dealing with the effect of the built environment of the user's place of residence is limited. Most agree that residents in the city centre are more likely to use shared mobility (Aguilera-García et al., 2024; Nikiforiadis et al., 2021; Prieto et al., 2017), presumably due to the higher supply of shared vehicles in these areas (Hawa et al., 2021; Shen et al., 2018). In the same trend, individuals living in areas with good access to public transport (Becker et al., 2017; Stillwater et al., 2009) and a more mixed land use pattern (Vega-Gonzalo, Aguilera-García, et al., 2024; Wang & Lindsey, 2019) are more likely to use shared mobility services.

3.4. The impact of shared mobility on car ownership

This section offers a comprehensive summary of prior studies concerning the influence of shared mobility on car ownership. It is worth mentioning that the majority of contributions concentrate on examining the effects of car-sharing and Mobility as a Service (MaaS) platforms, with surveys being the primary source of data in nearly all cases. The characteristics of previous works have been synthesised in Table 3-1.

The body of research contributions investigating the effect of car-sharing on car ownership levels is extensive. A considerable number of authors analyse observed and expected changes in the number of cars owned by households as a result of car-sharing utilisation (Kim et al., 2019; Jain et al., 2021; Haustein, 2021). However, a few works conducted stated choice experiments to delve into this topic (Zhou et al., 2020, Liao et al., 2020). Regardless of the methodological approach, there is a consensus that car-sharing use is significantly correlated with lower car ownership levels. This conclusion has been reached across various geographical contexts (see e.g., Becker et al., 2018 for Basel, Switzerland; Klinevicius et al., 2014 for Montreal, Canada; Ko et al., 2017 for Seoul, South Korea or Martin et al., 2010 for North America).

This correlation seems to be greatly influenced by the socio-economic characteristics of the individuals and their household. Factors such as age (Cervero et al., 2007; Kim et al., 2019), household size (Namazu & Dowlatabadi, 2018), the absence of children in the household (Cervero et al., 2007; Jochem et al., 2020) or the level of education (Le Vine & Polak, 2019; F. Zhou et al., 2020) seem to affect individuals' willingness to give up their cars or reduce the number of cars they own. The same is observed for the case of income, with low-income households being often more inclined to reduce or delay car purchases due to the use of car-sharing services (see for instance, Kim et al., 2019 for the case of Seoul, South Korea; Le Vine & Polak, 2019 for London, UK; or Ye et al., 2021 for Shanghai, China). It is noteworthy that contrasting results emerge concerning the effect of initial car ownership levels. For example, Le Vine & Polak (2019) observed that individuals with fewer cars were more likely to further decrease car ownership levels, whereas other studies (see e.g. Nijland & van Meerkerk, 2017 for The Netherlands; or Zhou et al., 2020 for Australian cities) found that households with higher levels of car ownership were willing to substitute one car with car-sharing services.

As for subjective attitudes and lifestyle preferences, they have been found to play an important role in shaping the willingness of individuals to reduce car ownership as a consequence of car-sharing availability. This is reasonable given that latent variables have been observed to greatly influence car ownership choices and the adoption and usage of

shared mobility. Nevertheless, the number of research papers that have incorporated this kind of variables into their modelling frameworks is still limited. For instance, Haustein (2021) observed that attitudinal factors such as the importance individuals attach to cars in terms of freedom, independence and social status associated to car ownership, significantly affect the reduction in car ownership induced by car-sharing. On the other hand, Chicco (2022) observed a surprisingly limited influence of environmental awareness and attitudes towards car-sharing in the decision to shed a car.

The built environment has also been observed to play a key role in the reduction of car ownership that car-sharing can achieve. Most contributions have accounted for the differences between individuals living in urban or suburban areas (Clewlow, 2016; Giesel & Nobis, 2016; Mishra et al., 2015). Many of these studies have concluded that urban residents display a greater inclination towards reducing car ownership levels compared to those in suburban or rural areas. Some researchers have expanded their analyses by incorporating more detailed data on the characteristics of residential areas. For instance, Ye et al. (2021) integrated explanatory variables capturing subway and car-sharing availability and Mishra et al. (2015) examined the impact of the level of accessibility in the place of residence and in the workplace, as well as population density at the census tract level.

The correlation between travel behaviour and shifts in car ownership has received comparatively less attention than the above factors. Most researchers dealing with this topic have examined the extent to which the frequency of car-sharing use influences reductions in car ownership or the inclination to do so, yielding mixed findings. For the case of the Netherlands, Liao et al. (2020) noted that a higher substitution of private cars by car-sharing did not always correlate with a greater willingness to relinquish the ownership of a car. On the contrary, other studies found that a more intensive use of car-sharing is associated with a greater reduction in car ownership levels (see e.g., Giesel & Nobis, 2016 for Berlin and Munich, Germany; Jochem et al., 2020 for 11 different European cities; or Zhou et al., 2020 for Australian cities). There is a remarkable lack of works considering the influence of frequency of use of conventional modes or other shared services apart from car-sharing. In fact, to the best of the author's knowledge, only Haustein (2021), Giesel & Nobis, 2016 and Jochem et al. (2020) included this kind of variables. In order to highlight this gap, which is further explained in Section 4.1, this works together with the details of the variables considered have been highlighted in Table 3-1. Interestingly, Haustein (2021) did not find significant correlations between travel habits (including days travelled by car, metro/train, bus, bike or foot) and changes in car ownership among car-sharing users in Copenhagen, Denmark. In contrast, Jochem et al. (2020) observed that individuals who combined the use of car-sharing with other

shared mobility services like bike-sharing were more likely to reduce the number of cars they owned.

A secondary, albeit smaller, body of research delves into the potential decrease in car ownership rates resulting from the integration of shared and traditional transportation modes through MaaS platforms (see for instance Kamargianni et al., 2018 for the Greater London area; Storme et al., 2020 for Ghent, Belgium; or Christensen et al., 2022 for Copenhagen, Denmark). Nonetheless, the conclusions regarding MaaS are not as definitive as those observed for car-sharing. Generally, the aforementioned studies indicate that the implementation of MaaS becomes a viable alternative to private car ownership only when supplemented with additional policies that encourage the reduction of car usage.

Finally, it is also worth mentioning the work conducted by Basu & Ferreira (2021), which analysed the impact of bike sharing on car ownership in the Metropolitan Area of Boston, by studying the reduction in vehicle holdings at 250-meter grid cells following the installation of new bike-sharing stations. They observed a significant and lasting reduction in car ownership, use and emissions.

A summary of the main characteristics of the research works mentioned throughout this section has been displayed in Table 3-1. In this table, the explanatory factors that have been seldom considered in the existing literature and that are included in the studies conducted in this thesis have been underlined and bolded. The contribution of this thesis regarding the set of explanatory variables considered is further discussed in Section 4.1.

Table 3-1: Summary of existing research works analysing the impact of shared mobility on car ownership

	Target group (sample)	Case study	Target variable	Factors considered
Car-sharing				
Ren et al. (2024)	Whole population (n = 494)	The Netherlands	Stated car ownership changes	- Socio-economic characteristics - Car-sharing price - Characteristics of the potentially purchased car
Chicco et al. (2022)	Car-sharing users (n = 612)	Cologne, Stuttgart and Frankfurt (Germany)	Revealed changes in car ownership	- Subjective preferences (latent variables) - Socio-economic characteristics - Characteristics of the car-sharing service - Declared frequency of use of car-sharing - Previous car ownership - Level of satisfaction with the car-sharing service
<u>Haustein (2021)</u>	Whole population (n _{car-sharing users} = 776, n _{control group} = 720)	Copenhagen, Denmark	Revealed changes in car ownership	- Subjective preferences (latent variables) - Socio-economic characteristics <u>Declared frequency of use of car, bus train, foot and bike</u> - Previous car ownership <u>Place of residence within the city (centre vs. suburbs)</u>
<u>Jain et al. (2021)</u>	Whole population (n _{car-sharing users} = 651, n _{control group} = 290)	Melbourne, Australia	Revealed and expected changes in car ownership	- Socio-economic characteristics - Previous car ownership <u>Place of residence within the city (centre vs. suburbs)</u>
Jain et al. (2020)	Car-sharing users (n = 37)	Melbourne, Australia	Qualitative analysis through focus groups and interviews	
Jochem et al. (2020)	Car-sharing users (n = 7,073)	11 European cities	Revealed car ownership changes	- Socio-economic characteristics <u>Declared mileage and frequency of use of car-sharing</u> - Previous car ownership <u>Adoption of bike-sharing</u> - City of residence
Liao et al. (2020)	Whole population (n = 1,003)	The Netherlands	Stated car ownership changes	- Socio-economic characteristics - Service's characteristics - Trip purposes when/if using car-sharing - Declared frequency of use of car-sharing - Characteristics of a potential private car the respondents could buy
Zhou et al. (2020)	Whole population (n = 1,433)	Four Australian cities	Stated car ownership changes	- Socio-economic characteristics - Service's characteristics - Characteristics of a potential private car the respondents could buy
Hui et al. (2019)	Car-sharing users (n = 627)	Hangzhou, China.	Expected car ownership changes	- Trip purposes when using car-sharing. - Level of satisfaction with the car-sharing service - Declared frequency of use of car-sharing - Motives behind the decision to use car-sharing
Le Vine & Polak (2019)	Car-sharing users (n = 298)	Greater London Area, UK	Revealed car ownership changes	- Socio-economic characteristics - Trip purposes when using car-sharing - Declared frequency of use of car, train, bike and car-sharing
Kim et al. (2019)	Car-sharing users (n = 3,447)	Seoul, South Korea	Revealed car ownership reduction	- Subjective perceptions about the service's characteristics - Car-sharing frequency of use - Trip purposes when using car-sharing
<u>Becker et al. (2018)</u>	Whole population (n _{car-sharing users} = 224, n _{control group} = 209)	Basel, Switzerland	Expected and revealed car ownership changes	- Socio-economic characteristics <u>Accessibility to public transport in the place of residence</u> - Place of residence within the city (centre vs. suburbs)

Table continues in the next page

A behavioural analysis of shared mobility's impact on car dependency

	Target group (sample)	Case study	Target variable	Factors considered
Car-sharing				
Namaz & Dowlatabadi (2018)	Car-sharing users (n = 3,405)	Vancouver, Canada	Stated car ownership changes	- Socio-economic characteristics - Previous car ownership - Car-sharing frequency of use - Trip purposes when using car-sharing - Reasons to use car-sharing
Ko et al. (2017)	Car-sharing users (n = 5,000)	Seoul, South Korea	Expected and revealed car ownership changes	- Socio-economic characteristics - Level of satisfaction with the car-sharing service - Characteristics of the car-sharing service
Nijland & van Meerkerk (2017)	Car-sharing users (n = 363)	The Netherlands	Revealed car ownership changes	Changes in car ownership are not explained but studied as part of a broader framework to analyse emissions reduction induced by car-sharing
Giesel & Nobis (2016)	Car-sharing users (n = 1,046)	Berlin and Munich, Germany	Revealed car ownership changes	- Subjective preferences regarding mobility choices - Socio-economic characteristics - Characteristics of the service Frequency of use of car, public transport and car-sharing
Martin & Shaheen, 2016	Car-sharing users (n = 6,167)	Five north American cities	Stated car ownership changes	City of residence
Clewlow (2016)	Whole population - California Household Travel Survey (n = 63,082)	San Francisco Bay Area	Revealed car ownership changes	- Place of residence within the metropolitan area - Accessibility to car-sharing in the census tract of residence
D. Kim et al. (2015)	Car-sharing users (n = 533)	Seoul, South Korea	Willingness to give up a current vehicle	- Subjective perceptions of service characteristics - Socio-economic characteristics - Trip purposes when using car-sharing
Klinckevicius et al. (2014)	Whole population (census level)	Montreal, Canada	Changes in average car ownership in census tract	- Socio-economic characteristics (census tract level) - Distance to downtown. - Population density
Firnborn & Müller (2012)	Whole population (n = 308)	Ulm, Germany	Expected car ownership changes	Changes in car ownership are not explained but studied as part of a broader framework to analyse emissions reduction induced by car-sharing.
Martin et al. (2010)	Car-sharing users (n = 6,281)	Several cities in United States and Canada	Revealed car ownership changes	- Socio-economic characteristics - Previous car ownership
Cervero et al. (2007)	Car-sharing users (n = 619)	San Francisco, United States	Revealed car ownership changes	Membership of car-sharing service
Bike-sharing				
Basu & Ferreira (2021)	250-meter cell grid	Metropolitan Area of Boston	Revealed car ownership changes	- Socio-economic characteristics - Built-environment features (land-use mix, density, points of interest and road design)
Mobility as a Service (MaaS)				
Christensen et al. (2022)	Seven families using car-sharing	Copenhagen, Denmark	Qualitative approach through semi-structured interviews	
Storme et al. (2020)	Whole population (n = 90)	Ghent, Belgium	Qualitative evaluation of a pilot project	
Kamargianni et al. (2018)	Whole population (n = 1,570)	Greater London, UK	Exploratory analysis of a survey for a report prepared for Transport for London	

3.5. The impact of shared mobility on car use

Since the advent of shared mobility systems, their theoretical capacity to reduce car trips in urban contexts has been often pointed and substantial number of works have focused on determining whether this potential is realized when this kind of mobility is deployed (Basu & Ferreira, 2021; Ceccato & Diana, 2021; Fukushige et al., 2023).

For the case of **car-sharing** services, the dominant impression is that they reduce car trips (Ceccato et al., 2021; Cervero et al., 2007). For instance, the results obtained by Sopjani et al. (2020) in Sweden showed that car-sharing could be a convenient and satisfactory option to reduce private car use among families with environmentally concerns. In the same line, Ceccato & Diana (2021) observed that car-sharing is more likely to substitute private car trips than walking or biking trips for the case of Turin, Italy. For the case of San Francisco (USA), Clewlow (2016) observed that the Vehicle Miles Travelled (VMT) of carsharing users decreased. Particularly interesting is to note that this reduction was found to be larger among those living in low-density areas. This highlights the potential of shared mobility to reduce the dependency on private cars outside city centres. It is worth mentioning that a considerable number of studies have pointed out that the reduction in car demand as a consequence of car-sharing is subjected to a reduction in car ownership levels (Chapman et al., 2020; Clewlow, 2016; Martin & Shaheen, 2016; Wu et al., 2020). On the other hand, some authors have observed that car-sharing has a higher likelihood of substituting public transport than private cars (Le Vine et al., 2014; Papu Carrone et al., 2020). Finally, it should be mentioned that there is surprising scarcity of works analyzing the individual attributes that might be correlated with higher substitution rates of the private car by car-sharing. For the case of moped scooter-sharing, the author of this thesis could not find any contribution dealing with the impact of this shared service on private car use.

The interactions of shared micromobility with private car use has also attracted some attention from the transport research community. Existing contributions have often found that, although car use is partly substituted by shared e-scooters or bikes, the extent of this substitution is rather limited (for e-scooters see e.g. Weschke et al. (2022) for Germany or Krier et al. (2021) for Paris, France; and for bike-sharing, see e.g. Basu & Ferreira (2021) for Boston, USA; Bullock et al. (2017) for Dublin, Ireland; or Fukushige et al. (2023) for Sacramento, USA). In addition, these services seem to mostly substitute active modes and public transport (Bieliński et al., 2021; Reck et al., 2022). Nevertheless, studies comparing different cities have noted that the substitution dynamics seem to diverge between American and European cities, with car substitution being more likely in the former (Badia & Jenelius, 2023; Fishman et al., 2014; Wang et al., 2023). Presumably, this result is due to the higher

modal share of public transport in the European context. Interestingly, some authors have pointed out that the probability of using shared micromobility to replace the private car increases when systems are designed as first/last mile connecting mode for public transport (Fan & Zheng, 2020; Saltykova et al., 2022).

Beyond the estimation of substitution rates, some authors have explored which factors influence the modal shift from car use to shared micromobility. For instance, Narayanan et al. (2023) or Weschke et al. (2022) have studied the impact of the service characteristics, such as price, ease to parking or travel times. Guo & Zhang (2021) analysed the role of the trip purposes and the motivations behind the use of e-scooters. Other studies have focused on the influence of individual characteristics and found inconclusive results. In fact, both gender and age seem to play an important but unclear role (Barbour et al., 2019; Fearnley, 2022; Fukushige et al., 2021; Guo & Zhang, 2021; Suchanek et al., 2021). The substitution effects of shared micromobility for individuals living outside the city centre, although infrequently studied, appear to be larger than for those living in denser areas (Gebhardt et al., 2021; Guo & Zhang, 2021). Presumably, this is due to the higher car dependency among these individuals.

4. Research questions, objectives and hypotheses

This chapter encompasses three sections. The first one (Section 4.1) presents the research gaps and the research questions that have been formulated based on the revision of existing works previously conducted in Chapter 3. Section 4.2 explains the general and specific research objectives of the thesis. Finally, the assumptions and hypotheses under which this thesis has been developed are presented in Section 4.3.

4.1. Research gaps and questions

The existing literature and main results regarding car ownership and use, shared mobility usage and how these two travel behaviour choices might interact have been presented in the previous section (see Chapter 3). Following this revision, some research gaps that will be addressed in this thesis can be pointed out. Subsequently, the research questions are derived from these identified gaps and are formulated to guide the objectives of this thesis.

Research gap 1

The scientific literature analysing the determinants of car ownership and use is undoubtedly extensive, as could be observed by the revision included in Sections 3.1 and 3.2. However, most of the existing contributions studying the individual characteristics that determine car ownership and use were carried out prior to 2017. Given that the determinants of car ownership and use have been observed to change over time as social changes happen and the context in which individuals make travel decisions evolves (Maltha et al., 2017), there seems to be a need for updated investigations of the drivers of these travel choices. This need became increasingly relevant in the framework of the post-pandemic period. During the COVID-19 pandemic individuals and households were faced with an unprecedented situation that induced stark changes in their attitudes, causing an uncertain impact on many behavioural patterns.

For the case of travel behaviour, two opposing forces were determining individual's choices. On the one hand, the decline in mobility, the rapid implementation of teleworking and other remote activities was viewed as opportunities to reduce the transport demand in urban areas (Zhang & Zhang, 2021). Simultaneously, concerns about contagion and the need to maintain social distancing led travellers to opt for individual modes of transportation over public transit (Almlöf et al., 2021). In fact, the ownership of private cars (perceived as the safest mode of transport at a time when any personal contact entailed a health risk) has been pivotal for household mobility during the pandemic (Moody et al., 2021). This combination of opposing forces leads to uncertainty in terms of the mid- and long- term effects of the global health crisis on car ownership and use. For this reason, this thesis aims to provide an up-to-date overview of the factors that affect the ownership and usage of private vehicles across different socio-economic groups and types of travellers employing recent data.

On the other hand, several contributions have previously compared differences in aggregated motorisation rates between urban areas (Cao & Huang, 2013; Wu et al., 2016; Yang et al., 2022). However, as pointed out in Section 3.1, there are few previous research works that have combined socio-economic data with city-level characteristics (size, urban form, GDP,

etc.) to analyse the drivers of car ownership and use at the individual level. The introduction of these variables would be relevant to better understand whether and how the urban context at the city level may influence individuals' decisions about car ownership and use.

The identification of these research gaps has led to the formulation of the first research question that this thesis aims to answer:

RQ1	What are the explanatory factors, including individual socio-demographics, travel habits and city characteristics, that currently drive car ownership and car use?
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Research gap 2

The literature review has shown that the current contributions examining the impact of shared mobility services on car ownership predominantly focus on the influence of car-sharing. These contributions seem to agree on the fact that this new mobility service has a significant and negative impact on car ownership among those who use them. Additionally, few works have studied the impact of MaaS on the number of cars that individuals decide to own. In this respect, while shared services are already available in most big and middle-sized cities, MaaS platforms have not been yet brought to the market for urban mobility. For these reasons, exploring to what extent the simultaneous access to multiple shared mobility services could impact car ownership decisions in the future is a relevant topic to be addressed in the literature. This is a subject of great scientific interest, even in the case of shared mobility services not integrated into a single MaaS platform.

On a similar note, several authors have pointed out the decreasing importance of private automobility as the cornerstone of urban transport systems. This pivotal role of private vehicles has been influencing daily practices and attitudes as well as infrastructure developments since the early 20th century and limiting the adoption of more sustainable and efficient modes (Manderscheid, 2014; Urry, 2004). In this context, shared mobility offers access to a set of different shared vehicles that could allow citizens to cover the whole spectrum of mobility needs without having to rely on private car ownership. For this reason and notwithstanding the still limited adoption of shared mobility services, the role that the shared mobility ecosystem could play in the socio-technical transition to a car-independent mobility is worth investigating (Epprecht et al., 2014; Sopjani et al., 2020).

Aiming to cover this research gap and to explore to what extent the access to a bundle of shared mobility services may impact individual's dependency on the private car, the second research question is formulated as follows:

RQ2 Does the increasing availability of multiple shared mobility services significantly affect car dependency in the mid-term?

Research gap 3

The literature review of previous works dealing with the impact of shared mobility on car ownership shows that most contributions include socio-economic characteristics as relevant explanatory variables. However, there seems to be a scarcity of works exploring the self-declared travel behaviour for conventional modes (active modes, car and public transport) and specially, for shared modes (bike-sharing, e-scooter-sharing, moped-sharing and car-sharing). To better highlight this gap, the cases in which these types of variables are included in previous studies have been highlighted in Table 3-1. It can be observed that only three previous contributions included frequency of use of different modes. First, Haustein (2021) only the travel behaviour for conventional modes was considered. Second, Jochem (2020) considered car-sharing frequency of use together with the adoption of bike-sharing, but did not include any conventional mode. Finally, Giesel & Nobis (2016) included the use of car and public transport together with car-sharing frequency of use but failed to include private active modes or any other kind of shared mobility services. The variables considered in each of these works has been summarized in Table 4-1, showing that there is no previous works that considers all the available conventional and shared modes.

Table 4-1: Summary of the travel behaviour variables considered in previous works

Travel behaviour variables	Haustein (2021)	Jochem (2020)	Giesel & Nobis (2016)
Active modes	X		
Public transport	X (bus)		X
Private car	X		X
Shared bikes		X (adoption)	
Shared scooters			
Shared cars		X	X
Shared mopeds			

In order to explore the potential of shared mobility (understood as mobility ecosystem that provides access to a wide variety of vehicles) as a replacement for private car ownership, it is necessary to investigate how people's opinions may be influenced by their current frequency of use of available shared modes. Additionally, combining shared mobility usage patterns with frequency of use of conventional modes could be key to understanding which travel profiles would be most likely to reduce their car dependency due to the expansion of shared mobility. To the best of the author's knowledge, no previous research work has conducted such analysis. Examining rich information regarding individual's travel behaviour along with other types of individual-level variables (e.g., socio-economic attributes, latent constructs, etc.) could provide valuable insights on which segments of the population are more likely to reduce their car dependency on the mid-term. In order to cover this research gap, Research Question 3 has been raised:

RQ3	Which individual attributes, considering socio-economic variables, subjective attitudes and travel behaviour, are correlated with a higher impact of shared mobility on individuals' car dependency?
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Research gap 4

The exhaustive description of the existing literature dealing with the impact of shared mobility services (mainly car-sharing) on car ownership (see Table 3-1) shows the limited number of previous contributions that have considered the spatial dimension of this issue.

First, there is a clear need for more contributions analysing the potential impact of shared mobility on car dependency in community typologies different than the purely urban context (namely, sub-urban and rural areas). Despite shared services not being yet available in these contexts in most cases, understanding whether and how individuals living in these areas might change their mid-term car ownership decisions due to shared mobility is a key step to inform a smarter and more efficient expansion of these services. In this regard, only the works by Haustein (2021), Jain et al. (2021) and Becker et al. (2018) have considered both urban and sub-urban context. They have introduced this factor in the individual-level modelling frameworks through a dummy variable capturing whether individuals live in the city centre or in the suburbs (see the highlighted works in Table 3-1).

Additionally, the revision of the literature has revealed a lack of works analysing in detail e.g. the effect of the built-environment using a more complete set of characteristics such as land-use mix, population density or level of accessibility. In fact, to the best of the author's

knowledge, the only work in which this type of variables is considered is the one by Becker et al. (2018). In this contribution, a variable capturing the individual's accessibility to public transport has introduced in the model.

RQ4	How does the spatial context affect the potential impact of shared mobility on car dependency?
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4.2. Research objectives

The **general research** objective of this thesis is to explore how the progressive expansion of shared mobility services, both in terms of available modes and spatial distribution, impacts car dependency. Hereafter, the **specific research** objectives that this thesis aims to fulfill and the ways in which they contribute to answering the research questions are explained (see for Table 4-2 a simplified description of the links between research questions and objectives).

- RQ1 is linked with objectives 1 to 3, which are aimed at drawing an accurate and updated identification of the main individual and city-level characteristics that influence car ownership and use.
- RQ2 is answered through the achievement of objectives 3 to 8. Objective 3 focuses on understanding whether the use of shared mobility services may impact individuals' decisions regarding their frequency of use of the private car. Objective 4 investigates the extent to which shared mobility can impact car dependence in urban areas and their surroundings. Objectives 5 to 8 are linked to RQ2 as they explore whether shared mobility may contribute to reduce car dependency.
- RQ3 is addressed in objectives 5 and 6. First, objective 5 explores the impact of the different individual-level variables and investigates which type of factors (among socio-economic variables, latent constructs or travel habits) plays a more relevant role to understand the impact of shared mobility on perceived car dependency. Thereafter, objective 6 investigates whether the effect and the role of these explanatory variables may differ across users and non-users of shared mobility services.
- RQ4 encompasses objectives 7 and 8 given that they both focus on the analysis of the spatial context, either at the city level or at the place of residence, in perceived capacity of individuals to become car independent as a consequence of the expansion of shared mobility.

Finally, objective 9 is linked with all the four research questions, as it aims to harness the results yielded through the achievement of the previous objectives to elaborate a series of policy recommendations on how to harness shared mobility to reduce car dependency in urban areas and its surroundings.

Table 4-2: Specific research objectives and their connexion with the research questions

	Research objective	Research questions
O1	Determine which socio-economic characteristics and travel-habits determine current trends in car ownership and use	RQ1
O2	Analyse the impact of the city characteristics on car ownership and use	RQ1
O3	Analyse whether the adoption of shared mobility services could affect car use	RQ1, RQ2
O4	Analyse to what extent the progressive expansion of shared mobility fleets affects car dependency among users and non-users of shared mobility services	RQ2
O5	Analyse the effect of subjective attitudes and socio-economic characteristics on the capacity to give up the ownership of a private car because of the expansion of shared mobility services	RQ2, RQ3
O6	Compare how different current travel behaviour patterns in relation to the use of traditional modes and shared mobility services affects the individual's need to own a car in the future	RQ2, RQ3
O7	Investigate how the spatial context affects the impact of shared mobility on individuals' car dependency	RQ2, RQ4
O8	Investigate how the city of residence affects the impact of shared mobility on individuals' car dependency	RQ2, RQ4
O9	Provide policy recommendations on how to exploit the potential of shared mobility to reduce car dependency	RQ1- RQ4

4.3. Research assumptions

The formulated research questions and objectives presented in the previous sections are based on a series of assumptions regarding the occurrence of an ongoing transition to a less car dependent mobility system and the role that shared mobility can play in this transition. As already mentioned, the thesis aims to provide some insights on the impact that shared mobility could have on individual's car dependency in the mid-term given a scenario of continuous expansion and increasing availability of this services. The purpose of this sub-section is to elaborate on these assumptions in order to clearly establish the underlying premises of this thesis.

Assumption 1

The first assumption within the context of this thesis is the fact that the different dimensions of car dependency (car ownership, car use, beliefs and attitudes, etc.) evolve over time. This is a consequence of the influence of the underlying culture, values and socio-economic environment on individual travel choices. For this reason, the segments of the population that tend to own more cars and used them more often are assumed to potentially change over time, as some previous works have noted (Kitamura, 2009; Maltha et al., 2017). In the current context, the world is facing a succession of crises, namely climate, sanitary and energy crisis, that greatly influence daily consumption choices. Then it can be reasonably assumed that the determinants of car ownership and use may have experienced noticeable changes. The disruptions that these crises have induced are in addition to the underlaying natural social changes in practice, values and attitudes that occur across generations, e.g.: less importance attached to ownership, the introduction of information technologies on daily life activities, etc.

Assumption 2

The second assumption in which this work lies is that a socio-technical transition to more sustainable transport regimes than the car-centric one is currently ongoing. This hegemonic regime presents the car not only as a mode of transport but also a symbol of status and freedom and gives the private car a prominent position with respect to other modes of transport. However, several authors have pointed out that this regime may be on decline (see e.g. Taillandier et al., 2023; Barry, 2008 or Urry, 2004). In this regard, it is being observed that new generations are starting to look for ways to move without the burdens that car ownership entails both for society and the individual. Thus, a system in which individuals are expected to necessarily own a car to meet their mobility needs and private cars are at the centre of infrastructure development and daily life practices is starting to be challenged (Banister, 2008;

Delbosc & Currie, 2013; Hopkins & Stephenson, 2016). It is worth mentioning that some researchers consider that the observed reduction in car usage among new generations is just a delay with respect to the timing of life-cycle events, while other authors consider that the reduction of value attached to ownership, the increasing environmental awareness and the advent of new mobility services are behind this transition (Delbosc, 2017; Hopkins, 2017).

Assumption 3

Following the previous one, the third assumption is that shared mobility has the potential to play an important role in the transition to an alternative socio-technical mobility system. The need to replace the private car as the main player of urban mobility systems is motivated by the multiple negative externalities that it brings about. These negative effects include congestion, intensive energy use, air and noise pollution (in the case of internal combustion vehicles) and occupation of a large fraction of urban public space either for parking or for circulating (Delucchi, 2003). Against this scenario, it is considered that shared mobility could be used as a tool to encourage the decline of a car-centred mobility system and its negative effects. This potential is due to the possibility of replacing private cars by offering similar levels of flexibility and convenience for door-to-door trips. This is in addition to the fact that shared mobility may enable a more efficient use of the existing fleets, facilitate the electrification of vehicles and make available a wide variety of modes to meet different types of mobility needs. In this regard, it should be highlighted that this work assumes that a seamless integration of shared and traditional collective modes would set the ground for individuals to shift to a private car-independent mobility (Docherty et al., 2018; Ruhrort, 2020).

4.4. Research hypotheses

Considering the above-described assumptions and the review of the literature, a series of hypotheses have been raised regarding the answers that will be obtained to the research questions.

Hypothesis 1: The COVID-19 pandemic altered some of the main drivers of private car-based mobility of individuals, as well as in their car ownership decisions.

It is expected that the COVID-19 pandemic has led to changes in the traditional factors of car use and ownership that were observed in the previous literature. For instance, it could be expected an increase in car ownership and use among population segments with less access to teleworking arrangements (e.g. low-qualified and low-income workers) while reducing it among those that could stay at home to prevent contagion.

Hypothesis 2: The progressive expansion of shared mobility fleets can significantly reduce individual's perceived need to own a car in the future.

As explained in the assumptions, it is considered that shared mobility can be a key agent on the transition to more sustainable mobility systems, in which private cars are relieved from the central position they currently play. In this regard, the hypothesis is raised that the wide availability of shared mobility systems leads to a reduction in the individuals' perceived need to own a car in the future.

Hypothesis 3: The impact of shared mobility on individuals' perceived car dependency is influenced by their subjective perceptions as well as by their socio-economic attributes.

Following the second hypothesis, the third one establishes that the impact of shared mobility on individual's car dependency is heterogeneous across different socio-economic and personality profiles. The interrelations between the drivers of car ownership and use with the determinants of shared mobility adoption will determine which individual characteristics are correlated with a higher likelihood of believing that car will not be necessary in the future as a result of shared mobility's expansion.

Hypothesis 4: The impact of shared mobility on individuals' perceived car dependency is influenced by the current travel behaviour with respect to both conventional and shared modes of transport.

Similarly, the fourth research hypothesis states that current travel behaviour determines the impact that shared mobility could have on individuals' car dependency. It is assumed that individuals with more sustainable and multimodal travel habits will be more likely to believe that they can give up their car as shared mobility services gradually expand. On the other hand, those with a more car-dependent travel behaviour will be more reluctant to consider that shared mobility could replace car ownership.

Hypothesis 5: The impact of shared mobility on individuals' perceived car dependency depends on their spatial context,

The last hypothesis is connected to the fourth research question and asserts that the spatial context both at the area of residence and at the city level has a significant effect on the potential of shared mobility to reduce car dependency. Although from previous literature it could be inferred that individuals living in denser areas with a better supply of public transport would probably be more likely to reduce their car dependency, this work rises the hypothesis that shared mobility can also be a valuable tool to reduce car dependency in low density areas.

5. Case study: European urban areas with special focus on the case of Spain

This chapter outlines the context for the different case studies considered in this thesis. First, Section 5.1 briefly remarks the main features of European urban areas with respect to mobility patterns and urban transport policies. Second, Section 5.2 presents the main characteristics of the four biggest Spanish cities (Madrid, Barcelona, Valencia and Seville), their shared mobility supply and the regulatory frameworks that have been implemented to ensure that this new kind of mobility contributes positively to a more environmentally and socially sustainable urban mobility. This section places special importance on the geography and transport ecosystem of the Region of Madrid, as this area has played an especially relevant role in the conducted analyses.

5.1. Characterisation of European urban mobility

Europe is one of the most urbanized regions in the world, with around 40% of its population living in urban areas (Eurostat, 2020). European cities have been traditionally characterized by population densities that are considerably higher than those in other contexts such as North America, but lower than South America or Asia (Lavalle et al., 2017). This compact urban structure has facilitated the provision of efficient public transport, good accessibility to services and high usage of active modes (Vandecasteele et al., 2019). This urban and transport planning has resulted in a mobility culture that, despite relying excessively on the automobile, is not as car centric as e.g. North America (Haustein & Nielsen, 2016). However, in the last 20 years, the proportion of extremely high-density areas (more than 400 inhabitants per ha. of residential built-up) has declined coupled with an increase in the number of low-density areas. This phenomenon tends to be particularly frequent around big dense urban areas with high GDP per capita and good accessibility by car to the city centre (Oueslati et al., 2015). Presumably, this increasing urban sprawl is due to parts of the city's population relocating to surrounding residential areas to enjoy more available space without losing access to the employment opportunities that concentrate in the city core (Vandecasteele et al., 2019). This relocation has an extremely negative impact on the sustainability of these households' mobility. The efficiency that public transport could have in this kind of areas is very low and the large amount of available space encourages households to own more vehicles and adopt a more car dependent mobility, with the consequent increase in external costs (Bart, 2010; Camagni et al., 2002). In this context, the COVID-19 pandemic further accentuated this problem, with families heavily relying on private cars to avoid contagion and relocating to sub-urban areas as a result of teleworking schemes and the need for more space during confinement (Duque-Calvache et al., 2021; Shakib et al., 2024).

Simultaneously, tackling the climate crisis and transforming European cities in healthier and more livable places has become a priority for the European Union, who has been encouraging local and regional institutions to deploy policies promoting sustainable transport (European Commission, 2020). This policy agenda is putting European cities at the international forefront of the development and implementation of measures aiming at reducing the emissions of urban transport and transforming urban areas into more livable and healthy places (European Commission, 2020). This agenda, for the specific case of urban areas, has been materialized in the 100 Climate Neutral Cities mission. This program aims to provide financial and strategical support to 100 cities in the European Union through the creation of specific action plans to ensure their full decarbonisation by 2030 (European Commission. DG RTD, 2021). Finally, it should be noted that these regulatory frameworks are being developed in a society that seems

increasingly aware of the need to fight and mitigate climate change and the positive impact of climate change policies in daily life (EIB, 2022). Altogether, this combination of factors makes European cities an interesting case study to analyse the new trends that have arisen in terms of car ownership and use in recent years.

5.2. Spanish urban areas and their shared mobility ecosystem

Within the European context described above, Spanish cities offer a particularly suitable case to analyse the impact of shared mobility on car dependency. Of particular interest are the four biggest cities in the country (Madrid, Barcelona, Valencia and Seville), given that they have the widest supply of shared mobility in the country, and it is where these services have been functioning for a longer time.

From a general point of view, it should be noted that the four cities are important economic and touristic poles, attracting a high number of citizens and travellers. This activity favours the adoption of new mobility services, but also puts special tension on their mobility systems, requiring a high level of transport planning and regulation. Additionally, the four cities are characterised by a mild and dry weather that encourages the use of shared micromobility and favours intensive social outgoing interaction and, therefore, mobility.

Spanish cities, encouraged by the national government, have been consistently implementing mobility measures aimed at restricting the use of the private car in city centres. In fact, according to the Climate Change Law approved in 2022, all cities bigger than 30,000 inhabitants are obliged to create a Low Emission Zone (LEZ) restricting the circulation of polluting vehicles (Real Decreto 1052/2022). Even before this regulation was passed, both Madrid and Barcelona had already deployed their LEZs in 2018 and 2020 respectively and, except for brief interruptions, have been in place ever since. Seville and Valencia, meanwhile, implemented their LEZ at the start of 2024. In the same trend, all four cities under study have deployed paying systems to regulate parking (RACE, 2022).

5.2.1. Public transport supply

Notwithstanding the significant differences that may exist between cities, the public transport system in all the considered metropolitan areas offers diverse mode options (Observatorio de la Movilidad Metropolitana, 2022). Madrid and Barcelona have a dense network of metro and sub-urban rail that complements the bus lines. For instance, **the Region of Madrid** has an extensive and competitive network of public transport services, including: 16 metro lines, 11

sub-urban rail lines, 5 light metro lines, 339 lines of urban buses and 349 of inter-urban buses that cover the whole territory. On the same trend, the **metropolitan area of Barcelona** has 18 metro lines, 373 lines of urban buses and 397 inter-urban buses, 19 suburban rail lines and 4 tram lines. As for the **metropolitan area of Valencia**, the public transport system includes 45 urban and 54 interurban bus lines, 6 metro lines, 3 tram lines and 6 sub-urban rail lines. Finally, the **metropolitan area of Seville** relies heavily on buses, offering 60 urban bus lines and 64 interurban lines, against a limited rail network that includes 5 sub-urban lines, one metro line and one tram line. It is important to note that in all four urban areas, the majority of public transportation services are concentrated in the core cities. Consequently, accessibility diminishes notably as one moves farther away from the city centre.

5.2.2. Shared mobility in Spain – evolution and current situation

Shared mobility supply is quite developed in Spanish cities, with almost all big and medium-size cities having at least one service and most of them having a public bike-sharing service funded (partly or wholly) by the local government. In most of these cities, station-based bike-sharing systems have been operating for a long time (for instance, in Valencia since 2010 and in Seville since 2007), but a sharp increase in the supply of shared mobility services occurred around 2018 (Europa Press, 2017; Romero, 2018). From this year on, a cascade of private shared mobility operators flooded the centres of Spanish urban areas (as in many other European countries) with shared vehicles. In addition, the innovative nature of the companies operating these services led to a certain instability of the market, with companies starting and ceasing operations in very short periods of time (Asenjo, 2020). This uncontrolled expansion provoked an initial rejection both from citizens and local institutions (Congostrina & Rodríguez, 2019; Mcloughlin, 2018) and made clear for transport planners that ad-hoc regulatory frameworks were needed for shared mobility to become part of urban mobility systems.

In the last years, Spanish local institutions have been making great progress on the development of regulations that mitigate the negative impacts of these services (a more detail description of these negative effects can be found in Section 2.3). Although significant progress still lies ahead, it can be considered that Spanish cities are now in the right moment to move a step forward and start considering strategies to exploit the potential of shared services as feeders of public transport and substitutes of the private car. For this reason, it is argued that Spanish urban areas provide a suitable case study to explore the impact of shared mobility on the future decisions regarding car ownership and how this potential could be capitalized. The following paragraphs provide an overview of the current status of shared

mobility ecosystems and a summary of the most relevant regulations that have been implemented, for each of the cities included in the study.

The shared mobility ecosystem of **Madrid** features a remarkable variety and size (Arias-Molinares & García-Palomares, 2020b). According to Fluctuo (2024), at the end of 2023 there were more than 20,000 shared vehicles of different kinds available in the metropolitan area. Madrid shared mobility system includes practically all the services currently available: bike-sharing (with public and private operators), car-sharing, kick scooter sharing and moped scooter sharing, almost all of which are free-floating services. As could be expected, the spatial distribution of the existing supply of services differs considerably between the city of Madrid and the surrounding municipalities, with most vehicles being operated within the core city and, in particular, in its central districts.

Currently, the number of operators of e-kick-scooters has been limited to three (Tier, Dott and Lime), which were granted licenses following a public tender in which the services had to meet a set of requirements regarding technologies to ensure safety and good parking practices (BOAM, 2022). Bike-sharing services are specially varied, with five operators of free-floating shared bikes (Ridemovi, Boltest, Bird, Ride Dott and Lime) and one public operator of station-based and free-floating shared bikes (BiciMad). Although neither the number of operators nor the number of licenses granted for free-floating shared bikes has been limited, the local government has developed a rather strict regulation on adapting the number of bikes to the demand, the management of damaged bikes and the data sharing framework (BOAM, 2020). Notwithstanding the considerable higher density of micromobility within the city of Madrid, some services are starting to expand to neighboring municipalities. It has recently been announced the future implementation of e-kick-scooter sharing and bike-sharing systems in the municipality of Parla (within the Madrid metropolitan area), and the extension of BiciMad bike-sharing service area from Madrid city to the bordering municipality of Alcorcón. Furthermore, some of the biggest municipalities surrounding Madrid city have developed their own bike-sharing services, such as Gbici in Getafe or Bicinrivas in Rivas-Vaciamadrid. For the case of car-sharing, six operators offer their services in the Region: Free2Move, WiBLE, Zity, GoTo, SharedNow and Voltio. Most of their vehicles are located within the city of Madrid, but in the last few years some of them are gradually expanding their services to some neighboring municipalities in the north and the west of the region, such as Alcobendas, Pozuelo, Las Rozas or Majadahonda. Finally, four operators of moped sharing can be found in the region (Acciona, GoTo, Cooltra and Cabify). They display a very similar geographical distribution to that of car-sharing, as they operate in the city of Madrid and in some neighboring municipalities within its metropolitan area. Apart from issuing fines for

improper parking, no notable regulatory measures for moped sharing or car-sharing have been imposed.

The supply of shared mobility in **Barcelona** is somewhat lower than in Madrid and, with few exceptions, can only be found within the core city. The local government ruled against deploying e-kick-scooters as they were considered incompatible with the transport planning of the city (Sust, 2023). The situation of bike-sharing in Barcelona is particularly interesting, with the Public Transport Authority managing two complementary services (Bicing and AMBici). While Bicing covers the demand within the city of Barcelona, AMBici offers the possibility of using shared bikes in the municipalities surrounding the city to reach the public transport network. There are also two private operators of free-floating bikes, eCooltra and Donkey bikes. As for moped-sharing, Barcelona, unlike other cities, has not set a limit to the number of operators but has capped the number of licenses to 7,000. These licenses are currently distributed between four operators – Yego, eCooltra, Cabify and Acciona. It is noteworthy that these services have made Barcelona the city with the second highest ridership of both shared bikes and shared mopeds worldwide (Fluctuo, 2023a).

Similarly to the case of Barcelona, **Valencia** has no car-sharing or kick-scooter sharing. The main regulatory measure of shared services that has been put in place is the limitation in the number of licenses issued for moped-sharing services to 2,000. These licenses have been granted to the three operators that met the established requirements: eCooltra, Cabify and Acciona (Plaza, 2022). Although most of the mopeds are located within the city of Valencia, some services have started to expand to surrounding municipalities. As for shared bikes, the local government operates the public service, Valenbisi.

Finally, the shared mobility offer in **Seville** is quite diversified, but none of the operators has yet expanded their fleets beyond the city limits. The supply includes one public bike-sharing system (Sevici) and two operators of free-floating shared bikes (Ridemovi and Lime). 2,000 licenses for a period of two-year were granted to these two companies following a public tender process (Ameneiro, 2022). A similar procedure was conducted for the case of e-kick-scooters, for which 2,000 licenses were granted to two companies (Reby and Voi). However, during the duration of the two years pilot, Reby went bankrupt, leaving Voi as the only kick-scooter sharing provider in the city. In parallel, in order to avoid bad parking practices, more than 300 dedicated parking points were located throughout the city and the operators are required to ensure that their applications do not allow vehicles to be parked outside these points (Ayuntamiento de Sevilla, 2021). As for moped-scooters, four operators (eCooltra, Yego, Acciona and Cabify) are currently offering their services, without significant restrictions.

Table 5-1 provides a summary of the information exposed above, together with the size of the cities and their metropolitan areas.

Table 5-1: Overview of the current shared mobility offer in Spanish cities

	Size of the city (inhabitants)	Size of the metropolitan area (inhabitants)	Shared mobility services - Service municipalities out of the core city
Madrid	3.2 million	7.3 million	Shared cars (6 operators) - Yes Shared mopeds (4 operators) - Yes Shared e-kick-scooters (3 operators) - No Shared bikes – dock-less (5 private operators) - No Shared bikes – station-based (1 public operator) - Yes
Barcelona	1.7 million	5.5 million	Shared mopeds (4 operators) - No Shared bikes – dock-less (1 private operators) - No Shared bikes – station-based (1 public operator) - Yes
Valencia	0.8 million	2.5 million	Shared mopeds (3 operators) - Yes Shared bikes – station-based (1 public operator) - Yes
Seville	0.7 million	1.6 million	Shared mopeds (4 operators) - Yes Shared e-kick-scooters (2 operators) - No Shared bikes – dock-less (2 private operators) - No Shared bikes – station-based (1 public operator) - No

5.3. The spatial structure of the Region of Madrid

The spatial structure of the Region of Madrid deserves special attention, as it offers a particularly interesting case study to analyse the potential of shared mobility to reduce car dependency in a territory with a remarkable variety of community typologies (urban, sub-urban and rural). This is in addition to the wide and rich shared mobility ecosystem that the city and its surroundings features.

The Region of Madrid has a total population of 7.3 million inhabitants, and mainly includes the city of Madrid and its metropolitan area. Noticeably, they constitute the third largest city and metropolitan area in Europe. The region, which has experienced a marked urban sprawl in recent decades, has in broad terms three main areas: i) the city of Madrid, with a total of 3.2 million inhabitants, which follows the European pattern of a highly dense town and is an important focus of business and economic activity in southern Europe; ii) the metropolitan area, comprising surrounding municipalities with a strong social and economic interdependency with the city of Madrid; and iii) the rural areas, including many other municipalities within the region with low population densities (3-4 inhab. per km²). As can be observed, the Region of Madrid has large differences in terms of population density, level of economic activity, community types (urban, sub-urban and rural), built environments and land-use mixes (Instituto de Estadística CM, 2022b). This heterogeneous structure offers a rather unique setting to analyse the impact of shared mobility on car dependency in different but close spatial contexts.

As explained before, the Region of Madrid offers a wide supply of public transport, which results in fairly sustainable mobility patterns. According to the last mobility survey (CRTM, 2018), a total of 15.8 million journeys are made in the region in a working day, 39% of which are made by private car. Sustainable modes have a strong presence in modal share, with walking and public transport comprising, respectively, 34% and 24% of total trips in a working day. However, the unequal distribution of public transport supply, which is mainly concentrated in the city of Madrid and the neighbouring municipalities, leads to important differences in terms of modal share across metropolitan rings. For instance, in the city centre only 20% of the trips are made by car, while in the outer ring of the region (outside the metropolitan area) this percentage rises up to almost 60% (CRTM, 2018). Together with the lower availability of public transport, the lower population density and the less mixed land use patterns in outer areas of the region presumably also play a role. This geographic heterogeneity is also evident when considering car ownership rates. The city of Madrid has one of the lowest motorisation rates in the region (456 cars/1,000 inhab.), while the surrounding municipalities show significant increases in this ratio. For example, in Majadahonda, a wealthy town in the metropolitan area located 20 km away from Madrid city centre, the car ownership rate is 1,854 cars/1,000 inhab. Similarly, in Buitrago del Lozoya, located in a rural area near the northern boundary of the Region, the ratio reaches 910 cars/1,000 inhab. (Instituto de estadística CM, 2022a).

6. Materials and methods

This chapter presents the methodology that has been implemented in this thesis to fulfil the research objectives. First, an overview of the main steps that compose this methodology are provided in Section 6.1. Second, Section 6.2 presents the methodological approach that has been adopted to capture car dependency in this research. Third, Section 6.3 describes the main characteristics of the different datasets that have been employed, together with a summary of the main aspects captured by each dataset. Section 6.4 presents the geographical data that has been gathered to complement the surveys. Finally, Section 6.5 justifies the modelling frameworks that have been adopted based on the characteristics of the available data and the research goals to be fulfilled.

6.1. Overview

The methodology followed throughout this thesis encompasses four steps that are schematically represented in Figure 6-1 and further described through this section.

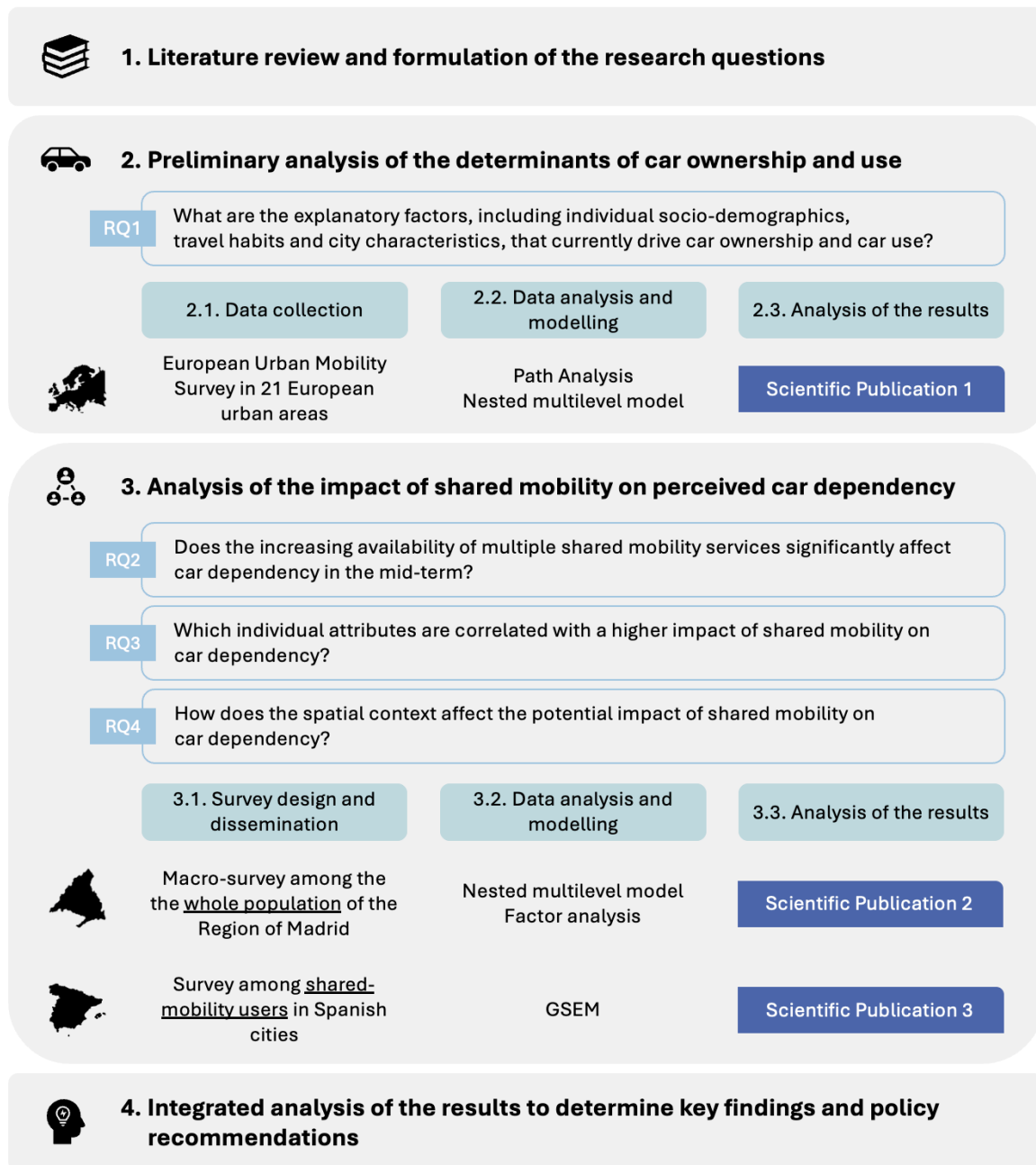


Figure 6-1: Overview of the methodology

1. Literature review and formulation of the research questions

Firstly, a thorough review of the scientific literature has been done mainly focusing on (1) the existing research works that have explored the determinants of car ownership and use in urban contexts and (2) the impact that shared mobility services have on these two mobility-related decisions. The exploration of the current literature has allowed to point out some existing gaps that still need to be filled and consequently formulate the research questions of this thesis.

2. Preliminary analysis of the determinants of car ownership and use

The second step of the methodology focuses on answering RQ1, dealing with the determinants of car ownership and use. This step aims to (1) gain deeper understanding of the drivers of car ownership and use, considering the mediation effect that the number of cars owned in the household may have in the frequency of use of this mode by individuals; (2) obtain an updated overview of the determinants of car ownership and use given the changes that the COVID-19 pandemic could induced in these decisions; and (3) identify the individual and city-level characteristics that currently determine car ownership and usage in European urban areas. The investigation of these aspects allowed to establish the basis for the later interpretation of the overall results of this thesis. It is noteworthy that, for this preliminary analysis, the thesis took advantage of an existing Europe-wide urban mobility survey conducted by the European Commission in 21 European urban areas. The modelling framework chosen to analyse this dataset was a Path Analysis combined with a Multilevel model. The former allowed to disentangle the correlations between the potential direct and indirect impact of socio-economic characteristics and travel habits of the individual on car ownership and use. The later was implemented to account for the possible heterogeneity that could exist between residents in different European regions, countries or cities. In this respect, multilevel models include random coefficients that allow capturing these dissimilarities between observations belonging to a different cluster (geographical area). The analysis resulting from this step of the methodology has led to SP1.

3. Analysis of the impact of shared mobility on perceived car dependency

This step of the methodology aims to analyse the impact that shared mobility could have in car dependency if it were to reach a level of development that would make it a feasible alternative to ownership. This goal constitutes the main contribution of this thesis and provides answers to RQ2, RQ3 and RQ4.

During this phase, two different studies were conducted by employing two different approaches. On the first place, a broader analysis focusing on the general population (i.e., both users and non-users of shared mobility) was conducted in the Region of Madrid. For this analysis, a macro-survey campaign was conducted to gather information from residents in this region. One of the main goals of this study was to explore how shared mobility could reduce car dependency in sub-urban and rural areas surrounding a big city. For this reason, a special emphasis was put on achieving geographic representativeness (see Section 6.4 for more details). This information was analysed using a Nested Multilevel Model, which allowed to account for the spatial heterogeneity that could exist between the different areas (metropolitan rings and municipalities) of the region regarding car dependency. Together with individual characteristics, travel-habits and spatial characteristics, the questionnaire included a set of indicators capturing subjective attitudes and preferences that could affect the adoption of shared mobility. These indicators were thereafter employed to construct latent variables that could influence the impact of shared mobility in perceived car dependency. This analysis resulted in the elaboration of SP2.

The second study of this phase has a more specific nature and is aimed at understanding the impact of shared mobility on car dependency among users of these services. This second approach allowed to understand in more depth how different levels of usage of shared mobility and the combination of various shared services may affect the need to own a car in the future. For this study, the opportunity arose to conduct a survey in cooperation with Acciona, an operator that provides moped sharing services, which offered a beneficial opportunity to access a considerable number of users in four Spanish cities (namely, Barcelona, Madrid, Seville and Valencia). Aiming to jointly model the effect of latent constructs, socio-economic variables, travel habits and built-environment characteristics on both the frequency of use of shared mobility services and the potential impact on people's car dependency, a Generalised Structural Equations Model (GSEM) was built for this study. This analysis led to the elaboration of SP3.

4. Integrated analysis of the results to determine key findings and policy recommendations

The final step of the methodology consists of the joint analysis of the results yielded by the different models and SPs. This integrated interpretation has allowed to draw cross-cutting conclusions, provide concise answers to the research questions that were raised and propose policy recommendations regarding the mid-term impact of shared mobility on car dependency in urban areas.

6.2. Methodological approach to capturing the impact of shared mobility on car dependency

Since this work aims to analyse the impact of shared mobility on car dependency, this section provides a necessary explanation of the approach that has been followed to capture this phenomenon.

One of the most frequently adopted conceptualisations of car dependency is the one offered by Mattioli et al. (2016) in which three levels of dependency are considered: i) a *micro-level*, that considers car dependency at the level of the individual; ii) a *meso-level*, that considered trips whose purpose entails the need of a car (e.g. carrying goods or escorting children); and iii) a *macro-level*, that focuses on the dependency induced by the spatial characteristics of a place and the dominant culture of a society. In this work, the impact that shared mobility may have on car dependency is measured through a statement focusing in the micro- and the meso- level of Mattioli's conceptualisation: *"Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future"*. The specific ways in which these dimensions are captured and why they are considered relevant for the purpose of this work are explained hereafter.

The given statement establishes ownership as the central element of the relation of dependence, similar to other contributions which have considered that the need to own a vehicle ultimately reflects the individual's dependency on private cars to fulfil one's mobility needs (Carroll et al., 2021; Wiersma, 2020). In addition, car ownership has been found to be the best predictor of car use and several authors have pointed out that once a car is purchased, household mobility habits change and the car becomes the dominant mode of transport (Sohn & Yun, 2009; Van Eeno et al., 2022), even in contexts of good accessibility to public transport (Cullinane & Cullinane, 2003). Moreover, in the pursuit of developing sustainable mobility policies, the emphasis on ownership is a well-founded approach, as car ownership involves substantial ownership costs and comparatively lower operational costs for individuals. This means that attracting car owners to other transport options, even in situations when they are more convenient and sustainable, becomes a challenging task for transport planners (Matowicki et al., 2023; Sohn & Yun, 2009).

On the other hand, the thesis focuses on the medium-term impact that shared mobility may have on the dependency of individuals on private vehicles. This has led the analysis to focus on individual perception of the need for a private car, rather than on actual car ownership. The rationale behind this formulation is that the study aims to estimate the impact that a potential change in the macro- and meso-level of car dependency, namely the expansion of

shared mobility fleets across the whole territory of metropolitan areas, may induce in the micro-level of car dependency. As mentioned above, in many cases there is no (or very little) supply of shared mobility services, as is the case in less central areas of large cities or in the municipalities of metropolitan areas, typically characterised by a lower supply of public transport. The scenario in which individuals without a car could rely on shared mobility (exclusively or in combination with public transport) to meet their daily mobility needs has not yet materialized. Therefore, the only feasible approach to measure its potential mid-term impact at the micro-level at the present moment is to examine how this hypothetical situation would influence their subjective perception of the (near) future. This approach is supported by a consistent body of works that explores the subjective perceptions of individuals as key factors affecting car dependent habits and travel choices (Behren et al., 2018; Handy et al., 2005; Lucas, 2009).

6.3. Survey data

The data employed throughout this thesis are primarily derived from three distinct cross-sectional surveys conducted in disparate geographical regions and over varying time periods. They all provide a comprehensive set of socio-economic characteristics of the respondents and their households, their self-declared travel behaviour and other mobility habits, car ownership levels, access to different private modes and place of residence. An overview of the operational characteristics of the survey campaigns and the specific variables captured in each of the surveys is displayed in Table 6-1. More details regarding the design and dissemination methods of each specific survey can be found in Sections 6.3.1, 6.3.2 and 6.3.3.

Table 6-1: Summary of the variables included in the surveys

	European Urban Mobility Survey	Macro-survey to residents in the Region of Madrid	Survey to users of shared mobility in four Spanish cities
Number of valid responses	10,152	15,666	3,897
Geographical scope	21 European urban areas	Region of Madrid	Barcelona, Madrid, Valencia and Seville
Time period	March-May 2021	November-December 2022	March-April 2022
Target population	Whole population	Whole population	Shared mobility users
Survey manager	European Commission	SIGMADOS	Shared mobility operator
Surveying techniques	CATI and CAWI	CATI and CAWI	CAWI
Variables included in the surveys			
Socio-economic characteristics	Yes	Yes	Yes
Teleworking habits	Yes	Yes	
Attitudinal indicators		Yes	Yes
Self-declared frequency of use of:			
Private car	Yes	Yes	
Public transport	Yes	Yes	
Private active modes	Yes	Yes	
Bike sharing	Yes	Yes	Yes
Scooter sharing	Yes	Yes	Yes
Car-sharing	Yes	Yes	Yes
Moped sharing		Yes	Yes
Car ownership in the HH	Yes	Yes	
Access to private car			Yes
Distance from home to working/studying place	Yes	Yes	
Self-declared Accessibility to public transport	Yes		
Information regarding the place of residence	City of residence	Municipality/District of residence	Zip code of residence
CAWI: Computer-Assisted Web Interview, CATI: Computer-Assisted Telephonic Interview			

6.3.1. An EU-wide Urban Mobility Survey

The primary source of updated data to analyse the determinants of car use and ownership after the COVID-19 pandemic was a cross-section survey conducted by the European Commission between March and May 2021 (Christidis et al., 2022). During the period in which the survey was being conducted, strict lockdown measures were already lifted but certain mobility and health-related restrictions remained enforced by governments. The survey campaign gathered information from 10,152 individuals over 16 years old living in 21 different European urban areas. The observations are equally distributed, with approximately 500 responses per urban area. In particular, 400 responses were collected using a Computer-Assisted Web Interviewing (CAWI) method. The remaining 100 responses were obtained through Computer-Assisted Telephone Interviewing (CATI) to ensure adequate representation of socio-economic groups not accessible through online surveys. It should be noted that the target respondents included residents in the territory comprised within the Functional Urban

Areas¹ (FUAs) as defined by the OCDE, including the core city and the metropolitan area. These FUAs, illustrated in Figure 6-2, encompass Paris, Lille and Calais (France), Charleroi (Belgium), Madrid and Málaga (Spain), Lisbon and Porto (Portugal), Milano and Catania (Italy), Berlin and Dresden (Germany), Stockholm and Malmö (Sweden), Bacau and Cluj-Napoca (Romania), Poznan and Krakow (Poland), Brno and Praha (Czech Republic) and Dublin (Ireland). Notably, these surveyed FUAs vary significantly in terms of size, geographical location and urban characteristics such as population density and urban sprawl. This diversity of geographical contexts for which this survey provides information makes it an ideal tool for this thesis. It allows an up-to-date exploration of the factors influencing car ownership and use and the relationship between them in different urban areas, while assessing the differences that may exist across different European cities.

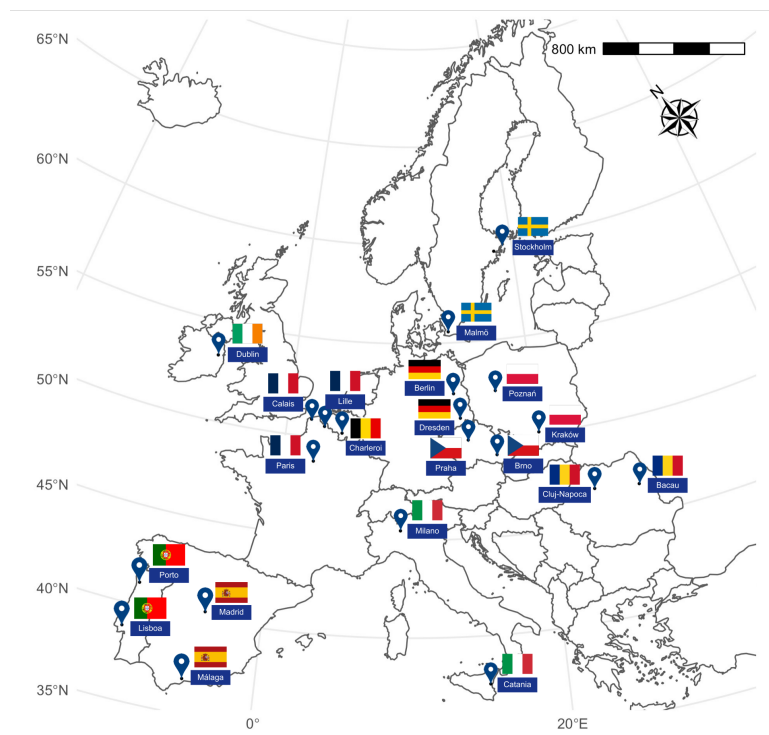


Figure 6-2: Location of the cities included in the European-wide urban mobility survey
(Source: **SP1** - Vega-Gonzalo et al., 2023)

¹ The European Commission and the OECD have collaborated to develop the concept of Functional Urban Areas (FUAs), aiming to offer a tool enabling precise comparisons of urban regions across nations. This approach transcends administrative boundaries, which frequently fail to accurately reflect the true urban dynamics or may vary considerably between countries. A FUA comprises a central dense urban core and the adjacent, less densely populated areas that form part of the city's labor market, referred to as the commuting zone. Further details on the concept and definitions of FUAs can be found in Dijkstra et al. (2019).

6.3.2. A macro-survey among residents in the Region of Madrid

In order to analyse the effect that shared mobility could have on perceived car dependency among the general population, a macro-survey was carried out among residents in the Region of Madrid. This region offers a particularly suitable case to analyse the mid-term impact of shared mobility given the wide variety and large supply of shared mobility services in operation (for more information see Section 5.2). The survey was conducted between November and December 2022, targeted at residents in the Region of Madrid over 16 years of age. Following the campaign, 15,666 valid observations were gathered after the removal of incomplete responses, validation and data cleaning procedures.

The gathering process was commissioned after a competitive public tender process to SIGMADOS, a market research company renowned for its expertise in mobility surveys. The campaign employed: i) Computer-assisted Telephone Interviewing (CATI) for telephone interviews, using official phone databases; and ii) Computer-assisted Web Interviewing (CAWI) for online questionnaires, ensuring access to populations with diverse access to technology. The survey had an estimated duration of 12 to 15 minutes. Notably, a stratified sampling approach was employed to ensure demographic and spatial representativeness, so as to capture variations observed in the Region of Madrid in terms of e.g. population density, motorisation rates and public transport supply. This included a sampling method designed to capture spatial heterogeneity across sub-areas while keeping intra-zone representativeness in terms of gender and age distribution.

Due to the possible significant impact of residential location within the Region on individuals' views regarding the potential of shared mobility to alleviate reliance on private cars, respondents were requested to provide their municipality of residence. For those residing in the city of Madrid, their district of residence was also requested, given the city's pronounced heterogeneity. This data allowed for the matching of each respondent with the built environment characteristics of their residential area, including aspects such as land use and transport accessibility. Further details on this association can be found in Section 6.4.

It is relevant to mention that, as part of the attitudinal indicators included in the survey, respondents were also requested to declare their level of agreement through a 5-point Likert-scale, with the following statement *“Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future”*. These responses were employed as the outcome variable of the model to analyse the potential impact of the expansion of shared mobility on perceived car dependency among the general population.

6.3.3. A survey among users of moped scooters in Spain

This survey campaign was managed by the operator of electric shared mopeds *Acciona movilidad* and targeted to users that were registered in their platform. Therefore, all the respondents in the sample are users of at least one shared mobility service. The questionnaire was distributed by the company through personal emails between March and April 2022. The geographical scope of the analysis included the metropolitan areas in Spain in which the company provides services, namely Madrid, Barcelona, Valencia and Seville. Some responses were obtained from residents in other Spanish cities where Acciona does not operate, which were removed for two main reasons. On the first place, the decision to use electric moped-scooters for these individuals was associated with the access to these services at a specific point in time (e.g., a temporary visit to a city with moped-sharing services) but it is not a mobility option they could consistently include in their travel habits, given that it is not available in their place of residence. Secondly, as it is further explained in Section 6.4, the survey data was complemented with information regarding the built environment of the residential location. For these respondents, this information would have characterised a spatial environment different from where they make the decision to use shared mobility. After removing these observations, a total of 3,897 valid responses were obtained for the analysis. As in the macro-survey to residents in the Region of Madrid, a question aimed at capturing the perception of individuals regarding the need to own a car given the expansion of shared mobility was included. In particular, respondents were asked in a Yes/No format whether they believe that *“a private vehicle would still be necessary in the future given the increased provision of shared mobility services.”*.

6.4. Spatial data

As commented above, all the surveys provided some kind of geographical information regarding the residence of the individual. This information has been exploited to complement the survey (questionnaire data) in all the three cases with spatial data. The processing and homogenisation of the spatial data has been done using QGIS and R.

- In the case of the European Urban Mobility Survey, it was possible to include some city characteristics dealing with size, urban sprawl, GDP per capita and the performance of the private car, public transport and bike. The *modal performance* captures the speed, frequency and density of the network and is defined as the ratio of the population that can be reached in 30 minutes by each mode and the population within 8 km (2 km for walking). A complete explanation of the methodology adopted to calculate mode

performance can be found in ITF (2019a). As part of this survey, respondents were also asked whether they live in the core city or in the metropolitan area.

- The macro-survey conducted in the Region of Madrid collected information regarding the municipality of residence or the district of residence (in the case of people living in the city of Madrid). This information allowed to include several variables (at the municipality or district level) regarding population density, accessibility to public transport and land-use entropy to characterise the built environment of the respondents. Additionally, individuals were classified into four categories according to their place of residence within the metropolitan area: city centre, Madrid municipal area, metropolitan area and rural area.
- Finally, the survey focused on shared mobility users in four Spanish cities provided the zip-code of residence of each respondent. This information was used to identify in which part of the metropolitan area they lived (city centre, municipal area or metropolitan area) and to build several variables capturing the land-uses and the accessibility to different public transport modes in the area of residence.

The list of spatial variables introduced to complement each survey can be found in Table 6-2.

6.5. Modelling techniques

Given the research questions and the characteristics of the data (see Section 6.3 for more details) a series of modelling frameworks have been designed and implemented to fulfil the research objectives. The reasoning behind the choice of each framework as well as the specific data set used for each model were already described in the overview of the methodology (see Section 6.1). Rather, this section provides some technical details of each modelling framework. All the econometric models have been implemented using STATA 17.0.

6.5.1. Disentangling chained travel choices through path analysis

Path Analysis (PA) is a widely used statistical technique in behavioural sciences (González et al., 2008; Van Acker & Witlox, 2010). PA can be considered an extension of traditional regression models in which several sub-models are jointly estimated, reproducing the variance-covariance matrix between all variables included in the model (Land, 1969). It takes as given the structure of relations between all the different variables and the succession of regressions. Consequently, this structure should be established by the modeller based on previous evidence and a sound hypothesis regarding the decision processes faced by the individual (Lleras, 2005). Therefore, the variables can be classified as **exogenous**, if they do

not have a causal relationship with other variables in the model or **endogenous**, if they are assumed to be explained by one or several variables included in the model.

Table 6-2: Spatial variables to characterise individuals' place of residence

European Urban Mobility Survey (city of residence)	Place of residence within the city:
	Core city
	Metropolitan area
	Population
	GDP per capita
	Urban sprawl (% of core city over total surface)
	Car performance
	Public transport performance
Macro-survey to residents in the Region of Madrid (Municipality/district)	Bike performance
	Place of residence within the city:
	City centre
	Municipal area
	Metropolitan area
	Rural area
	Land use entropy
	Proportion of residential use
	Proportion of industrial use
	Proportion of retail use
	Proportion of offices
	Proportion of public services
	Population density (1,000 inhabitants/km ²)
	No. urban bus stops
	No. metro stations
Survey to users of shared mobility in four Spanish cities. (zip code of residence)	No. interurban bus stops
	No. sub-urban train stations
	Place of residence within the city:
	City centre
	Municipal area
	Metropolitan area
	Density of urban bus stops (no./km ²)
	Density of metro/tram stations (no./km ²)
	Density of interurban bus stops (no./km ²)
	Density of sub-urban train stations (no./km ²)
	Density of collective housing area (m ² /km ²)
	Density of single-housing area (m ² /km ²)
	Density of parking area (m ² /km ²)
	Density of commercial area (m ² /km ²)
	Density of industrial area (m ² /km ²)
	Density of offices area (m ² /km ²)

PA is particularly useful when a variable that can be explained by a series of explanatory factors is, in turn, an explanatory factor of a subsequent variables. For instance, when trying to model the frequency of car use of an individual, the place of residence or the number of cars owned by the household would undoubtedly be explanatory factors of this travel behaviour together with the characteristics of the individual. In turn, the place of residence and car ownership are, as well, determined by the socio-economic characteristics of the individual. Consequently, building a modelling framework that allows to simultaneously introduce several cause-effect relationships in cascade provides a more accurate picture of

the drivers of individuals' behaviour by accommodating recursive effects that may arise. Furthermore, it allows to disentangle the direct effects from the indirect effects that might be occurring through an intermediate outcome variable. For a detail description of PA, the reader is referred to Streiner (2005).

6.5.2. Capturing attitudes and beliefs through latent variables

As explained in the literature review (see Chapter 3) subjective attitudes and lifestyle preferences play a key role in travel choices, both with regard to car ownership and use (Heinonen et al., 2021; Soza-Parra & Cats, 2023) and the adoption and use of shared mobility services (Eccarius & Lu, 2020; Van Veldhoven et al., 2022). However, these attitudes are not directly observable, so measure scales that allow to quantify them should be derived from observed behaviours or choices. For this reason, aiming to fulfil O6, a set of attitudinal indicators were included in the conducted surveys.

These indicators are used to construct latent variables aimed at capturing subjective attitudes and lifestyle preferences that could influence individuals' perceptions of the need to own a private vehicle in the future. This step of the modelling process is done through Factor Analysis. Initially, various tests are conducted to verify that the data gathered in the survey processes match the assumptions needed for a robust implementation of a Factor Analysis. In particular, the KMO measure of sampling and the Bartlett's test of sphericity are employed to ensure the suitability of the data.

Subsequently, an **Exploratory Factor Analysis (EFA)** is conducted, following a Common Factor Analysis methodology and Promax rotation, to determine the optimal number of factors that could be derived from the dataset, as well as to identify the most suitable indicators that compose each of those factors. The EFA phase of the analysis allows to define preliminary hypotheses regarding which indicators could be grouped together to build reliable measurement scales for the latent constructs that are intended to be captured. This reliability is evaluated through Cronbach's alpha, which measures the level of correlation between the indicators that make up a factor (Cronbach, 1951).

Finally, a **Confirmatory Factor Analysis (CFA)** is executed to estimate a final model to appropriately measure the latent constructs whose impact on perceived car ownership will be determined later. Based on the factor coefficients estimated and the results yielded by the Cronbach's alphas, a final hypothesis regarding the number of factors and their structure is put forward. The CFA allows to assess the goodness-of-fit of this model through the calculation of a set of indexes, namely the Root Mean Square Error of Approximation (RMSEA), the

Comparative Fit Index (CFI), Tucker Lewis Index (TLI), Standardized Root Mean Square Residual (SRMR) and the Goodness of fit index (GFI).

The impact of these latent constructs can be included in the wider modelling framework, together with the socio-economic variables and the declared travel behaviour, in two ways. On the one hand, it can be introduced as the structural part of a GSEM (see Section 6.5.3 for more details), in which case the factor loadings are re-estimated together with the entire model (see e.g., Aguilera-García et al., 2022 or Wang & Chen, 2020). This procedure is the one followed in the analysis of the survey focusing on the impact of shared mobility on private car dependency among users of this kind of services. On the other hand, the factor scores can be computed and introduced as explanatory variables in a consequent discrete choice model (see e.g. Chen & Li, 2017 or Fleischer et al., 2012). This approach has been followed in the analysis of the survey focusing on the impact of shared mobility on perceived car dependency among the general population.

6.5.3. Combining latent and observed variables in GSEM

Structural Equations Models (SEM) are an analytical framework that bring together different statistical techniques, namely factor analysis, generalised linear regression models and path analysis. In addition to the advantages of path analysis models (presented in Section 6.5.1), SEM allow to combine latent variables (see Section 6.5.2) that capture subjective attitudes and preferences, with observed variables such as socio-economic attributes or travel habits. The possibility of building more complex models in which different kinds of variables are introduced is especially relevant in the context of this work, given that travel decisions seem to be influenced by subjective preferences at least as much as individual demographic characteristics do. At the same time, preferences and beliefs are in turn directly influenced by socioeconomic attributes (e.g. age, income or occupation) and both subjective and objective attributes have an effect on mid-term decisions, such as car ownership, that again influence travel choices (Salomon & Ben-Akiva, 1983; Scheiner & Kasper, 2003).

In addition, GSEM, which are the ones employed in this work, generalise traditional SEM by allowing the introduction of different types of link function (logit, gaussian, gamma, etc.) between the exogenous and endogenous variables. As a result, this makes it possible to model dependent variables other than those of a continuous nature, such as ordinal, nominal or binary responses.

From an analytical point of view, GSEM are made up of two main parts – the structural and the measurement part. The structural part constructs the latent variables based on the observed indicators collected in the survey and estimates the correlations between them and

with the socio-economic variables. Equation 1 shows the mathematical formulation of this phase, where η is the vector of latent variables, Π is the correlation matrix of the latent variables, ξ is the matrix of socio-economic variables, Γ is the coefficients matrix of the socio-economic variables and ζ is the vector of disturbances for each latent variable.

$$\eta = \Pi\eta + \Gamma\xi + \zeta \quad (1)$$

Once the structure of the latent variables and its correlations with the socio-economic variables have been estimated, these variables are introduced, together with the observed exogenous variables, as determinants of the utility functions that determine the co-endogenous variables. In this way, in the measurement part, the whole variance-covariance matrix of the co-endogenous and exogenous variables (both latent and observed) is jointly estimated in the following way.

$$Y = BY + \Phi w + \Theta\eta + \epsilon \quad (2)$$

Where Y is a matrix of responses to the co-endogenous variables, B is the vector of coefficients of the co-endogenous variables, w and η are the matrixes of observed exogenous and latent variables, Φ and Θ are their coefficient matrixes and, finally, ϵ is the vector of error terms for each co-endogenous variable.

6.5.4. Multilevel models to capture spatial heterogeneity

Car dependency has been observed to be a behavioural pattern highly influenced by the built-environment and the place of residence within the metropolitan area (Ding & Cao, 2019; Cao et al., 2019). In the same fashion, the adoption and usage of shared mobility is largely dependent on the spatial accessibility to these services and to public transport, which is directly related to the place of residence (Becker et al., 2018; Haustein, 2021). Taking these considerations into account, it seems reasonable to assume that the potential reduction in car dependency due to the availability of shared mobility services could be determined to a large extent by spatial drivers. However, the usage of survey data can sometimes hinder these spatial considerations given that spatial econometric techniques are best suited to analyse area-level patterns rather than individual behaviour (Anselin, 2022). Consequently, to avoid the aggregation of individuals' information that could result in information loss, multilevel models (also known as mixed-effects or hierarchical models) provide a valuable modelling technique to account for the potential lack of independency of survey observations that may happen with responses from individuals living in the same part of the region, overcoming the so-called "atomistic-falacy" (Schmidt-Catran & Fairbrother, 2016). In addition, the implementation of multilevel models with a hierarchical or nested structure allows to analyse

the spatial heterogeneity at several grouping levels. For instance, taking the case of a two nested levels binary logit model considering k groups for the higher level and j groups for the lower level, the probability Y_{ijk}^* of individual i belonging to group j nested in group k of making a certain choice, given a vector of individual characteristics X_{pijk} , can be formulated as shown in Equation (3). In this equation ε_{ijk} represents the error term capturing the individuals' residuals.

$$Y_{ijk}^* = \beta_{0jk} + \sum_{p=1}^P \beta_{pj k} X_{pijk} + \varepsilon_{ijk} \quad (3)$$

The intercept β_{0jk} and the slope $\beta_{pj k}$, can be decomposed in the following way. The intercept is composed by the fixed intercept β_0 plus a random term that varies across municipal areas (u_{jk}) and another random term that varies across metropolitan rings (u_k). The same decomposition is applied to the slope.

$$\beta_{0jk} = \beta_0 + u_{jk} + u_k, \beta_{pj k} = \beta_p + u_{jk} + u_k \quad (4)$$

As a result, the total variation in the model (E_{ijk}) can be expressed as:

$$E_{ijk} = \varepsilon_{ijk} + u_{jk} + u_k \quad (5)$$

The introduction of random coefficients u_{jk} and u_k allows to capture the unobserved effects that may influence the travel choices of individuals residing in the same area of residence (Hedeker, 2008). In case it is observed that the variance across groups is statistically significant, explanatory factors at the group level can be introduced in the model to explain the inter-group variance. In case the introduction of these factors resulted in a loss of statistical significance, it could be concluded that they were able to capture most of the heterogeneity between the groups. Therefore, the random intercepts should be removed from the model specification. Finally, random slopes could also be introduced to analyse whether the effect of different regressors may change across different geographical units. More details on the specificities of the multilevel models used for the purpose of this research can be found in Chapters 7 and 8.

7. An updated analysis of the determinants of car use and ownership in European urban areas

The content of this chapter corresponds to the following Scientific Publication (SP)

- SP1** Vega-Gonzalo, M., Gomez, J., & Christidis, P. (2023). **How has COVID-19 changed private car use in European urban areas? An analysis of the effect of socio-economic characteristics and mobility habits.** *Transportation research part A: policy and practice*, 172, 103679.

7.1. How has COVID-19 changed private car use in European urban areas? An analysis of the effect of socio-economic characteristics and mobility habits

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Abstract

The private car has been identified as the main winner among transport modes in urban areas during the COVID-19 pandemic. The fear of contagion when using public transport or the decrease in road congestion are likely to have induced changes in citizens' travel habits with respect to cars. This work investigates the impact of the pandemic on individuals' habits and preferences regarding their car ownership levels and car usage in the European urban context, with a special focus on the role played by individual socio-demographics and urban mobility patterns. For this purpose, a Path Analysis approach has been adopted to model car ownership and use before and after COVID-19. The main data source employed in this research is an EU-Wide Urban Mobility Survey that collects detailed information (individual and household socio-economic characteristics, built environment attributes and mobility habits) of 10,152 individuals from a total of 21 European urban areas of different sizes, geographical locations and urban forms. The survey data has been complemented with city-level variables that account for differences across the cities that may explain changes in car-related behaviour. The results show that the pandemic has induced an increase in car use among socio-economic groups that are generally associated with low car dependent behaviour, revealing that policy instruments that discourage the use of the private car in urban areas are needed to avoid reversing past trends in the reduction of urban transport emissions. High-income, well-educated teleworkers are observed to be the ones that have reduced their car use to a larger extent. On the contrary, low-income individuals are mostly maintaining similar levels of car mobility. Finally, frequent public transport users are more likely than occasional users to have substituted this mode by the private car.

Key words: Travel behaviour; Car use; Car ownership; EU-wide travel survey; Path Analysis; Urban areas; COVID-19 pandemic.

1. Introduction

The COVID-19 pandemic has induced stark behavioural changes that heavily disrupted urban transport. Initially, the decline in mobility, the widespread application of teleworking regimes and the increased adoption of online shopping were seen as an opportunity to advance towards the decarbonisation of urban transport and a more sustainable urban mobility (Zhang & Zhang, 2021). At the same time, the fear of contagion and the desire to keep social distancing have pushed travellers to individual modes and away from public transport (Almlöf et al., 2021). In fact, in 2021 urban congestion levels were observed to be back to normal, in many cases even surpassing those from 2019 (TomTom, 2021), thus suggesting that at the aggregate level the effect of the pandemic on private car usage has not lasted. Nevertheless, the assumption that household mobility habits have remained unchanged after a crisis of such dimension is probably unrealistic. Citizens faced an uncertain situation that forced them to rethink all aspects of daily life, with mobility choices being one of the most affected areas. The nature and extent of these changes in travel behaviour are not homogeneous across socio-economic groups or geographical locations (Dueñas et al., 2021). Factors such as the type of employment, the income level, the place of residence within the city or the sanitary measures deployed in each region, are key constraints for the possibilities of adaptation of households to the new situation.

In particular, the ownership of private cars - being perceived as the most secure mode of transport in a moment in which any personal contact entailed a health risk - has been crucial for household mobility during the pandemic (Moody et al., 2021). This increase in the perceived value of having access to a car may have led to changes in car ownership and frequency of use, as well as the explanatory variables influencing them. For instance, car ownership and use are usually higher among high-income households, but in the context of the pandemic, these groups have been observed to telework more often (Olde Kalter et al., 2021). By contrast, low-income and low-qualified employees, more dependent on public transport and with more difficulties to telework, have in some cases reduced their mobility and car use to a lesser extent during the pandemic (Beck & Hensher, 2020). An additional issue to be addressed in this context is the role of shared mobility (i.e, bike-sharing, car-sharing, scooter-sharing, etc.) as an instrument to mitigate this increase in car dependency. Before the pandemic, these services were often considered to be sustainable substitutes of private cars in urban areas (see e.g. Clewlow, 2016) and to help reducing motorized travel (Midgley, 2011). However, it is likely that the pandemic has also affected travellers' perceptions and habits regarding these mobility options, thus changing their interrelation with car use.

Practitioners and policymakers all over the world are particularly concerned about the impacts of COVID-19 on urban mobility and how to mitigate them through the design of appropriate policy measures to move urban transportation towards higher sustainability standards. For instance, the European Union (EU), both at the national and supranational level, is making an unprecedented financial and political effort to ensure a recovery that fits the environmental and social sustainability principles established in the European Green Deal (European Commission, 2019). The successful and efficient deployment of the post-pandemic recovery plans is largely dependent on the capacity of institutions to support households in the transition to a more sustainable way of moving. This capability can only be achieved through a sound understanding of the current preferences and habits of citizens with respect to private cars and the identification of the factors that push them to rely on this mode to fulfil daily life activities.

This work explores the extent to which socio-economic attributes and past travel habits (i.e., frequency of use of the private car, public transport and shared mobility) of individuals and households have affected changes in private car use and ownership after the advent of COVID-19 in European cities. To achieve this goal, we analyse an EU-wide Travel Survey which covers 21 European urban areas of different sizes, geographical locations and urban forms. The methodology used for the analysis is based on a Path Analysis that simultaneously encompasses four main variables: (1) household car ownership before COVID-19; (2) frequency of use of private car before COVID-19; (3) changes in household car ownership levels due to COVID-19; and (4) changes in frequency of private car use in the post-pandemic period.

This paper is organized as follows. After this first introductory section, a literature review is presented in Section 2, covering the main existing evidence on car ownership, car use and the effect of the COVID-19 pandemic in urban mobility. Section 3 describes and analyses the survey used in this research, as well as the city level data collected to characterise the multiple cities included in the study. Section 4 explains the modelling framework that has been adopted to achieve the proposed goals and provides further details on the variables and techniques employed for the modelling phase. In Section 5, the modelling results are presented, together with a critical comparison with the previous literature. The discussion of those results, jointly with the main lessons and policy recommendation that can be drawn from them, are explained in Section 6. Finally, Section 7 compiles the conclusions that can be drawn from the analysis, discusses its limitations and suggests avenues for further research.

2. Literature review

Car ownership and car use are inevitable entangled, as the chosen frequency of car use is inevitably preceded and constrained by the number of cars the individual has access to. However, most of the existing literature focuses on one of those choices and, in the case of contributions modelling car use, they tend to consider car ownership solely as an explicative variable of travel behaviour (Buehler, 2011; He & Thøgersen, 2017; Nolan, 2010). A smaller group of research studies have built different modelling frameworks decoupling the explicative effects of car ownership and travel behaviour, by considering car ownership as endogenous to socio-economic and built environment characteristics while being exogenous to car use (see e.g., Ben-Akiva & Lerman, 1974; Ding et al., 2018; van Acker & Witlox, 2010). Both approaches seem to obtain similar results regarding the effect of car ownership on car use: households that own more cars rely on this mode more frequently and drive longer distances (Dieleman et al., 2016; van Acker & Witlox, 2010).

In the following, the factors that have been previously observed to influence car ownership and car use are revised (Sections 2.1 and 2.2), together with an overview of the existing research addressing the effect of COVID-19 on car use in the urban context (Section 2.3).

2.1. Factors affecting car ownership

According to the existing literature, socio-demographic characteristics have a clear impact on car ownership levels. Income plays a key role in the number of cars per household, with wealthier households owning higher number of cars (Dargay, 2001; Nolan, 2010; Potoglou & Kanaroglou, 2008). The income level is related to education level and employment status, so that qualified workers receive higher salaries than individuals in less-qualified positions and therefore tend to own more cars (Chu, 2002; Ding et al., 2018). Additionally, GDP per capita at the national or regional level has also been observed to affect car ownership levels (Dargay et al., 2007; Dargay & Gately, 1999). The age and number of members in the household also influence car ownership. Moreover, they are inevitably linked to life-cycle effects that are also related to car ownership changes. For instance, Dargay (2001) observed a clear rise in car ownership for young adults in the UK and a decline when the head of the household reaches the retirement age and the children start leaving the household. This decrease in car ownership for older adults, as well as the positive relationship between the number of adults in the household and the number of cars, is corroborated in Cornut (2016) for the Paris region and in Matas & Raymond (2008) for Spain. For the case of children, their presence in the household seems to increase the probability to own a car (Dieleman et al., 2016; Oakil et al.,

2016), but many authors have concluded that the number of children does not have a significant effect on the number of cars (Cornut, 2016; Yang et al., 2021).

Furthermore, the built environment inevitably influences the number of cars owned per household. Land-mix (Jiang et al., 2017; Zegras, 2010), as well as population density and employment density, are found to reduce car ownership (Ding & Cao, 2019; van Acker & Witlox, 2010). The same trend is observed regarding household proximity to public transport (Zhang et al., 2017) or proximity to the city centre (Ding & Cao, 2019; Cao et al., 2019). As for the existing shared mobility services, the only one that seems to affect car ownership is car-sharing, although differing results have been obtained. For instance, Becker et al. (2018) and Martin et al. (2010) have found significant reductions in car ownership among car-sharing users in Basel (Switzerland) and US cities respectively, while Haustein (2021) and Zhou et al. (2020) concluded a non-significant effect on the number of cars given the low levels of adoption generally observed for this service in Copenhagen (Denmark) and major Australian cities.

2.2. Factors affecting private vehicle use

In general, socio-economic factors affecting car ownership also influence car usage but not always in the same way. Income, employment and level of education are positively correlated with more frequent and longer car trips (Jiang et al., 2017; Schwanen et al., 2004; Shen et al., 2016). By contrast, the net impact of teleworking on car use remains still unclear (Lopez Soler et al., 2021). Early studies on this topic identified a small but significant negative effect of telecommuting on the number of trips and vehicle-kilometres travelled by car (Choo et al., 2005; Koenig et al., 1996). More recent studies suggest that reductions in commuting trips are accompanied by a reallocation to other purposes, such as longer distances travelled during the weekend or more fragmented trips (see e.g., Kim et al, 2015 for the Washington area and de Abreu e Silva & Melo, 2017 for the UK). Regarding the effect of household size and structure, it has been observed that the number of children increases car demand (Dargay & Hanly, 2007; Kim & Ulfarsson, 2008), while the effect of the overall household size is not yet clear (Ding et al., 2018; Yang et al., 2021). The study of the relationship between age and car use has yielded two theories. Some studies found that car use peaks for middle-aged adults and starts declining afterwards (Shen et al., 2016; Yang et al., 2021), while other authors obtained a monotonous positive effect of this variable (Nolan, 2010; van Acker & Witlox, 2010).

As for the relation between built environment and car use, existing contributions have generally concluded similar effects than those of car ownership (Chen et al., 2008; de Abreu e

Silva et al., 2012). Nevertheless, some authors suggest that its impact on car use is mainly indirect and occurring through a mechanism of modified car ownership levels (Cao et al., 2007; Ding et al., 2018; van Acker & Witlox, 2010). Commuting distance is often found to have a positive effect on car use (de Abreu e Silva et al., 2012; Ding et al., 2014, 2017). At the city level, high car accessibility (Jun, 2008), urban sprawl and low land-mix are observed to increase car use (García-Palomares, 2010; Yang, 2008).

Finally, the effect of shared mobility services on car use seems to be rather limited. The effect of car-sharing on private car use has received little attention, but in general, existing results point out a moderate reduction on the use of private car among carsharing adopters (Clewlow, 2016; Kopp et al., 2015). The theoretical potential of bike sharing systems in reducing car use in urban areas is often highlighted (Midgley, 2011; Shaheen et al., 2010). However, the empirical contributions analysing the real impact on car reduction are scarce. The literature review carried out by Fishman et al. (2013) showed that shared bikes are more likely to substitute other sustainable modes than private cars. Later, the same authors found that the substitution rate of car trips by bike-sharing is largely dependent on the overall proportion of trips that are done by car in the city (Fishman et al., 2014). As for scooter-sharing, the authors have not been able to find any existing research addressing the interrelations of these services with private car use.

2.3. The impact of the COVID-19 pandemic on urban mobility

As soon as the global health emergency was declared, and the enforcement of lockdowns and mobility restrictions spread throughout the world, a massive effort was made by the transport research community to gather evidence and provide insights on how this crisis was affecting transport behaviour. Existing research works have shown that the effect of lockdowns and restriction were largely dependent on socio-economic characteristics (Almlöf et al., 2021; Fatmi, 2020) and that public transport trips dropped significantly less than car trips (Aloi et al., 2020; Eisenmann et al., 2021; Labonté-Lemoyne et al., 2020). Interestingly, for the case of Bogotá (Colombia), Dueñas et al. (2021) observed that high income residents, who were observed to move more before the pandemic, reduced their mobility to a much greater extent than lower income groups. Schaefer et al. (2021) studied the effect of COVID-19 in mobility in the Hanover Region (Germany) in June 2020 and observed that residents in the city centre were more likely to increase their car use than individuals living in less dense areas. Recently, Basu & Ferreira (2021) carried out a survey among residents of the metropolitan area of Boston (US) between April and October 2020, finding out that 20% of zero-car household included in the sample intended to buy a car because of COVID-19.

The characterisation of mobility trends right after the first COVID-19 outbreak reveals diverging consequences of the pandemic across sociodemographic groups. In this respect, individuals traveling less or relying in sustainable mobility options before the pandemic, have been pushed towards an increase in car dependency or to higher levels of mobility than other groups. However, the extent to which this tendency disruption will have a lasting effect on urban mobility in coming years remains an open question. The number of research works addressing these long terms impacts is still scarce. Christidis et al. (2021) combined pre-pandemic data and the TRIMODE model to predict the post-pandemic recovery of transport activity in EU Member States. Currie et al. (2021) carried out a survey in Melbourne (Australia) during the summer of 2020 on expected travel behaviour once the virus is no longer present and found that car use is expected to grow with respect to pre-pandemic times even with the mobility reduction associated to teleworking. Similar research in terms of survey timing and expectations analysis was performed by Angell & Potoglou (2022) in the Cardiff Region (UK), also finding evidence that suggests a car dependent mobility recovery. The review of these works shows that the current knowledge of the long-term effect of the pandemic on urban mobility has been mainly based on expected behaviour of the individuals when the pandemic had just started and most European countries were still under strict lockdowns or applied restrictions to mobility.

The above literature review points out some research gaps to be addressed. First, there is a need to explore individual urban travel behaviour when lockdowns where already over, but some sanitary measures were still in place. Secondly, since the private car has been signalled as the main winner among urban transport modes during the pandemic, a specialized study on how the COVID-19 pandemic has changed the determinants of household car ownership and usage is especially relevant to understand its consequences for urban mobility in coming years. Third, the analysis of the relationship between changes in car use after the end of lockdowns and previous frequency of use of public transport and shared mobility will provide relevant insights to better understand how the car is interacting with more sustainable modes after the start of the pandemic. Last, this paper represents an innovative contribution that exploits an EU-wide survey, with more than 10,000 observations from a total of 21 European cities, that simultaneously accounts for both variability across individuals and urban areas of different profiles. This confers this research a high level of generality and a remarkable value for the understanding and regulating of pandemic urban mobility in the European Union after the start of the COVID-19 pandemic.

3. Data – an EU-Wide Urban Mobility Survey

This section presents the data employed for this research. The main source is an EU-wide travel survey conducted in 21 European cities, which is described in Section 3.1 and explored preliminarily in Section 3.2. This information has been complemented with data at the city level, that captures the economic, demographic and urbanistic attributes of the urban areas included in the study, which is reported in Section 3.3.

3.1. Survey description

The main data source exploited in this research is a cross-sectional EU-wide survey carried out in 2021 by the European Commission in 21 Functional Urban Areas² (FUAs, from now on) throughout the EU (Christidis et al., 2022). The FUAs surveyed are represented in Figure 6-2 and include: Paris, Lille and Calais (France), Charleroi (Belgium), Madrid and Málaga (Spain), Lisbon and Porto (Portugal), Milano and Catania (Italy), Berlin and Dresden (Germany), Stockholm and Malmö (Sweden), Bacau and Cluj-Napoca (Romania), Poznan and Krakow (Poland), Brno and Praha (Czech Republic) and Dublin (Ireland). As can be observed, the FUAs surveyed are heterogeneous in terms of size, geographical location and urban form (population density, urban sprawl, etc.).

The survey campaign was carried out from March to May 2021, when lockdowns were no longer in place, but some mobility and sanitary restrictions were still maintained by governments. A total of 10,152 individuals (approximately 500 individuals per city) were surveyed, but 89 observations were removed due to missing data or lack of consistency in the responses. For each city, 400 responses were collected using a CAWI (Computer-Assisted Web Interviewing) methodology. The remaining 100 responses were collected through CATI (Computer-Assisted Telephone Interviewing) questionnaires to ensure that socio-economic groups that are not reachable through online surveys were adequately represented in the sample.

The survey collected information concerning: i) individual and household socio-economic characteristics (e.g. gender, age, level of income, etc.); ii) built environment attributes (e.g. residential location, household distance to public transport stops or stations, etc.); and iii) self-reported mobility habits before and after the advent of COVID-19³ (e.g. frequency of use of

² The concept of FUA has been jointly developed between the European Commission and the OECD to provide a tool that allows for accurate comparison of urban areas across countries beyond administrative delimitations that often do not match the real dynamics of an urban areas or might differ significantly across countries. A FUA is composed by a dense city core and the surrounding sparser areas that are part of the city's labour market, known as commuting zone (further details on the concept and definitions of FUAs can be found in Dijkstra et al. (2019).

³ These variables capture the overall frequency of use of the different modes without any disaggregation by trip purpose.

private car, shared mobility services, public transport, etc. before and after the advent of COVID-19 periods, reasons behind the changes in travel behaviour, etc.). The distribution of the main of these variables for the sample is displayed in Table 7-1.

The preliminary analysis of the sample shows that the survey provides an accurate representation of European socio-demographics and includes an adequate level of heterogeneity for the purposes of this research. Nevertheless, some groups seem to be over-represented when compared to official EU statistics (Eurostat, 2021b), which may be due to the survey collection methods and the fact that the survey was exclusively conducted in urban areas. This may explain the somehow higher presence of individuals aged between 24 and 49 in the sample (50%) compared to official EU statistics (32%). This is presumably due to urban areas having a younger population than rural areas, as noted by The World Bank (2016). The same is observed for e.g. the level of education, since 42.7% of surveyed individuals reported to have a university degree, while this percentage goes down to 31.1% for the EU population according to Eurostat (2021a). Again, this is probably due to the higher concentration of qualified jobs in urban areas that tend to attract more educated workers (Hartal et al., 2021).

The analysis of the level of income is particularly difficult given the heterogeneity in prices and purchasing power across EU countries. To allow for a fair comparison, income levels originally collected (with numerical categories) are adjusted as relative income levels considering the living standards in each country. It is worth noting that low-income households are the most frequent group in the sample (19.8%). Percentages decrease progressively as the income level increases, with high-income households being the smallest category (11.7% of the sample). The survey also provides interesting input concerning employment and teleworking conditions, as well as changes observed during COVID-19, since previous and posterior employment situations were collected. This temporal distinction allowed the quantification of the increase in teleworking potentially induced by COVID. Interestingly, the percentage of workers benefiting from any type of teleworking regime rose from 10% to 30% of the sample during COVID. Results concerning other occupation categories, such as unemployed people, are perfectly consistent with the official unemployment rates in the EU Area at the time the survey was carried out (Eurostat, 2021c).

Table 7-1 also provides an overview of the household-related built environment across individuals in the sample. Most of them (70.5%) reported that they live within the core city of the Functional Urban Area (FUA) and within walking distance from a public transport station or stop (79.3%). These inputs suggest that a significant part of the surveyed individuals live in high density areas, well connected to public transport, in line with empirical findings as

regards European urban layouts (see e.g., Bassolas et al., 2019). Furthermore, 61% of respondents have declared to live closer than 20 km away from their workplace.

Finally, Table 7-1 includes the sample statistics concerning mobility habits before and after the advent of COVID-19. The results indicate high motorisation rates among surveyed individuals. The average number of cars per adult in the household pre-COVID is 0.64 cars per household. We can also observe that the majority pre-COVID profile includes users of private vehicle who travelled by car 5 or more days per week (38.1%). The second biggest group corresponds to individuals who did not use private car before COVID-19 (25.7%). Findings particularly interesting are provided concerning changes in private car usage induced by COVID-19. Almost half of the individuals (45.0 %) reported that the pandemic has induced changes in their frequency of use of private car. Specifically, 24.3% of respondents declared that they use their car less frequently compared to pre-COVID times, while 20.7% reported that their usage of private car has increased. It is worth noting that the built environment conditions described above would imply that most of the surveyed individuals have the conditions in place to reduce their car dependency, given their proximity to the public transport network in their city. As for the use of public transport, almost half of individuals in the sample (44.5%) used it occasionally (about once per week or less) and 35.9% of them chose this mode 3 times per week or more. This is consistent with the modal share generally observed in European cities, despite the great variability across cities (EIT Urban Mobility, 2021).

The results concerning the frequency of use of shared mobility⁴ indicate the still growing adoption of these services. For all the three mobility options reported (bike-sharing, scooter sharing and carsharing), the majority of respondents (percentages between 70% and 80%) stated that they do not use these services, which seems reasonable given the still minor presence of these modes in urban modal split. The service used most frequently seems to be bike-sharing, with 15.3% of occasional users and a 5.2% of frequent users in the sample. For scooter-sharing and car-sharing, the category *not available* has been included to capture the fact that these services are not available in certain FUAs surveyed in this campaign.

⁴ Those who reported using this service about once a week or less have been considered occasional users, and those that use it three or more times per week have been considered frequent users. This aggregation has been done due to the reduced number of individuals per category when using the disaggregated frequency of use.

Table 7-1: Distribution of socio-economic characteristics in the sample

			Respondents/ <i>Mean</i>	% (EU average*)/ <i>SD</i>
Socio-economic characteristics	Gender	Male	4,463	44.4 (51.1)
		Female	5,600	55.6 (48.9)
	Age	16 – 25 years old	1,597	15.9 (10.6)
		26 – 35 years old	2,017	20.0 (32.7)**
		36 – 49 years old	2,994	29.8 (32.7)**
		Over 49 years old	3,455	34.3 (35.5)
	Employment & Teleworking conditions (pre-COVID)	Employed – No teleworking	5,430	54.0
		Employed – Teleworking	954	9.5
		Unemployed	803	8.0
		Student	889	8.8
		Other	1,987	19.8
	Employment & Teleworking conditions (post-COVID)	Employed – No teleworking	3,260	32.4
		Employed – Partial teleworking	1,574	15.6
		Employed – Full time teleworking	1,550	15.4
		Unemployed	803	8.0 (6.6)
		Student	889	8.8
		Other	1,987	19.8
	Level of Education	Primary and secondary	1,190	11.8 (23.6)
		Post-secondary and Tertiary	4,431	44.0 (45.3)
		University	4,302	42.8 (31.1)
		Prefer not to say	140	1.4
	Household Income	Low	1,993	19.8
		Lower – middle	1,764	17.5
		Middle	1,372	13.6
		Higher – middle	1,259	12.5
		High	1,184	11.8
		Do not know	1,370	13.6
		Prefer not to answer	1,121	11.1
	No. Children in the household (numerical)		0.69	1.087
Built environment attributes	Residential location	Core city	7,092	70.5
		Commuting area	2,971	29.5
	HH Distance to Public Transport	Walking distance	7,976	79.3
		Further than walking distance	1,545	15.3
		Do not know	542	5.4
	HH Distance to the work/study centre	Less than 5 km	3,091	30.7
		Between 5 km and 20 km	3,046	30.3
		Between 20 and 50 km	858	8.5
		More than 50 km	278	2.8
		Others	2,790	27.7
Mobility habits	Private car usage (pre-COVID)	Never	2,590	25.7
		Less than once a week	914	9.1
		About once a week	907	9.0
		2 -3 days per week	1,813	18.0
		5 days per week or more	3,839	38.1
	Public transport usage (pre-COVID)	Never	1,977	19.6
		Less than once a week	3,145	31.3
		About once a week	1,330	13.2
		2 -3 days per week	1,472	14.6
		5 days per week or more	2,139	21.3
	Change in private car usage (post-COVID)	Decrease	2,441	24.3
		Same	5,536	55.0
		Increase	2,086	20.7
	Number of cars per adult in household pre-COVID (numerical)		0.641	0.431
	Change in car ownership due to COVID	No change in car ownership	8,988	89.3
		Bought a car	812	8.1
		Sold a car	263	2.6
	Bike-sharing usage (pre-COVID)	Non-users	8,002	79.5
		Occasional	1,540	15.3
		Frequent	521	5.2
	Scooter-sharing usage (pre-COVID)	Non-users	7,778	77.3
		Occasional	985	9.8
		Frequent	309	3.1
		Not available	991	9.8
	Car-sharing usage (pre-COVID)	Non-users	7,439	73.9
		Occasional	1,232	12.2
		Frequent	401	4.0
		Not available	991	9.9

*The percentage for the whole EU population according to Eurostat database has been included when available.

**Eurostat data group individuals between 26 and 49 years old into a single category.

3.2. Survey analysis – preliminary findings

This section conducts a preliminary analysis on the sample distribution concerning the main variables of interest for this research, particularly change in car ownership and car use derived from COVID-19. To that end, the distribution of these two variables have been graphically represented across the most relevant socio-economic and mobility variables collected in the survey.

Figure 7-1 displays the distribution for the variable capturing *change in car ownership due to COVID-19*. We can observe that the effect of age is clearly (and surprisingly) negative, so that those households with individuals between 16 and 25 years old present a higher proportion of car buyers. Interestingly, full-time teleworkers also purchased more cars than any other employment category, followed by partial teleworkers and students. Similarly, middle- and middle-low-income households and residents living in the city core are more likely to have bought a car, although the differences with the rest of the categories included in the corresponding variables are less pronounced. As for mobility variables, it is worth mentioning the clear positive effect of initial levels of car ownership on the probability of having bought a car due to the pandemic. In addition, the distribution for the variable capturing the use of private car in pre-COVID times shows that car purchases are more frequent among individuals who used their private car only occasionally (about once per week or less) before the pandemic. This may suggest an increase in the motorisation rates of citizens that seldom relied on their private car before the pandemic.

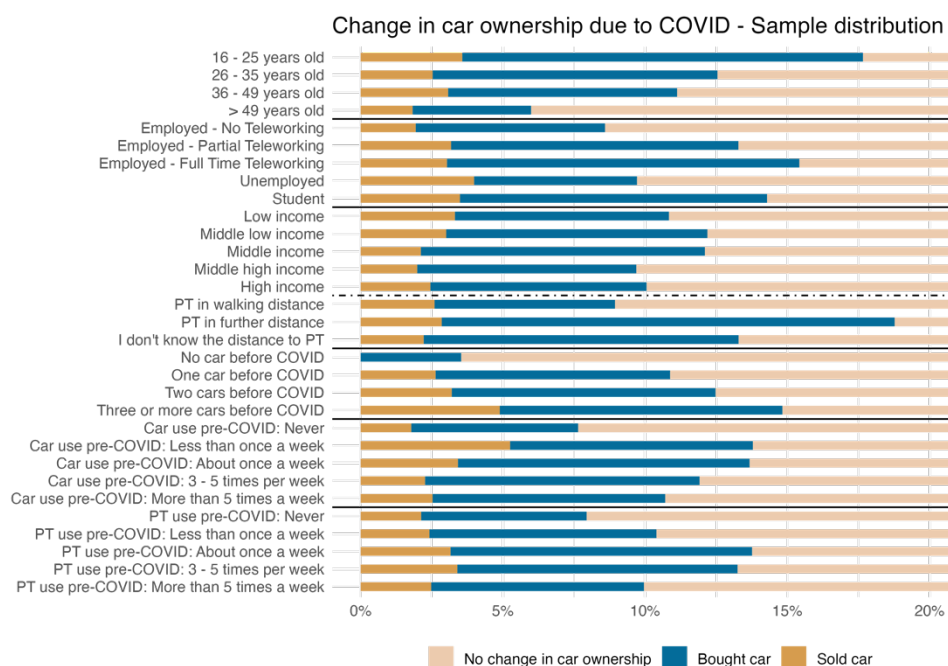


Figure 7-1: Sample distribution of the change in car ownership due to COVID

Furthermore, Figure 7-2 presents the distribution of the variable *change in car use after COVID-19* across some of the most important socio-economic and mobility variables. It can be clearly observed that the proportion of individuals who have decreased their car use is higher among older adults, compared to their younger counterparts. Additionally, it can be observed that the age group between 26 and 35 years old presents a higher proportion of individuals who have used their car more often after COVID-19. The effect of income is also worth highlighting, as while households with higher incomes are the ones experiencing larger reductions of car use, low-income households are the most likely ones to keep similar levels of car-based mobility. The relationship between the number of cars owned by the household before the pandemic and changes in car use does not seem to follow any clear trend. By contrast, households having purchased a car due to the pandemic tend to have increased their car use, while those that have sold a car have decreased its use, as seems reasonable. The distribution for the variable controlling for car use before COVID shows that those households that have increased more their use of car were frequent users (more than 3 days per week), while occasional users (about once a week or less) are the ones who display bigger reductions. Finally, the plot shows that frequent users of public transport before the pandemic are more likely to have increased their car use, except for those that used it five times per week or more. For this group, the observed increase in the frequency of car use is lower than for all the other profile. On the other hand, they have also decreased their car use the least.

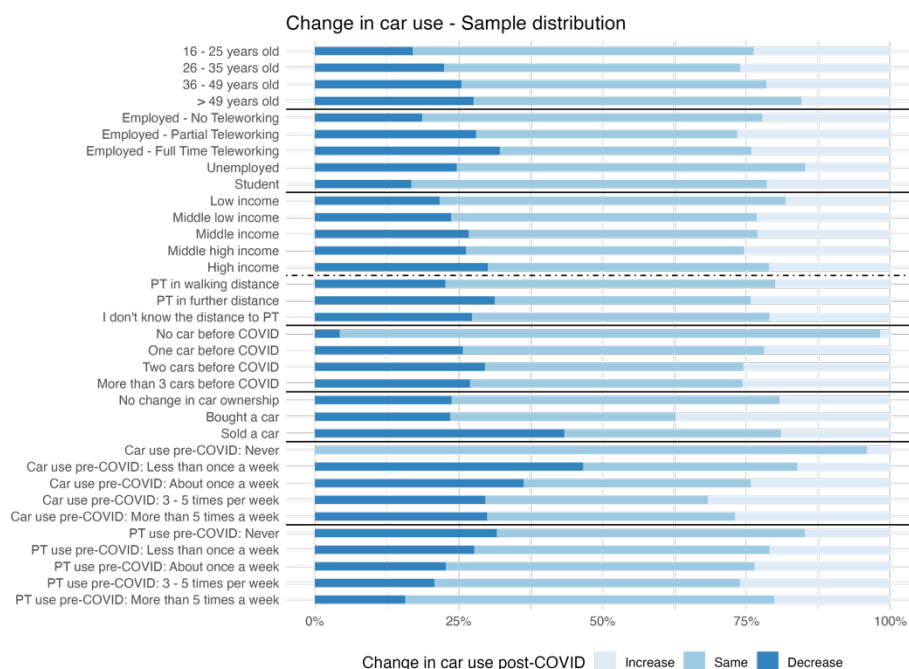


Figure 7-2: Sample distribution of the change in car use after COVID-19

3.3. City level data

The information collected from the European Urban Mobility Survey was complemented by a set of city-level variables to take into account the potential influence of the specific context of each urban area on the variability on car usage and car ownership potentially observed across cities. These variables are intended to capture to some extent the demographic, economic, urban and accessibility features of each city, and include: i) *city population*, which allows to explore whether COVID-19 might have affected car ownership and usage in FUAs of different sizes; ii) *city GDP per capita (US\$)*, aiming to explore whether the economic conditions of a FUA might partly explain the effect of COVID-19 in urban mobility; and iii) the *urban form* measured as the share of the city core with respect to the whole area of the FUA. In this respect, since commuting areas are generally characterised by less density and lower land-use mixes, their relative size is likely to influence car dependence both before and after the pandemic. These three variables have been obtained from the OECD Regions and Cities database (OECD, 2021a).

The analysis also included the *modal performance* of car, bike and public transport in each city, according to the Urban Access Framework proposed by the OECD (OECD, 2021a). These performance indices are aimed at capturing the speed, frequency and density of the network for biking, public transport and private car. Mode performance of a certain mode is defined as the ratio of the population that can be reached in 30 minutes by this mode and the population within 8 km (2 km for walking). A complete explanation of the methodology adopted to calculate mode performance can be found in ITF (2019). These variables were firstly proposed by OECD in 2019, therefore they do not capture changes on accessibility during or due to COVID-19.

All city-level attributes have been transformed into nominal variables. For each variable, there are four categories, each of which group 25% of the cities and one category that includes the cities for which the variable was not available. This categorisation has been done because, as the delimitations of the cities in the survey follow the definition of FUAs provided by the OECD, a set of city-level variables consistent with this delimitation was only found in the OECD Regions and Cities database. This database does not provide any variables for non-OECD territories (Romania) and only a few of them for some smaller cities (Charleroi or Calais). Therefore, to keep these FUAs in the study, it was necessary to create a “no data available” category to group these cases.

4. Methodology

4.1. Modelling framework – Path Analysis

In order to explore the potential changes induced by COVID-19 on car ownership and car usage in EU urban areas, a Path Analysis framework has been adopted in this research. Path Analysis (PA) is a statistical technique that allows to model situations in which a certain variable is dependent on a set of explanatory factors and can be, in turn, considered as an explanatory factor for another dependent variable (Streiner, 2005).

This approach allows the disentanglement of the direct and indirect effects of an exogenous factor through an intermediate outcome variable. It should be noted that a series of assumptions regarding the causal relationships that exist among the endogenous variables included in the modelling is necessary (Lleras, 2005). PA can be considered as an extension of the traditional regression models in which several sub-models are estimated at the same time, accounting for the correlations between all the endogenous and exogenous variables included in the model (Land, 1969). PA is an econometric technique widely adopted in the field of transport research. The reader is referred to e.g., Streiner (2005) for further information.

Initially, together with the PA, a nested multilevel model with a random intercept for each of the four endogenous variables was proposed to account for potential differences across European macro regions (Mediterranean, Western, Eastern and Northern), countries and cities. For further information on multilevel modelling, the reader is referred to Peugh, 2010. The unconditional means model (also known as null model) was estimated by including only the random intercepts in order to test whether the variation between European macro regions, countries and cities was significant. Thereafter, the rest of the exogenous variables were included.

4.2. Model structure

The model defined for this research follows the sequential structure represented in Figure 7-3 and includes four endogenous or outcome variables. The first two outcome variables capture individuals' car ownership and frequency of use of private car before the pandemic, while the last two capture potential changes in car ownership and usage induced by COVID-19.

The exogenous variables included as explanatory factors can be grouped in three types. Firstly, the individual and household's **socio-economic characteristics** and **travel behaviour before COVID-19** (frequency of use of public transport and shared mobility) constitute the main focus of this work. Nevertheless, the research controls for the effect of other additional variables. Secondly, some additional variables capturing the level of **accessibility** of the household have been included, given that

a clear influence of this factor on car use and ownership has been previously observed in the literature (van Acker & Witlox, 2010; Ding & Cao, 2019). Third, a set of **city-level attributes** has been included to capture certain aspects that may influence private car ownership and usage (population, level of urban sprawl or performance indicators of different transport modes), for each of the 21 cities included in the study.

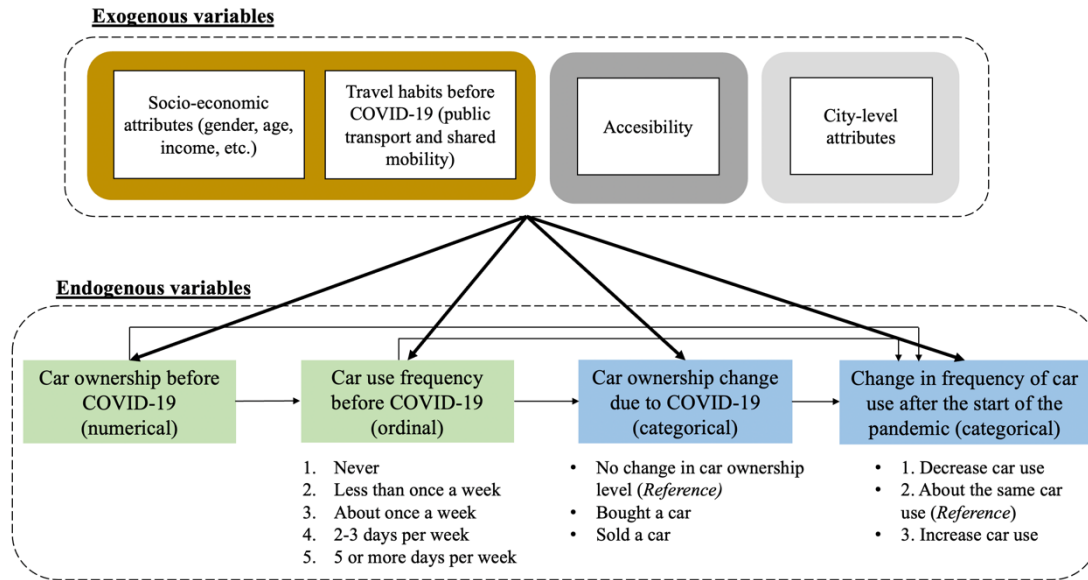


Figure 7-3: Path diagram of the proposed model

As can be observed in Figure 7-3, the socio-demographics of individuals and households, together with built environment and city attributes, influence car ownership during pre-COVID times. Subsequently, private car usage during pre-COVID times is considered influenced by individuals' and household socio-demographics, built environment and city attributes, usage of shared mobility services and car ownership for pre-COVID times. Next, individuals' and household socio-demographics, together with built environment and city attributes, influence car ownership after the advent of COVID-19. Finally, all the variables mentioned above are considered to influence the change in private car use after the start of the pandemic.

Each of the four outcome variables included in the Path Analysis is described below:

- **Car ownership before COVID-19.** Numerical variable that captures the **number of cars per adult in the household** before the beginning of the pandemic.
- **Frequency of use of private car before COVID-19.** Ordinal variable with the following five categories: (1) *Never used*, (2) *Less than once a week*, (3) *About once a week*, (4) *Between 2 and 3 days per week* and (5) *5 days per week or more*.
- **Changes in car ownership due to COVID-19.** Categorical variable with three options: (1) *No change in car ownership*, including those individuals who have neither bought

nor sold a car or that have declared to both sell and buy a car, as a result of the pandemic; (2) *Bought a car*, including those individuals who reported having bought a car (either first-hand or second hand,) due to the COVID-19 pandemic; and (3) *Sold a car*, including individuals who have sold a car due to the pandemic. It is worth noting that the survey questions employed to build this variable, made explicit reference to COVID-19 as the trigger for the decision to make changes in household car ownership.

- **Change in car use frequency after the start of the pandemic.** Categorical variable that captures individuals' frequency of use of private car after the start of the pandemic, compared to pre-COVID times. This variable has three categories: (1) *Decreased use*; (2) *About the same use (reference category)*; and (3) *Increased use*.

These four co-endogenous variables are of three different types: linear ('Number of cars per adult'), ordinal ('Frequency of private car before COVID-19') and nominal ('Changes in car ownership due to COVID-19' and 'Change in car use frequency after the start of the pandemic'). The specification of the sub-models for each of these types are linear regression, ordinal logit regression and multinomial logit regression, respectively.

5. Modelling results

This section comments the modelling results obtained from the PA exploring changes in private car ownership and usage motivated by COVID-19. Detailed results for the full model and the whole set of explanatory variables can be found in Appendix 7-A. Nevertheless, for length reasons, only the modelling results for the variables of greater interest for this study (socio-economic characteristics and pre-pandemic travel habits) are displayed in Table 7-2 below. The results include the regression coefficients for each of the co-endogenous variables included in the model, the p-values associated with each coefficient and the odds ratio (OR). The final specification of the model has been obtained through a process of testing alternative combinations of variables. The variables that were not significant at the 90% level and for which the likelihood ratio tests showed that their removal from the model did not significantly affect the goodness of fit, were gradually removed from the model to obtain a more parsimonious specification. This approach has been widely adopted in the field of transport research (see e.g., Alemi et al., 2018; Aguilera-García et al., 2020). Additionally, some of the coefficients in the final specification of the model are duplicated, which shows that two or more categories have been merged⁵.

⁵ This procedure has been followed when two or more consecutive categories of a variable were only significant at the 90% level when being introduced separately and the performance of the Wald test showed that the differences across the coefficients for those categories were not significantly different.

The results yielded by the construction of the unconditional means model mentioned in the previous section (Section 4.1) revealed that there only exist significant differences across cities for all the four endogenous variables (the random intercepts were not significant at the macro region and country level). However, when the city level attributes were introduced as exogenous variables, the variance of the random intercepts across cities lost its significance. This effect proved that the set of city attributes were able to capture the geographical differences across cities and therefore, the use of multilevel model was no longer required.

5.1. Cars per adult in the household before COVID-19

The modelling results confirm the strong influence of socio-economic characteristics on car ownership, as previous research contributions have largely concluded. For instance, the influence of income and level of education on the number of cars in the household before the pandemic is in line with previous results obtained in the literature, since both higher incomes and higher levels of education have been associated with higher car ownership (see e.g., Chu, 2002 for New York or Potoglou & Kanaroglou, 2008 for Hamilton). According to the modelling results, respondents aged under 25 have higher levels of car ownership than older respondents (particularly, those between 26 and 49 years old). Given that previous contributions suggest the peak for car ownership in older ages (see e.g., Cornut, 2016 for Paris or Matas & Raymond, 2008 for Spain), further investigation of the data has been done to interpret this result. Younger adults (between 16 and 25 years old) in our sample live in households with an average number of adults significantly higher than other age groups. In this respect, more adults in the household have been associated to a higher individual travel demand and higher levels of car ownership, as noted by e.g., Cornut (2016). As for the effect of mobility patterns, it is worth noting the statistically significant relationship between less frequent use of public transport and the number of cars per adult in the household. In terms of size effects, the analysis of the marginal effects shows that while the predicted average number of cars per adult for those that never use public transport is 0.780, this number goes down to 0.473 for those that use it every day.

The results concerning the effect of the built environment on car ownership levels are coherent with the previous literature. Individuals living in the commuting area, which are characterised by lower densities and less accessibility to public transport, owned more cars before the pandemic. The same trend is observed for those who cannot reach public transport on foot (Zhang et al., 2017). Longer distances to the place of work are clearly related to higher number of cars in the household, also in agreement with other authors such as Bhat & Guo (2007).

5.2. Frequency of car use before COVID-19

The second model in the PA explores the frequency of use of private car before the COVID-19 pandemic, which is captured through an ordinal variable. The modelling results are consistent with the previous literature in the sense that older wealthier males, working in fully in-person regimes and with high levels of education, were the most frequent car users in pre-COVID times, similarly to e.g., Shen et al. (2016) or Yang et al. (2021). For example, an individual belonging to a high-income household is 17% more likely to use the car 5 or more days with than someone living in a low-income household. Furthermore, the results for the age variable are in line with the findings by Nolan (2010) and van Acker & Witlox (2010) and suggest a positive effect of age in car usage. As for the number of children in the household, they significantly increase the frequency of car use in pre-COVID times. An additional kid in the household entails a 14% increase of the probability of using the car 5 days per week or more. This is probably because the use of public transport or active modes is less convenient when having to accommodate children. This positive effect has already been observed in several previous studies such as Dargay & Hanly (2007) or Kim & Ulfarsson (2008).

Regarding the effect of public transport frequency of use, there is again a very clear and negative relationship between these two variables. For non-users of public transport before COVID-19, the odds ratio of using the car more frequently is 7.49 higher than for those who use public transport every weekday or more. This value decreases steadily as the frequency of use of public transport increases, suggesting a substitution effect between these two modes. Concerning the effect of shared mobility, the results suggest that the use of these services had a significant effect on the frequency of car use. According to the results, the frequency of use of private car is lower among intensive users of bike sharing, while both frequent and occasional users of car sharing seem to use the car more often than non-users of these services. The analysis of the marginal effects shows that the frequent and occasional use of car-sharing increases, respectively, by 21% and 13% the likelihood of using the car five times per week.

Table 7-2: Modelling results for the number of cars per adult and the frequency of car use before COVID-19

Variable (<i>base category</i>)	Number of cars per adult before COVID-19 (numerical)	Frequency of car use before COVID-19 (ordinal ⁶)
	Coeff.	Coeff. (OR)
SOCIO-ECONOMIC ATTRIBUTES		
Gender (<i>Female</i>)		
Male	--	0.353*** (1.423)
Age (<i>16 - 25 years old</i>)		
26 - 35 years old	-0.033*	0.327*** (1.387)
36 - 49 years old	-0.037*	0.337*** (1.400)
Over 50 years old	-0.042**	0.570*** (1.768)
Education (<i>Primary and Secondary school</i>)		
Post-Secondary and tertiary school	--	0.230*** (1.348)
University	0.048***	0.504*** (1.656)
I prefer not to say	--	0.404* (1.498)
Employment post-COVID (<i>Employed – no TW</i>)		
Employed - TW	--	-0.256*** (0.774)
Student	-0.049**	-0.761*** (0.467)
Unemployed	-0.062***	-0.443*** (0.642)
Others	-0.050***	-0.562*** (0.570)
Income (<i>Low income</i>)		
Middle – low income	0.068***	0.213*** (1.238)
Middle income	0.113***	0.273*** (1.315)
Middle high income	0.152***	0.139** (1.149)
High income	0.191***	0.270*** (1.309)
I don't know	0.060***	--
I prefer not to say	0.098***	--
Kids in household	0.055***	0.224*** (1.251)
Kids in household ²	-0.008***	-0.027*** (0.973)
TRAVEL BEHAVIOUR BEFORE COVID-19		
Public transport use before COVID-19 (<i>5 or more days per week</i>)		
3-5 days per week	0.106***	0.605*** (1.832)
About once a week	0.154***	0.945*** (2.572)
Less than once a week	0.235***	1.740*** (5.696)
Never	0.297***	2.013*** (7.485)
Bike sharing use before COVID-19 (<i>non-users</i>)		
Occasional	n/a	--
Frequent	n/a	-0.200* (0.818)
Car sharing use before COVID-19 (<i>non-users</i>)		
Occasional	n/a	0.219*** (1.244)
Frequent	n/a	0.349*** (1.417)
Not available	n/a	0.256** (1.292)
CO-ENDOGENOUS VARIABLES		
Number of cars per adult before COVID-19	n/a	1.995*** (7.354)
Constant	0.291***	n/a
Thresholds		
Threshold 1	n/a	1.643***
Threshold 2	n/a	2.290***
Threshold 3	n/a	2.854***
Threshold 4	n/a	3.907***

* p≤0.05, ** p≤0.01, *** p≤0.001

⁶ This ordinal variable contains 5 categories. Never used < 3-5 days per week < About once a week < Less than once a week

5.3. Change in car ownership due to COVID-19

The third sub-model of the PA (see Table 7-3) explores changes experienced in household car ownership due to COVID-19. It should be reminded (see Section 4.2) that this categorical variable included three levels: no change in car ownership (reference category), the household purchased a car due to COVID-19 and the household disposed of a car due to COVID-19.

Car purchases

As could be expected, socio-demographic characteristics have a key role in explaining car purchases due to COVID-19. As for age, it has a statistically significant negative effect on the probability of having purchased a car and shows that households with younger adults are more likely to have bought a car due to the pandemic. In addition to the strong statistical relationship, the analysis of the average marginal effects shows that the size of this effect is considerable. For example, individuals between 36-49 are 73% less likely to have bought a car than individuals under 25. The effect of teleworking becomes particularly strong when explaining car purchases due to COVID-19, revealing an unexpected pattern: full-time and partial teleworkers are respectively 46% and 31% more likely on average to have bought a car due to the pandemic than in-person workers. This effect may be due to the willingness to accept larger commuting distances by teleworkers and the consequent residence relocation to suburban areas with less accessibility by public transport, as suggested by e.g., de Abreu e Silva & Melo (2018) for Great Britain. The effect of the income variable on the probability of purchasing an additional car due to COVID-19 is only significant for middle low- and middle-income households, with a higher probability of having increased their car ownership than all the other groups. However, for these categories the size effects are rather small, as both groups display an increase of around 0.1% in the probability of having bought a car with respect to low-income groups.

Past travel behaviour does not seem to have a relevant explanatory power on car purchases during COVID. The model only concludes that non-users of both private car and public transport before the pandemic are less likely to have bought a car due to COVID, suggesting that the pandemic has not led car dependent individuals to introduce the private car in their daily transport habits.

Among the city level attributes, only city size and urban form have a statistically significant effect according to the results. The first variable shows that households in cities with more than 3 million inhabitants (Madrid, Paris, Berlin and Milan) or whose city core covers more than 30% of the FUA surface (Dresden, Malmo, Porto and Charleroi) are less likely to have bought a car. None of the mode performance variables were found to significantly impact the

decision to buy a car due to COVID-19. This may point out that these purchases were driven by changes induced by the sanitary crisis rather than by an evaluation of the most convenient mode of transport in normal conditions.

Sold a car

The modelling results indicate that younger and middle-aged adults, together with unemployed individuals, are the socio-demographic groups most likely to have sold a car due to the COVID-19 pandemic. As for the role of income, it can only be stated that middle- and middle-high income households are less likely to have sold a car compared to other income groups, as could be observed in the preliminary analysis conducted in Section 3.2. It should be reminded that income had a clear statistically significant positive effect on car ownership levels before COVID (see results in Section 5.1). Therefore, these results obtained for the period after the start of the pandemic might suggest that middle-high-income and high-income households had enough cars for the reduced mobility of the pandemic to allow the possibility of forgoing a car, while the car ownership levels of poorer household might not have been high enough for the pandemic to reduce them even further. This hypothesis is supported by the positive and significant, although small, effect of the number of cars per adult on the probability of selling one. An additional car per adult leads to a 2% increase in the probability of having sold a car.

Table 7-3: Modelling results for the car ownership change and the frequency of car use after the start of the pandemic

Variable (<i>base category</i>)	Car-ownership change due to COVID (<i>No change in car ownership</i>)		Change in frequency of car use after the start of the pandemic (<i>About the same use</i>)	
	Bought car	Sold car	Decrease use	Increased use
	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)
SOCIO-ECONOMIC ATTRIBUTES				
Gender (<i>Female</i>)				
Male	--	--	--	--
Age (<i>16 – 25 years old</i>)				
26 – 35 years old	-0.558*** (0.572)	--	--	--
36 – 49 years old	-0.820*** (0.441)	--	--	-0.266*** (0.767)
Over 50 years old	-1.170*** (0.310)	-0.481*** (0.618)	--	-0.479*** (0.619)
Education (<i>Primary and Secondary</i>)				
Post-Secondary and tertiary	--	--	--	--
University	--	--	0.236***	--
I prefer not to say	--	--	--	--
Employment post-COVID (<i>Employed – no TW</i>)				
Employed - full TW	0.522*** (1.686)	0.316* (1.372)	1.033*** (2.811)	--
Employed - partial TW	0.332*** (1.394)	0.316* (1.372)	0.721*** (2.057)	--
Student	--	--	--	--
Unemployed	--	0.569** (1.767)	0.390*** (1.477)	--
Others	--	--	0.492*** (1.635)	--
Income (<i>Low income</i>)				
Middle – low income	0.309** (1.362)	--	0.172** (1.188)	0.187** (1.205)
Middle income	0.282** (1.326)	--	0.172** (1.188)	--
Middle high income	--	-0.461** (0.631)	0.179* (1.196)	0.187* (1.206)
High income	--	-0.461** (0.631)	0.607*** (1.835)	--
I don't know	--	--	--	--
I prefer not to say	--	--	--	-0.207* (0.813)
Kids in household	0.309*** (1.362)	--	--	--
Kids in household ²	-0.032** (0.969)	--	--	--
TRAVEL BEHAVIOUR BEFORE COVID-19				
Public transport use before COVID-19 (<i>5 or more days per week</i>)				
3-5 days per week	--	0.329* (1.389)	--	--
About once a week	--	--	1.792* (1.215)	-0.323*** (0.724)
Less than once a week	--	--	1.278*** (3.591)	-0.549*** (0.578)
Never	-0.392*** (0.676)	--	1.410*** (4.098)	-0.802*** (0.449)
Bike sharing use before COVID-19 (<i>non-users</i>)				
Occasional	n/a	n/a	--	0.443*** (1.556)
Frequent	n/a	n/a	--	--
Car sharing use before COVID-19 (<i>non-users</i>)				
Occasional	n/a	n/a	0.194* (1.214)	0.463*** (1.588)
Frequent	n/a	n/a	0.503*** (1.653)	0.468*** (1.597)
Not available	n/a	n/a	--	0.429*** (1.520)
CO-ENDOGENOUS VARIABLES				
Number of cars per adult	--	0.721*** (2.056)	--	--
Car use before COVID-19 (<i>5 or more days per week</i>)				
3-5 days per week	--	--	1.792*** (15.992)	0.398*** (1.489)
About once a week	--	0.423* (2.513)	2.542*** (12.710)	--
Less than once a week	--	0.921*** (1.526)	2.772*** (6.001)	-0.601*** (0.548)
Never	-0.414*** (0.661)	--	--	-3.135*** (0.043)
Car ownership change due to COVID-19 (<i>no change</i>)				
Bought a car	n/a	n/a	--	0.622*** (1.863)
Sold a car	n/a	n/a	0.736*** (2.089)	--
Constant	-2.101***	-4.038***	-2.234***	-0.232**
Goodness of fits statistics				
Log-Likelihood (model)		-29,492.2	AIC	59,358.5
Log-Likelihood (null)		-34,573.6	BIC	60,708.0
LR test	$\chi^2 = 10162.82$, p-value = 0.000			

5.3. Change in frequency of car use after the start of the pandemic

Finally, we comment on the results for the last variable of interest, which is the change in the frequency of car use after COVID-19. This is captured by a categorical variable with three categories: *Decreased use*, *About the same use (reference category)* and *Increased used*. The analysis of the socio-economic characteristics driving the change in frequency of use points to an induced demand for cars, whereby those segments of the population that were considered to have lower levels of car use in the pre-COVID sub-models have increased their car use more than the rest of individuals. For the case of age, which had a clear positive effect on car use before COVID (that is, higher frequency among older individuals), the model finds that after the start of the pandemic adults over 39 years old are more likely to have reduced car use frequency than younger segments of the population. This “rebound effect” is also observed for the place of residence within the metropolitan area. The average marginal effects show that, before the pandemic living in the commuting area increased the probability of using the car five times per week or more by 11%. After the advent of COVID, this group of individuals is on average 14% less likely to have increased its car use. It is worth noting that a similar effect has been pointed out by Schaefer et al. (2021) in Hanover (Germany). An equivalent effect on the opposite direction is observed for the case of level of education and high-income. While both attributes were positively correlated with car use before the start of the pandemic, they now have a positive effect on the probability of decreasing car use. After the advent of COVID-19, the odds of having reduced their car use for individuals with university education and belonging to high-income households are, respectively, 1.3 and 1.8 times higher than for the reference categories.

The model yields very clear results for the different user profiles of public transport before COVID-19: frequent users (those who used it three times per week or more) are more likely to have increased their frequency of car use than occasional (about once per week or less) or non-users of public transport. The results for the shared mobility variables show that occasional users of bike-sharing prior to COVID-19 are more likely to have increased their car use. Being an occasional user of shared bikes before COVID-19 increased by 21% the probability of using the car more often after the start of the pandemic. As for car-sharing services, both frequent and occasional users are more likely to have increased their frequency of car use than non-users. The analysis of the odds ratios allows to draw some conclusions regarding the relationship between shared and private cars after the advent of COVID-19. Before the start of the pandemic, the odds ratio of using the car more often than non-users was 1.42 and 1.24 for frequent and occasional users, respectively. After the start of the pandemic, all types of car-sharing users are more likely to have increased their car use, having

both occasional and frequent users around 60% (OR = 1.6) higher odds than non-users to have increased their car use.

Some interesting insights are found when analysing the relationship between car use before and after the start of the pandemic. The probability of keeping the same car mobility levels for non-users of the private car is 35% higher than for those within the base category (5 or more days per week). On the other hand, occasional users of the car before the pandemic are significantly more likely to have decreased their car use than the base category. The effect size of this relationship is substantial: the average marginal effect for those that use the car less than once a week is 1.42 and for those that use it approximately once per week is 1.11. Finally, the effect of changes in household car ownership confirms the coherence of the model, as those who purchased a car have increased their car use and those who sold one have reduced its use.

In addition to the main effects observed in the model, a set of interactions between some socio-economic attributes and past travel habits have been introduced for the post-COVID sub-models. Nevertheless, statistically significant results were only obtained for the "Change in frequency of car use" regression. It should be noted that the interactions' coefficients have been simultaneously estimated together with all the explanatory factors that were included in the model. However, to improve the readability of this paper, the coefficients for the interactions found statistically significant are displayed separately in Table 7-4. As mentioned before, the table with the entire model can be found in the Appendix 7-A.

High-income seems to slightly moderate the decrease in car use that was observed among those who used the car less than five times per week. The interactions between car use and bike sharing use before COVID-19 show that among occasional users of shared bikes, those who used the car less than once a week are more likely to have further decreased their use of car, while occasional users of shared bikes who used the car between 3 and 5 days per week are more likely to keep the same level of car use. Some interesting results have been observed for the interactions between public transport and car use before COVID-19. Individuals who never used public transport before COVID-19 or did it less than once a week, and who did not use the car daily, are slightly more likely to maintain the same levels of car use as before the start of the pandemic. On the other hand, it is noteworthy that individuals who never used the car and used public transport less than once a week are more likely to have increased their car use.

Table 7-4: Modelling results for the interactions included in the Change in car use after start of the pandemic

Variable (<i>base category</i>)	Change in frequency of car use after the start of the pandemic (<i>About the same use</i>)	
	Decreased use	Increased use
	Coeff.	Coeff.
Employed – partial TW#Car use pre-COVID: less than once a week	-0.838***	--
Employed – partial TW#Car use pre-COVID: about once a week	-1.059***	--
Employed - full TW#Car use pre-COVID: less than once a week	-0.989***	--
Employed - full TW#Car use pre-COVID: about once a week	-0.806***	--
Employed - full TW#Car use pre-COVID: between 3 and 5 times per week	0.617***	--
Medium-low-income#Car use pre-COVID: between 3 and 5 times	-0.447*	--
High-income#Car use pre-COVID: less than once a week	-0.744**	--
High-income#Car use pre-COVID: about once a week	-0.764**	--
High-income#Car use pre-COVID: between 3 and 5 times	-0.424*	--
Bike sharing use pre-COVID: occasional#Car use pre-COVID: less than once a week	0.562***	--
Bike sharing use pre-COVID: occasional#Car use pre-COVID: about once a week	--	-0.749***
Bike sharing use pre-COVID: occasional#Car use pre-COVID: between 3 and 5 times	-0.399**	-0.619***
PT use pre-COVID: never#Car use pre-COVID: less than once a week	-1.174***	--
PT use pre-COVID: never#Car use pre-COVID: about once a week	-1.292***	--
PT use pre-COVID: never#Car use pre-COVID: between 3 and 5 times	-1.165***	-0.583**
PT use pre-COVID: less than once a week#Car use pre-COVID: never	--	1.617***
PT use pre-COVID: less than once a week#Car use pre-COVID: less than once a week	-1.658***	--
PT use pre-COVID: less than once a week#Car use pre-COVID: about once a week	-1.556***	--
PT use pre-COVID: less than once a week#Car use pre-COVID: between 3 and 5 times	-0.747***	--

* p≤0.05, ** p≤0.01, *** p≤0.001

6. Discussion and policy recommendations

The analysis of the modelling results of the PA yields some relevant conclusions regarding the mid-terms effects of the COVID-19 pandemic in car use and car ownership in European cities and gives rise to propose some policy recommendations to make urban mobility more sustainable.

(1) Reverting effect of the COVID pandemic on previous trends in car usage. The combined analysis of travel choices before and after the advent of COVID-19 allowed to capture a somewhat reversal effect of the pandemic on several trends regarding car usage, observed both in our model and in previous literature. This effect is observed among younger individuals (aged 16 - 36) and residents in the core city, who were previously identified as low car dependency groups but who have significantly increased their car use during COVID-19. Addressing the growing number of users who have shifted to the private car as a result of COVID-19 should be a high priority, since it can reverse past trends in reducing the negative externalities of urban transport. The provision of good quality, affordable and perceived safe public transport is essential to invert this trend again.

(2) Reduction in car use among high-income, well-educated teleworkers. The model shows that high-income and high levels of education are correlated with a reduction in car use after the advent of COVID-19. These attributes are also characteristics associated with the typical profile of teleworkers (Lopez Soler et al., 2021). The model corroborates this relation as it shows that both partial and full-time teleworkers are using their car less often after the start of the pandemic. Taken together, these results would suggest that the increase in teleworking induced by the pandemic has been successful as regards the reduction in car use. Nevertheless, it also shows that teleworking as a tool to reduce car use for urban trips, is a policy instrument with a limited scope, given that its benefits seem to be restricted to privileged socio-economic groups. Additionally, the model shows that low-income households are the least likely ones to have reduced their car use and are mostly maintaining similar levels of car mobility. As low-income and low-educated individuals are in general less prompt to telework (Sweet and Scott, 2022), policies should be deployed to ensure that these groups can cover their mobility needs in an environmentally and economically sustainable manner in the context of the post-pandemic.

(3) Migration of frequent public transport users to the private car. The results for the different profiles of public transport users before and after the start of the pandemic show that the crisis has clearly changed the behaviour of individuals with respect to these two modes in the urban context. While the model shows a strong negative relationship between frequency of use of public transport and car usage before the pandemic, after the lockdown, frequent users of public transport (three times per week or more) are clearly more likely to have increased their car use than occasional or non-users. This effect is probably suggesting that a large proportion of individuals who used public transport as their main mode of transport for daily trips have switched to the private car, confirming the strong substitution effect between these two modes induced by the pandemic. Interestingly, this trend is not extensible to changes in car ownership, as those who never used public transport before the pandemic are the least likely group to have bought a car due to-COVID-19.

(4) Diverging patterns in car-sharing users. The modelling results show that the adoption of car sharing has a statistically significant effect on car use both before and after the advent of COVID-19. Before the start of the pandemic, a more frequent use of shared cars was associated with a higher frequency of car use, revealing a complementary relationship between them. During COVID-19, users of car-sharing are both more likely to have increased and decreased their car use, showing that the pandemic has led to a polarisation with respect to car use among car-sharing users.

7. Conclusions and further research

This study conducted a PA model with the aim of exploring the extent to which to the COVID-19 pandemic has motivated changes in household car ownership and usage in European urban areas, as well as the factors that determine them. To that end, the research exploits an EU-wide survey of residents in 21 European cities of different sizes and urban forms. Thus, the study presents a comprehensive picture of the current role of the private car across European cities and may be a useful input for policy makers both at the national and European level. The model provides insights on to what extent socio-demographic characteristics of the individual and the household, as well as their travel habits before the start of the pandemic, have affected the changes in their car-related mobility after the advent of the virus.

One of the main strengths of this work is the broad geographical scope, and the variety of explanatory variables and chained effects that are included in the model. However, this amplitude somewhat limits the study of the specific factors that might be affecting each particular outcome variable. In this regard, some avenues for further research can be suggested. First, an exhaustive study of the reasons that have motivated the purchases or sales of cars during the pandemic, the consideration of the type of car that has been purchased or the inclusion of information on the main car user within the household would provide a clearer picture of the role of the car in European households. Second, the widespread adoption of teleworking regimes during the pandemic has probably induced the relocation of residence farther away from the workplace in many cases, which may have important implications for mobility patterns. The exploration of such choices in the definition of the PA model would allow the identification of further interrelations between residential changes, car ownership changes, and car usage habits.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

EU disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

Appendix 7-A: Modelling results including all explanatory variables for the four sub-models

Variable (<i>base category</i>)	Number of cars per adult before COVID-19 (numerical)	Frequency of car use before COVID- 19 (ordinal)	Car-ownership change due to COVID-19 (<i>No change in car ownership</i>)		Change in frequency of car use after the start of the pandemic (<i>About the same use</i>)	
			Bought a car	Sold a car	Decreased use	Increased use
	Coeff.	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)
SOCIO-ECONOMIC ATTRIBUTES						
Gender (<i>Female</i>)						
Male	--	0.353*** (1.423)	--	--	--	--
Age (<i>16 - 25 years old</i>)						
26 - 35 years old	-0.033*	0.327*** (1.387)	-0.558*** (0.572)	--	--	--
36 - 49 years old	-0.037*	0.337*** (1.400)	-0.820*** (0.441)	--	--	-0.266*** (0.767)
Over 50 years old	-0.042**	0.570*** (1.768)	-1.170*** (0.310)	-0.481*** (0.618)	--	-0.479*** (0.619)
Education (<i>Primary and Secondary school</i>)						
Post-Secondary and tertiary school	--	0.230*** (1.348)	--	--	--	--
University	0.048***	0.504*** (1.656)	--	--	0.236***	--
I prefer not to say	--	0.404* (1.498)	--	--	--	--
Employment pre-COVID (<i>Employed – no TW</i>)						
Employed - TW	--	-0.256*** (0.774)	n/a	n/a	n/a	n/a
Student	-0.049**	-0.761*** (0.467)	n/a	n/a	n/a	n/a
Unemployed	-0.062***	-0.443*** (0.642)	n/a	n/a	n/a	n/a
Others	-0.050***	-0.562*** (0.570)	n/a	n/a	n/a	n/a
Employment post-COVID (<i>Employed – no TW</i>)						
Employed - full TW						
Employed - partial TW	n/a	n/a	0.522*** (1.686)	0.316* (1.372)	1.033*** (2.811)	--
Student	n/a	n/a	0.332*** (1.394)	0.316* (1.372)	0.721*** (2.057)	--
Unemployed	n/a	n/a	--	--	--	--
Others	n/a	n/a	--	0.569*** (1.767)	0.390*** (1.477)	--
	n/a	n/a	--	--	0.492*** (1.635)	--
Income (<i>Low income</i>)						
Middle – low income	0.068***	0.213*** (1.238)	0.309** (1.362)	--	0.172** (1.188)	0.187** (1.205)
Middle income	0.113***	0.273*** (1.315)	0.282** (1.326)	--	0.172** (1.188)	--
Middle high income	0.152***	0.139** (1.149)	--	-0.461** (0.631)	0.179* (1.196)	0.187* (1.206)
High income	0.191***	0.270*** (1.309)	--	-0.461** (0.631)	0.607*** (1.835)	--
I don't know	0.060***	--	--	--	--	--
I prefer not to say	0.098***	--	--	--	--	-0.207* (0.813)
Kids in household	0.055***	0.224*** (1.251)	0.309*** (1.362)	--	--	--
Kids in household ²	-0.008***	-0.027*** (0.973)	-0.032** (0.969)	--	--	--

* p≤0.05, ** p≤0.01, *** p≤0.001

A behavioural analysis of shared mobility's impact on car dependency

Variable (<i>base category</i>)	Number of cars per adult before COVID-19 (numerical)	Frequency of use before COVID-19 (ordinal)	Car-ownership change due to COVID-19 (<i>No change in car ownership</i>)		Change in frequency of car use after the start of the pandemic (<i>About the same use</i>)	
			Bought a car	Sold a car	Decreased use	Increased use
	Coeff.	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)
TRAVEL BEHAVIOUR BEFORE COVID-19						
Public Transport use before COVID-19 (<i>5 or more days per week</i>)						
3-5 days per week	0.106***	0.605*** (1.832)	--	0.329* (1.389)	--	--
About once a week	0.154***	0.945*** (2.572)	--	--	1.792* (1.215)	-0.323*** (0.724)
Less than once a week	0.235***	1.740*** (5.696)	--	--	1.278*** (3.591)	-0.549*** (0.578)
Never	0.297***	2.013*** (7.485)	-0.392*** (0.676)	--	1.410*** (4.098)	-0.802*** (0.449)
Bike sharing use before COVID-19 (<i>non-users</i>)						
Occasional	n/a	--	n/a	n/a	--	0.443*** (1.556)
Frequent	n/a	-0.200* (0.818)	n/a	n/a	--	--
Car sharing use before COVID-19 (<i>non-users</i>)						
Occasional	n/a	0.219*** (1.244)	n/a	n/a	0.194* (1.214)	0.463*** (1.588)
Frequent	n/a	0.349*** (1.417)	n/a	n/a	0.503*** (1.653)	0.468*** (1.597)
Not available	n/a	0.256** (1.292)	n/a	n/a	--	0.429*** (1.520)
CO-ENDOGENOUS VARIABLES						
Number of cars per adult before COVID-19	n/a	1.995*** (7.354)	--	0.721*** (2.056)	--	--
Car use before COVID-19 (<i>5 or more days per week</i>)						
3-5 days per week	n/a	n/a	--	--	1.792*** (15.992)	0.398*** (1.489)
About once a week	n/a	n/a	--	0.423* (2.513)	2.542*** (12.710)	--
Less than once a week	n/a	n/a	--	0.921*** (1.526)	2.772*** (6.001)	-0.601*** (0.548)
Never	n/a	n/a	-0.414*** (0.661)	--	--	-3.135*** (0.043)
Car ownership change due to COVID-19 (<i>no change</i>)						
Bought a car						
Sold a car	n/a	n/a	n/a	n/a	--	0.622*** (1.863)
	n/a	n/a	n/a	n/a	0.736*** (2.089)	--
ACCESSIBILITY						
Residential location (<i>Core city</i>)						
Commuting area	0.081***	0.183*** (1.200)	--	--	--	-0.177** (0.838)
Distance to public transport (<i>Walking distance</i>)						
Farther than walking distance	0.070***	0.212*** (1.236)	0.910*** (2.483)	--	0.293*** (1.340)	--
I don't know	--	--	0.727*** (2.070)	--	--	--
Distance to the work/study place (<i>Less than 5 km</i>)						
Between 5 km and 20 km	0.043***	0.508*** (1.661)	--	--	0.196** (1.217)	0.304*** (1.356)
Between 20 and 50 km	0.077***	0.562*** (1.755)	--	--	0.324*** (1.383)	--
More than 50 km	0.101***	0.651*** (1.918)	-0.580* (0.560)	--	0.324*** (1.383)	0.378** (1.460)
Others	--	--	--	--	--	--

* p≤0.05, ** p≤0.01, *** p≤0.001

Variable (<i>base category</i>)	Number of cars per adult before COVID-19 (numerical)	Frequency of use before COVID-19 (ordinal)	Car-ownership change due to COVID-19 (<i>No change in car ownership</i>)		Change in frequency of car use after the start of the pandemic (<i>About the same use</i>)	
			Bought a car	Sold a car	Decreased use	Increased use
	Coeff.	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)	Coeff. (OR)
CITY-LEVEL VARIABLES						
Population (<i><850,000 inhabitants</i>)						
850,000 - 1,400,000	--	--	--	--	--	--
1,400,000 - 3,000,000	--	--	--	--	0.589*** (1.802)	--
> 3,000,000	--	--	--	--	0.589*** (1.802)	-0.233** (0.792)
GDP per capita (<i><36,000 US\$</i>)						
36,000 - 42,000	--	--	--	--	-0.519*** (0.595)	--
42,000 - 62,000	0.037*	--	--	--	-0.234** (0.791)	--
>62,000	0.057*	--	--	--	--	--
Core city surface share (<i><9%</i>)						
9% - 15%	0.044***	--	--	--	--	--
15% - 30%	0.079***	0.264*** (1.303)	-0.336*** (0.715)	--	0.872*** (2.392)	--
>30%	--	-0.533*** (0.587)	-0.336*** (0.715)	--	0.369** (1.446)	--
Car performance (<i><0.23</i>)						
0.23 – 0.29	--	--	--	--	-0.391** (0.676)	--
0.29 – 0.53	0.052***	--	--	--	-0.391** (0.676)	--
>0.53	0.052***	0.244* (1.277)	--	--	-0.703** (0.495)	--
Public transport performance (<i><0.11</i>)						
0.11 – 0.18	-0.073***	--	--	--	--	--
0.18 – 0.22	-0.069**	-0.343*** (0.710)	--	--	-1.165*** (0.312)	--
>0.22	--	-0.487*** (0.614)	--	--	-0.897*** (0.408)	--
Bike performance (<i><0.41</i>)						
0.41 – 0.58	--	-0.424*** (0.655)	--	--	-0.601*** (0.548)	--
0.58 – 0.61	--	-0.277*** (0.758)	--	--	-0.500*** (0.607)	--
>0.61	--	-0.555*** (0.574)	--	-0.653*** (0.520)	-1.023*** (0.360)	--

* p≤0.05, ** p≤0.01, *** p≤0.001

A behavioural analysis of shared mobility's impact on car dependency

Variable (<i>base category</i>)	Number of cars per adult before COVID- 19 (numerical)	Frequency of use before COVID-19 (ordinal)	Car-ownership change due to COVID-19 (<i>No change in car ownership</i>)		Change in frequency of car use after the start of the pandemic (<i>About the same use</i>)	
			Bought a car	Sold a car	Decreased use	Increased use
	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.
INTERACTIONS						
Employed - partial TW#Car use pre-COVID: less than once a week	--	--	--	--	-0.838***	--
Employed - partial TW#Car use pre-COVID: about once a week	--	--	--	--	-1.059***	--
Employed - full TW#Car use pre-COVID: less than once a week	--	--	--	--	-0.989***	--
Employed - full TW#Car use pre-COVID: between 3 and 5 times per week	--	--	--	--	-0.806***	--
Medium-low-income#Car use pre-COVID: between 3 and 5 times	--	--	--	--	0.617***	--
High-income#Car use pre-COVID: less than once a week	--	--	--	--	-0.447*	--
High-income#Car use pre-COVID: less than once a week	--	--	--	--	-0.744**	--
High-income#Car use pre-COVID: between 3 and 5 times	--	--	--	--	-0.764**	--
Bike sharing use pre-COVID: occasional#Car use pre-COVID: less than once a week	--	--	--	--	-0.424*	--
Bike sharing use pre-COVID: occasional#Car use pre-COVID: about once a week	--	--	--	--	0.562***	--
Bike sharing use pre-COVID: occasional#Car use pre-COVID: between 3 and 5 times	--	--	--	--	--	-0.749***
PT use pre-COVID: never#Car use pre-COVID: less than once a week	--	--	--	--	-0.399**	-0.619***
PT use pre-COVID: never#Car use pre-COVID: about once a week	--	--	--	--	-1.174***	--
PT use pre-COVID: never#Car use pre-COVID: between 3 and 5 times	--	--	--	--	-1.292**	--
PT use pre-COVID: less than once a week#Car use pre-COVID: never	--	--	--	--	-1.165***	-0.583**
PT use pre-COVID: less than once a week#Car use pre-COVID: less than once a week	--	--	--	--	--	1.617***
PT use pre-COVID: less than once a week#Car use pre-COVID: about once a week	--	--	--	--	-1.168***	--
PT use pre-COVID: less than once a week#Car use pre-COVID: between 3 and 5 times	--	--	--	--	-1.556***	--
PT use pre-COVID: less than once a week#Car use pre-COVID: between 3 and 5 times	--	--	--	--	-0.747***	--
Constant	0.291***	n/a	-2.101***	-4.038***	-2.234***	-0.232**
Threshold 1	n/a	1.643***	n/a	n/a	n/a	n/a
Threshold 2	n/a	2.290***	n/a	n/a	n/a	n/a
Threshold 3	n/a	2.854***	n/a	n/a	n/a	n/a
Threshold 4	n/a	3.907***	n/a	n/a	n/a	n/a

8. The impact of shared mobility on perceived car dependency

The content of this chapter corresponds to the following Scientific Publications (SP)

- SP2 Vega-Gonzalo, M., Gomez, J., Christidis, P., & Vassallo, J. M. (2024). **The role of shared mobility in reducing perceived private car dependency**. Transportation Research Part D: Transport and Environment, 126, 104023.
- SP3 Vega-Gonzalo, M., Aguilera-García, Á., Gomez, J., & Vassallo, J. M. (2024). **Analysing individuals' use of moped-sharing and their perception about future private car dependency**. Cities, 146, 104741.

8.1. The role of shared mobility in reducing perceived private car dependency

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Abstract

Existing contributions have explored the effect of specific shared mobility services on car ownership reduction, but there is still a lack of analysis regarding the impact of shared mobility, understood as new mobility concept. To fill this gap, a survey gathering 15,666 responses from residents in the Region of Madrid was conducted. A Multilevel Ordered Logit explored the individual and spatial dimensions of the potential of shared mobility to reduce car ownership. The results show that frequent car users and individuals owning more cars are less likely to believe they could give them up, but the adoption of moped-scooter-sharing or car-sharing moderates this effect. For those who do not own a car, shared mobility seems to be effective reducing their perceived need to own one in the future. Finally, the potential reduction of car ownership is more evident in dense urban areas, but a considerable spatial heterogeneity is observed throughout the metropolitan area.

1. Introduction

The increasing urgency of the climate crisis has turned the achievement of sustainable urban mobility a priority for most European cities. Consequently, policy makers are seeking for the optimal mix of policy instruments to reduce the negative externalities generated by road transport while ensuring accessibility. A crucial objective of these policy instruments is to reduce the dependency on private cars and encourage a modal shift to more sustainable modes (Kuss & Nicholas, 2022). The excessive ownership and use of private cars in urban areas result in a long list of externalities, such as GHG emissions, air and noise pollution, traffic congestion, excessive occupancy of the public space, road safety, etc.

Together with an extensive catalogue of ‘stick’ policy measures such as congestion pricing systems, Low Emissions Zones or parking regulation (Kuss & Nicholas, 2022), shared mobility is one of the tools that cities have at their disposal to reduce car ownership and use (Machado et al., 2018; Ruhrort, 2020). Shared mobility encompasses those transport services that can be accessed in a short-term basis and on-demand through the utilisation of mobile apps and without the intervention of any intermediary (Invers, 2022a). This kind of services has potential to prompt positive effects on sustainability such as increasing the utilisation rate of existing vehicles, reducing their life-cycle emissions, facilitating the electrification of the fleets, reducing air and noise pollution, and decreasing the amount of public space devoted to parking, which could alternatively be allocated to other purposes (Shaheen et al., 1998). However, it is commonly agreed that most of the above-mentioned benefits potentially associated with shared mobility can only occur through a reduction in car ownership levels (Cervero et al., 2007; Martin & Shaheen, 2016; Vejchodská et al., 2023). Additionally, car ownership entails high fixed costs and relatively low operational costs for the individual. This means that attracting car owners to other transport options, even in situations when they are more convenient and sustainable, becomes a challenging task for transport planners (Sohn & Yun, 2009, Matowicki et al. 2022).

Notwithstanding the potential of shared mobility services, their adoption remains currently limited, confining them to a niche-innovation status (Nykvist & Whitmarsh, 2008) and limiting their role in the achievement of a more sustainable mobility. Nevertheless, several authors have pointed to the decline of private automobility as the core of the mobility regime, which has been shaping individual practices and perceptions since the early 20th century (Manderscheid, 2014; Urry, 2004). As the ongoing socio-technical transition towards a new mobility regime progresses, shared mobility promises to play a prominent role in setting up

pathways towards a more sustainable way of meeting society's mobility needs that do not require extensive private car ownership (Epprecht et al., 2014; Sopjani et al., 2020).

As a consequence of this transition towards a reduced role of the private car, a body of research has explored the impact of shared mobility on car ownership reduction, with almost all contributions devoted to carsharing services (see e.g. Le Vine & Polak, Zhou et al., 2020 or Klinevicius et al., 2014). Despite the interest of this topic and the fact that carsharing is the most obvious substitute for private cars, it is far from being the most abundant and widely used shared mobility service in many urban areas around the world (see e.g., data from Invers, 2022a). Furthermore, it should be noted that many other shared mobility options (e.g., scooter-sharing, bike-sharing, etc.) operate in urban areas apart from carsharing, whose effect on car ownership has hardly been analysed, and which together form a system of shared mobility services that can be conceived as a whole. The integration of the existing shared modes together with public transport and private active modes has even been materialized through the creation of Mobility as a Services (MaaS), which are facilitating this transition towards a multimodal and sustainable mobility (Arias-Molinares & Garcia-Palomares, 2020a).

This work puts forward the hypothesis that the paradigm shift from ownership to usage can significantly transform the meaning that individuals attach to private vehicles and change transport-related practices and beliefs, even among those who have not yet adopted this kind of mobility. For this reason, this paper makes an overall analysis, different to the mode-specific ones adopted in previous contributions, aimed at understanding how the availability of shared mobility services can affect vehicle ownership decisions of the general population in the future. With this purpose, this research explores the extent to which a widespread deployment of shared mobility fleets can be a powerful policy instrument to drive the socio-technical transition to a car-independent mobility regime and provide recommendations on how best to exploit this potential. Particularly, it investigates the extent to which the expansion of shared mobility services may influence the perception among the general population on being able to become private car independent in the future. Following various previous contributions in which car dependency was associated with both car ownership and usage (see e.g., ITF, 2021 or Hopkins et al., 2021), it has been considered that individuals are car independent when they can cover one's mobility needs without a private car. To carry out this research, a Multilevel Ordered Logit model was conducted to explore individuals' level of agreement with the statement *"Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future"*. The information was collected from a survey campaign in the Region of Madrid (Spain), collecting more than 15,000 valid observations. The model accounts for important explanatory factors such as individuals'

and households' socio-demographics, declared travel behaviour, vehicle ownership and lifestyle preferences. Interestingly, the multilevel approach also allows capturing potential spatial heterogeneity in perceived private car dependency (e.g., differences between urban, metropolitan and rural areas).

After this introductory chapter, the paper is structured as follows. Section 2 reviews the existing contributions addressing vehicle ownership reduction through shared mobility solutions. In Section 3 a summary of the characteristics of the case study selected for this research (Region of Madrid) is provided in terms of socio-demographics, transport services and mobility dynamics, and geographical heterogeneity. Section 4 includes a thorough description of the survey data and its gathering process. Section 5 presents the methodological framework and the different model specifications estimated in this research. Section 6 presents and comments the modelling results, and Section 7 provides a discussion of the main findings and provide policy recommendations. Finally, Section 8 outlines the main conclusions that can be drawn from the analysis, addresses the limitations of the study and suggests some avenues for further research.

2. Literature review

The first part of this section provides a brief summary of the main results that have been observed for the determinants of car ownership in general. Thereafter, a more extensive overview of the existing contributions on the impact of shared mobility on reducing car ownership. It should be noted that most research works addressing this topic focus on the role of carsharing and Mobility as a Services (MaaS) platforms, and almost all of them use surveys as data source for the analysis.

2.1. Determinants of car ownership

The determinants of car ownership have been extensively analysed in the literature, what has allowed to observe some general trends. The number of cars owned by a household is usually higher among wealthier households (Nolan, 2010; Potoglou & Kanaroglou, 2008) and with more members (Cornut, 2016), especially if some of the members are children (Oakil et al., 2016). With respect to age, the probability of owning one or more cars increases with age for young adults (usually around 35 years old) until the retirement age is reached (Nolan, 2010, Dargay, 2001). However, some authors have observed that the new generations are delaying the decision to buy a car, presumably due to a delay in the life-cycle events that usually trigger car purchases: a new child, finding and stable job, marrying, etc. (Goodwin, 2012, Klein & Smart, 2017). Subjective attitudes have been observed to be determinant of car ownership

decisions (Soza-Parra & Cats, 2023). In particular, aspects such as social norms (to what extent the individual perceives that having a car is an accepted and widespread practice in society), the social status attached to private cars, the perceived convenience of the private car or the environmental consciousness have been observed to be important determinants of car ownership (Belgiawan et al., 2014, Heinonen et al., 2021; He & Thøgersen, 2017). Finally, the spatial context has also been found to be a key determinant of car ownership levels, with a higher mixture of land uses and population density negatively influencing the number of cars owned by the household (Jiang et al., 2017, Ding & Cao, 2019). Furthermore, people living closer to city centres have been observed to own less cars (Ding & Cao, 2019; van Acker & Witlox, 2010)

2.2. The impact of shared mobility on car ownership

The scientific literature analyzing the impact of carsharing on car ownership levels is rather extensive. Most research works combine the analysis of past and expected changes in car ownership (i.e., revealed and expected preferences) as a consequence of carsharing use (Kim et al., 2019, Jain et al., 2021, Haustein, 2021), although some works conducting stated choice experiments can also be found (Zhou et al., 2020, Liao et al., 2020). Regardless of the methodological approach, there is a wide agreement on the significantly negative influence of carsharing on the number of cars owned by the household irrespective of the geographical context (see e.g., Becker et al., 2018 for Basel, Switzerland; Klinevicius et al., 2014 for Montreal, Canada; Ko et al., 2017 for Seoul, South Korea or Martin et al., 2010 for North America). This effect seems to be correlated with sociodemographic characteristics such as age (Cervero et al., 2007; Kim et al., 2019), the absence of children in the household (Cervero et al., 2007; Jochem et al., 2020) and level of education (Le Vine & Polak, 2019; Zhou et al., 2020). As for the role of income, low-income households seem to be more prone to get rid of a car or delay a purchase due to car sharing (see for instance, Kim et al., 2019) for the case of Seoul, South Korea, Le Vine & Polak, 2019 for London, UK or Ye et al., 2021 for Shanghai, China). Interestingly, opposite results can be found regarding the effect of previous levels of car ownership. For instance, Le Vine & Polak (2019) found that those who already owned few cars were more likely to further reduce car ownership, while other authors (see e.g. Nijland & van Meerkerk, 2017 for The Netherlands or Zhou et al., 2020 for Australian cities) observed that households with two or more vehicles were willing to replace one of their cars by the use of carsharing.

The effect of subjective perceptions towards car ownership and car sharing has also been analysed by Haustein (2021) and Liao et al. (2018). Their studies revealed the statistically significant effect of various attitudinal factors, such as the significance people attribute to cars

(e.g., freedom, independence, social status, etc.), the priority they place on environmental considerations when selecting transportation options or their perceived level of daily mobility needs. Additionally, Kim et al. (2015, 2019) also examined how users' attitudes towards different characteristics of carsharing services might affect their willingness to reduce their car ownership.

Concerning the effect of the built environment and spatial context, several contributions have controlled for the behavioural differences between living in an urban vs a suburban area (Clewlow, 2016; Giesel & Nobis, 2016; Mishra et al., 2015). Most of them have pointed out that the reduction in car ownership or the willingness to do it, is significantly higher among residents in urban areas, than among those living in sub-urban or rural neighborhoods. Some authors have further enriched their analysis with more detailed data regarding the characteristics of the area of residence. In particular, Ye et al. (2021) included in their analysis explanatory variables capturing whether subway or carsharing was available within 800 meters of the place of residence for residents in Shanghai. Mishra et al. (2015) captured the effect of residence and workplace accessibility and population density at the census tract level on differences in vehicle holdings between carsharing users and non-users in the San Francisco Bay Area.

The relationship between travel behaviour and changes in car-ownership has been less frequently analysed. Most authors have studied the extent to which individuals' frequency of use of carsharing influences car-ownership reductions (or willingness to reduce), again with contrasting results. While Liao et al. (2020) observed for the case of The Netherlands that greater substitution of the private car by carsharing was not necessarily associated with a higher willingness to shed a car, other authors observed that a more frequent use of carsharing is correlated with greater reductions in car ownership (see e.g., Giesel & Nobis, 2016 for Berlin and Munich; Jochem et al., 2020 for 11 different European cities or Zhou et al., 2020 for Australian cities). Surprisingly, Haustein (2021) did not obtain significant results for travel habits (days travelled by car, metro/train, bus, bike or foot) in explaining changes in car ownership among carsharing users in Copenhagen, Denmark. By contrast, for the case of Hangzhou (China), Hui et al. (2019) observed that among users of round-trip carsharing, those who use their private car to commute are more likely to postpone the purchase of a car than those who used other modes for commuting. Reasonably, Jochem et al. (2020) found that the use of carsharing was more likely to reduce car ownership among users of other shared mobility services such as bike-sharing.

A second, and considerably smaller, group of works explores the potential reduction in car ownership levels coming from the integration of shared and traditional modes via Mobility as

a Service (MaaS) platforms (see for instance Kamargianni et al., 2018 for the case of Greater London; Storme et al., 2020 for the case of Ghent, Belgium; or Christensen et al., 2022 for Copenhagen, Denmark). However, the findings for MaaS are not as conclusive as those observed for carsharing. In general, the above-mentioned studies show that the deployment of MaaS is only a feasible alternative to private cars when it is complemented with other policies that incentivize car use reduction. Finally, it is worthy highlighting the research work by Basu & Ferreira (2021), who analysed the impact of bike-sharing on car dependency. Their findings show that the access to a bike-sharing station can significantly reduce individuals' car use and households' car ownership.

As can be observed, the existing literature exploring changes in car ownership levels (expected or revealed) as a consequence of shared mobility usage, has mostly focused on the role played by carsharing, and has concluded a significant effect of these services in reducing car ownership. However, the effect of other shared mobility services available (e.g., scooter-sharing, bike-sharing, etc.) on vehicle ownership decisions and, more importantly, the impact of all these services taken together as a system, needs to be further studied.

This research presents, to the best of the authors' knowledge, some innovative aspects: (1) it analyses the impact that shared mobility may have, not as a specific modal option, but as the availability of a set of different mobility alternatives, on the perceived ability of the general population to move towards car-independent mobility (i.e., completely giving up car-ownership); (2) the employment of a nested multilevel model allows to study the spatial heterogeneity of shared mobility's effects on future car ownership decisions considering a wide variety of built-environment contexts (from highly urbanized to rural zones) and to understand to what extent this variability is due to the spatial characteristics of the different areas; and (3) together with the socio-economic attributes, latent variables and built-environment characteristics, the research addresses the influence of individuals' declared travel behaviour regarding traditional modes and shared services, which is rarely included in previous research works. The joint analysis of these factors, based on the information collected in a large survey campaign (more than 15,000 valid responses), allows drawing robust conclusions on which travel habits may be associated with a greater willingness to give up car ownership because of the increased supply of shared mobility.

3. Data: an extensive survey campaign in the Region of Madrid

3.1. Case study: the Region of Madrid

For the purpose of this research, we selected the case study of the Region of Madrid (Spain). With a total population of 6,7 million inhabitants, this region includes the third largest city and metropolitan area in Europe. Beyond its size and relevance within the European urban context, its shared mobility ecosystems, which is one of the biggest and most diverse ones across Europe (Invers, 2022b), makes it an especially interesting case for the purpose of this research. The region, which has experienced a marked urban sprawl in recent decades, has in broad terms three main areas: i) the city of Madrid, with a total of 3.3 million inhabitants, which follows the European pattern of a highly dense town and is an important focus of business and economic activity in southern Europe; ii) the metropolitan area, comprising surrounding municipalities with a strong social and economic interdependency with the city of Madrid; and iii) the rural areas, including many other municipalities within the region with low population densities (3-4 inhab. per km²). Thus, as can be observed, the Region of Madrid has large differences in terms of population density, level of economic activity, (Comunidad de Madrid, 2022a), community types (urban, sub-urban and rural), built environments and land-use mixes.

The Region of Madrid has an extensive and competitive network of public transport services, including: 12 metro lines, 11 sub-urban rail lines, 5 light metro lines and 677 lines of urban and inter-urban buses that cover the whole territory. As a result, mobility in Madrid presents a fairly sustainable pattern, particularly in districts located in the city centre. According to the last mobility survey (CRTM, 2020), a total of 15,8 million journeys are made in the region in a working day, 39% of which are made by private car. Sustainable modes have a strong presence in modal share, with walking and public transport comprising, respectively, 34% and 24% total trips in a working day.

Notwithstanding the above, modal share in Madrid greatly varies across the metropolitan rings. For instance, in the city centre only 20% of the trips are made by car, while in the outer ring of the region (outside the metropolitan area) this percentage rises up to almost 60% (CRTM, 2018). This is most likely due to the lower population density, the lower mixed land use patterns, and the limited availability of public transport in these areas. In fact, the public transport network within the region is primarily concentrated around the city of Madrid, resulting in decreasing accessibility as one moves away from the city centre. This geographical

heterogeneity is also evident when considering car ownership rates. In contrast to the city of Madrid, which has one of the lowest motorisation rates in the region (456 cars/1,000 inhab.), the surrounding municipalities show significant increases in this ratio. For example, in Majadahonda, a wealthy town in the metropolitan area located 20km away from Madrid city centre, the car ownership rate is 1,854 cars/1,000 inhab. Similarly, in Buitrago del Lozoya, located in a rural area near the northern boundary of the Region, the ratio reaches 910 cars/1,000 inhab. (Comunidad de Madrid, 2022b).

The shared mobility ecosystem of Madrid features a remarkable variety and size (Arias-Molinares & García-Palomares, 2020b). According to Invers (2022b), at the end of 2023 there were almost 20,000 shared vehicles of different kinds available in the metropolitan area. Madrid shared mobility system includes practically all the services currently available: bike-sharing (with public and private operators), carsharing, kick scooter sharing and moped scooter sharing, almost all of which are free-floating services. As could be expected, the spatial distribution of the existing supply of services differs considerably between the city of Madrid and the surrounding municipalities. At the time of the writing of this paper, micromobility services (*e-kick-scooter sharing* and *bike-sharing*) are currently concentrated in the city of Madrid. There are three operators of e-kick-scooters (Tier, Dott and Lime), five operators of free-floating shared bikes (Ridemovi, Boltest, Bird, Ride Dott and Lime) and one public operator of station-based and free-floating shared bikes (BiciMad). However, it has recently been announced the future implementation of e-kick scooter sharing and bikesharing system in the municipality of Parla (in the metropolitan area) and the extension of BiciMad bikesharing service area from Madrid city to the bordering municipality of Alcorcón. For the case of *carsharing*, six operators offer their services in the Region: Free2Move, WiBLE, Zity, GoTo, SharedNow, Voltio. While most of their vehicles are located within the city of Madrid, in the last few years some of them are gradually expanding their services to some neighboring municipalities in the north and the west of the region, such as Alcobendas, Pozuelo, Las Rozas or Majadahonda. Finally, four operators of *moped sharing* can be found in the region (Acciona, GoTo, Cooltra and Cabify) which display a very similar geographical distribution to that of carsharing since they operate in the city of Madrid and in some neighboring municipalities within its metropolitan area.

3.2. Description of the survey

This study explores individuals' perception of the need to own a private vehicle in the future due to the availability of shared mobility services. For this purpose, a survey campaign was carried out in the Region of Madrid from November to December 2022. The target population comprises those people residing in the Region of Madrid who are over 16 years of age. As a

result of the survey campaign, a total of 15,666 valid observations were obtained after excluding incomplete answers, validation and data cleaning.

The survey was conducted by SIGMADOS, a market research company with a remarkable know-how in conducting surveys in mobility, which was awarded the contract for the survey campaign after a competitive public tender process. Two collection methods were selected in the survey campaign. First, Computer-assisted Telephone Interviewing (CATI), which involved telephone interviews based on official telephone databases of the Region of Madrid. This method allowed reaching segments of the population with difficulties in accessing technologies. Second, Computer-assisted Web Interviewing (CAWI), which collected the information from online questionnaires to panelists. CAWI surveys were employed as a complement to reach those segments of the population whose lifestyles make phone localisation difficult. The estimated duration of the survey was between 12 and 15 minutes and the authors are not aware of the provision of any incentives to encourage participation in the survey. It is worth noting that a stratified sampling process was adopted in this survey campaign to ensure the demographic and spatial representativeness of the sample given the spatial disparities observed in the Region of Madrid (see Section 3) concerning e.g., population density, motorisation rates, public transport supply, etc. To this end, a sampling method to collect a representative sample in terms of gender and age for several sub-areas within the the Region of Madrid was designed to capture potential spatial heterogeneity.

As the place of residence within the Region is likely to strongly influence individuals' opinions on the potential of shared mobility to reduce private car dependency, respondents were asked to report their municipality of residence and, in the case of people living in the city of Madrid, they also reported their district of residence given that the city of Madrid features a noticeable heterogeneity. This information made it possible to associate each respondent with the characteristics of the built environment (e.g., land use, transport accessibility, etc.) of her/his place of residence (see Section 4.3 for more details).

The survey collected five main aspects from respondents:

- *Individuals' and household socio-demographics*: gender, age, level of education, household annual income, occupation and working conditions (e.g. teleworking regime), household structure and place of residence and workplace.
- *Ownership and access to private modes*: number of vehicles in the household (cars, motorbikes and bikes) and the possession of driver's license.
- *Mobility habits*: individuals declared their frequency of use for different modes of transport (private car, public transport, walking, etc.), including shared mobility

services. It is noteworthy that the use of moped-sharing and carsharing, on the one hand and shared bikes and kick-scooters, on the other hand, were jointly asked in the questionnaire. The services that have been merged share several characteristics that are likely to determine the adoption and frequency of use in similar ways. For instance, both mopeds and cars require a driving license, they can only circulate on the road and can reach similar speed. On the other hand, both bikes and kick-scooters are considered as micromobility services, they do not require a driving license and both must circulate by bike lanes when available.

- *Subjective and lifestyle preferences*: a set of attitudinal indicators, measured in a 5-point Likert-scale format, captured individuals' psychological and lifestyle preferences (see more comments in Section 4.3) concerning a variety of factors regarding: tech savviness, environmental awareness, fear to COVID infection, etc.
- *Perceived need to own a private vehicle in the future*: respondents were asked to declare their level of agreement, through a 5-point Likert-scale, with the following statement "*Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future*". This is the variable of greater interest and the outcome variable of the modelling conducted in this research. (see details in Section 5). It should be noted that this statement encompasses two different parts. The first one, in which an increase of shared mobility services is stated, is given to the respondents as a circumstance that should be taken as truth when declaring their level of agreement with the possibility of dispensing with their private car⁷.

3.3. Sample characteristics and data description

Table 8-1 presents the main descriptive statistics of the explanatory variables included in the analysis. Additionally, for the purpose of comparison, the values from official statistics for the socio-economic variables are provided insofar as it is possible.

The distribution across gender and age is coherent with the statistics for the general population of the Region of Madrid, which is reasonable given the sampling method conducted during the survey campaign. In the same trend, the percentage of individuals with higher education is similar to official statistics (IECM, 2022; MECD, 2022). However, individuals

⁷ Despite the formulation, it is still possible that some respondents interpreted the statement in a way that led them to disagree because of the lack of trust in the expansion of shared mobility services. However, we argue that, given the specific context of Madrid regarding shared mobility that was explained in Section 3.1, providing the future expansion of shared mobility as a condition that should be taken as truth is reasonable. In the last years, both the private and public shared mobility operators have been geographically expanding their services to the outskirts of the city of Madrid as well as to other neighboring municipalities on an ongoing basis.

with upper secondary education (Baccalaureate and vocational training) seem to be over-represented to the detriment of those with lower-secondary education or lower. As for occupation, the percentage of employed individuals is also slightly higher than official statistics, with half of the sample not benefiting from any kind of teleworking regime. The distribution of the monthly household income is coherent with the average household income in the Region of Madrid in 2022 (INE, 2022a). It is worth noting that 20.5% of people surveyed were not willing to report their level of income, a percentage similar to previous research works conducted in Spain (see e.g. Gomez et al., 2021; Bueno et al., 2017).

As for travel-related variables, almost half of the sample (47.2%) lives in a household that owns one car and only 15.7% lives in a car-less household, which seems to be somewhat underrepresented in our sample compared to the official statistics (CRTM, 2018). Interestingly, 44.3% of respondents use their private car three or more time per week, while this percentage is ten points lower (33.4%) for the case of public transport, which is coherent with the latest mobility survey (CRTM, 2018) and taking into account the still ongoing recovery of public transport after the pandemic. The survey reveals low adoption rates for shared mobility services among the population, again in line with the latest survey. In fact, only 11.2% of the sample reported having ever used shared cars or mopeds, while for the case of shared kick-scooters or bikes this percentage drops to 6.2% of respondents.

Table 8-1: Description of the sample

		% in the sample	% in official statistics 2022
SOCIOECONOMIC ATTRIBUTES			
Gender	Male	45.7	47.9
	Female	54.3	52.1
Age	16 – 25 years old	9.3	12.2
	26 – 35 years old	19.2	14.0
	36 – 45 years old	20.1	17.8
	46 – 55 years old	18.4	19.4
	56 – 65 years old	19.8	15.2
	Over 65 years old	13.2	21.0
Level of education	Primary education	3.8	24.2*
	Lower-secondary education	7.6	24.2*
	Vocational training	18.4	25.5*
	Baccalaureate	15.8	25.5*
	University education	54.4	50.3
Occupation	Employed	71.3	62.1
	Student	3.8	
	Student and part-time employed	2.2	
	Homemaker	2.9	
	Unemployed	6.1	11.5
	Retired	13.7	18.0
Remote working/studying	No teleworking	46.9	
	I cannot choose the day I work/study from home.	22.1	
	I choose the days in which I want to work/study from home among some pre-established days.	8.8	
	I choose the days in which I want to work/study from home.	22.3	
Monthly household income	Less than 1,000 €	5.7	
	1,000 € - 1,500 €	13.5	
	1,500 € - 2,000 €	14.7	
	2,000 € - 3,000 €	21.3	
	More than 3,000 €	24.2	
	I prefer not to answer	20.5	
TRAVEL-RELATED VARIABLES			
Number of cars in the household	0 cars	15.7	24.8
	1 car	47.2	43.1
	2 or more cars	37.1	30.2
Driver's license	Yes	86.7	70.7
	No	13.3	
Destination of the most frequent trip	Urban area of residence	49.1	
	Urban area other than area of residence	50.9	
	I prefer not to answer	0.2	
Frequency of use of public transport	Never	25.9	
	Occasionally	27.9	
	1-2 times/week	12.7	
	3-4 times/week	9.5	
	More than 4 times per week	24.0	
Frequency of use of private car	Never	22.2	
	Occasionally	16.5	
	1-2 times/week	16.8	
	3-4 times/week	11.2	
	More than 4 times per week	33.3	
Frequency of use of active modes	Never	41.1	
	Occasionally	16.3	
	1-2 times/week	9.2	
	3-4 times/week	9.3	
	More than 4 times per week	24.1	
Frequency of use of shared kick-scooter/bike	Never	93.8	
	Occasionally	3.8	
	1-2 times/week	1.3	
	3-4 times/week	0.6	
	More than 4 times per week	0.4	
Frequency of use of shared car/moped-scooter	Never	88.2	
	Occasionally	7.3	
	1-2 times/week	2.3	
	3-4 times/week	1.1	
	More than 4 times per week	1.1	

*The categorisation of the official statistics groups together (1) primary and secondary education and (2) baccalaureate and vocational training.

3.4. Spatial disaggregation and zoning

This section provides some insight regarding the spatial effects that have been considered in this study. First, the region has been geographically divided in two nested levels, which will later be employed for the construction of a multilevel model (see Section 5 for more details). The *higher level* is made up of 4 metropolitan rings (see Fig. 1b), that correspond to the different areas of the region that were described in Section 3, with an additional division of the city of Madrid. Therefore, the first two rings belong to the city of Madrid (city centre and outskirts within the municipality of Madrid), the third includes the municipalities of the metropolitan area and the last one covers municipalities outside the metropolitan area, which mainly include rural areas. The *lower level* (see Fig. 1a), which for simplicity, will henceforth be referred as “Municipal area level”, is made up of 69 areas which correspond to three possible divisions: i) already existing municipal areas, when a critical number of responses within each municipality was achieved in the survey campaign; ii) clusters of municipal areas, that have been aggregated until a critical sample within each cluster was achieved; iii) for the case of the city of Madrid, the municipal area is divided into the 21 districts that make it up.

Second, a set of geographical variables have been calculated for each area of the municipal area level. These variables have been included in the modelling framework aiming to capture the impact of the built-environment characteristics on the perceived need to own a car in the future given the increasing supply of shared mobility. They include population density, accessibility to public transport and land use mix. The variety of land uses that can be found in each area has been captured through the computation of a land use entropy index, proposed by Bordoloi et al. (2013):

$$Land\ use\ entropy = - \sum_j P_j \frac{\ln P_j}{\ln J} \quad (1)$$

Where P_j represented the proportion of total land area of the j^{th} land-use in each spatial division. The land uses that have been considered for the computation of this index are: residential, industrial, retail, offices and public services.

Table 8-2 presents the main geographical variables considered in this research, together with their descriptive statistics:

Table 8-2: Summary statistics – variables collected at the municipal area level

	Mean (Standard deviation)	Min.	Max.
Land use entropy	0.560 (0.121)	0.249	0.818
Proportion of residential use	0.703	0.323	0.891
Proportion of industrial use	0.108	0.001	0.503
Proportion of retail use	0.040	0.003	0.107
Proportion of offices	0.040	0.001	0.152
Proportion of public services	0.108	0.038	0.437
Population density (1,000 inhabitants/km ²)	0.906 (1.012)	0.002	2.932
No. urban bus stops	162.8 (104.5)	0	420
No. metro stations	6.54 (5.7)	0	19
No. interurban bus stops	83.8 (77.5)	0	282
No. sub-urban train stations	1.7 (1.8)	0	7

3.5. Psychological and lifestyle preferences

As commented in Section 3.2, the questionnaire captured respondents' opinions towards different psychological and lifestyle preferences. A total set of 20 psychological indicators following a five-points Likert structure were included in the survey. This information was employed to build latent constructs capturing subjective preferences and beliefs that may affect individuals' perceptions of the need to own a private car in the future. To this end, a Factorial Analysis was conducted in a stepwise process. First, some tests were carried out to ensure that the data met the hypotheses assumed by the mathematical formulation of factor analysis. Thereafter, an Exploratory Factor Analysis (EFA) was applied, following a Common Factor Analysis approach, to determine the number of factors that could be extracted from the data and which indicators provided better measures for those factors. Finally, a Confirmatory Factor Analysis (CFA) was performed to compute the factor scores according to the structure obtained in the EFA and to calculate some goodness-of-fit indexes. For a full description of Factor Analysis, the reader is referred to Heck (1998). The scores obtained for each factor were included as explanatory variables in the model, similarly to many previous approaches capturing latent constructs (see e.g. Muñoz et al., 2013; Chen & Li, 2017; Fleischer et al., 2012).

The preliminary tests confirmed that Factor Analysis is a suitable technique for the data collected. The KMO measure of sampling adequacy takes a value of 0.769, which suggests that the common variance of indicators (e.g., the proportion of total variance that can be explained by common factors) is acceptable. In addition, the Barlett's test of sphericity, which tests whether the covariance matrix is significantly different from the identity matrix, yields a null p-value.

The EFA showed that only three factors had eigenvalues above 0.7, which was fixed as the threshold to retain a factor. On the other hand, only the factor loadings greater than 0.5 using a Promax rotation were carried out to the confirmatory phase of the analysis. The composition of the factors that were extracted as well as the values of the factor loadings that were kept

can be found in Table 8-3. The first group of indicators regards behavioural changes induced by fear of contagion during COVID-19 high incidence periods (waves), identified as “COVID-19 preventive behaviour”. The second factor, identified as “Environmental consciousness”, encompasses two indicators related to individuals’ concern about the environmental impact of daily activities. The third factor refers to “Tech-savviness” and captures individuals’ level of comfort with the use of technology for daily activities.

Table 8-3: Results of the Exploratory Factor Analysis

	COVID-19 preventive behaviour	Environmental consciousness	Tech- savviness
During COVID-19 high-incidence periods, I avoided touching any object that could have been touched by some else	0.6057	--	--
During COVID-19 high-incidence periods, I reduced my social interaction with acquaintances to avoid contagion	0.8036	--	--
During COVID-19 high-incidence periods, I left the house as little as possible due to COVID-19	0.7936	--	--
During COVID-19 high-incidence periods, I actively avoided crowds	0.7353	--	--
I try to use modes of transport that pollute as little as possible	--	0.6006	--
I usually recycle waste at home	--	--	--
I chose products that have as little environmental impact as possible	--	0.6345	--
I use social media frequently: Facebook, Twitter, Instagram, etc.	--	--	0.5349
I regularly perform daily tasks online: online banking, e-shopping, e-mail, etc.	--	--	0.6494
I can easily learn how to use new mobile applications	--	--	0.6533
Cronbach’s alpha	0.8383	0.6645	0.6851

The Cronbach’s alphas obtained for each factor are provided at the bottom of Table 8-3. This indicator measures the internal reliability of the measurement scale of the indicators. The values obtained for the three factors show an acceptable internal reliability according to the literature (Cronbach, 1951).

The validity of the described factors structure above was tested by means of a CFA, which confirmed the suitability of the hypothesized structure to capture the latent constructs. The goodness-of-fit indexes yielded the following values: Root Mean Square Error of Approximation (RMSEA) = 0.041; Comparative Fit Index (CFI) = 0.980; Tucker-Lewis index (TLI) = 0.972; Standardize Root Mean Square Residual (SRMR) = 0.024. According to the recommended values in the literature (Akaike, 1987; Hu & Bentler, 1999), these values would support the robustness of the model that has been built to capture the latent constructs.

3.6. Preliminary findings on perceived private car dependency

Table 8-4 shows the distribution of the outcome variable in the sample and its cross-tabulation with some explanatory variables. It is noteworthy that a quarter of the sample (25.5%) agrees with the statement *“Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future”*.

The cross-tabulation between the outcome variable and the socio-economic variables also shows that men and women display very similar distributions. Individuals over 65 years old are the age group with a higher level of agreement in the sample (31%) —probably due to the lower number of drivers in this group—, followed by those between 35 and 45 years old (25.5%). Interestingly, a higher level of flexibility for teleworking seems to affect in a positive way the agreement with the given statement. In fact, 56.9% of those who cannot telework consider that they will still need to own a private vehicle in the future, while this percentage goes down to 46.7% among respondents with full flexibility to decide when to telework. Although there are no major differences by income levels, it is noted that low-income households are slightly more likely to believe that they will not need to own a car in the future.

Table 8-4: Cross-tabulation of the explanatory variables vs. the dependent variable

		Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future				
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		32.0	20.9	21.6	16.7	8.8
SOCIOECONOMIC ATTRIBUTES						
Gender	Male	32.3	20.0	21.5	17.4	8.8
	Female	31.7	21.7	21.7	16.1	8.9
Age	16 – 25 years old	30.5	22.3	22.6	15.3	9.3
	26 – 35 years old	35.1	21.1	21.0	15.4	7.5
	36 – 45 years old	30.0	22.3	22.2	16.2	9.3
	46 – 55 years old	29.5	22.3	23.9	16.5	7.8
	56 – 65 years old	33.5	20.1	20.6	17.8	8.1
	Over 65 years old	32.7	16.8	19.5	18.9	12.1
Level of education	Primary education	44.4	14.8	16.2	13.8	10.8
	Lower-secondary education	40.7	18.4	18.6	13.8	8.6
	Vocational training	34.8	21.2	22.4	14.7	6.9
	Baccalaureate	33.7	19.2	22.0	15.8	9.3
	University education	28.4	22.1	22.0	18.2	9.3
Occupation	Employed	31.6	21.3	22.0	16.5	8.6
	Student	26.7	22.7	26.0	16.3	8.4
	Student and part-time employed	31.4	22.3	26.6	13.4	6.3
	Homemaker	40.9	20.2	18.4	15.1	5.3
	Unemployed	35.7	21.2	20.7	15.2	7.3
	Retired	32.1	17.9	18.7	19.5	11.8
Remote working/studying	No teleworking	38.3	18.6	18.9	15.1	9.1
	I cannot choose the day I work/study from home	27.4	24.3	23.6	16.6	8.1
	I choose the days in which I want to work/study from home among some pre-established days	25.7	24.4	24.0	18.6	7.3
	I choose the days in which I want to work/study from home.	25.7	21.0	24.5	19.2	9.6
Monthly household income	Less than 1,000 €	32.4	16.6	20.2	16.7	14.1
	1,000 € - 1,500 €	32.5	19.6	21.0	17.3	9.6
	1,500 € - 2,000 €	30.9	21.7	21.3	17.5	8.8
	2,000 € - 3,000 €	31.7	21.7	22.4	16.7	7.4
	More than 3,000 €	29.7	22.6	21.1	18.1	8.5
	I prefer not to answer	32.2	19.6	22.4	13.9	8.8
TRAVEL-RELATED VARIABLES						
Number of cars in the household	0 cars	22.7	14.9	20.4	23.9	18.1
	1 car	30.2	21.3	23.5	16.8	8.2
	2 or more cars	38.1	22.8	19.7	13.6	5.8
Driver's license	Yes	32.0	21.6	22.0	16.3	8.0
	No	31.7	16.2	19.1	19.0	14.1
Destination of the most frequent trip	Urban area of residence	27.8	20.1	22.9	19.0	10.3
	Urban area other than area of residence	36.1	21.7	20.4	14.5	7.4
	I prefer not to answer	21.6	21.6	29.7	13.5	13.5
Frequency of use of public transport	Never	46.8	18.9	14.6	12.7	7.0
	Occasionally	31.1	24.8	24.3	13.6	6.2
	1-2 times/week	23.2	21.9	25.4	19.9	9.6
	3-4 times/week	23.3	20.3	24.3	22.2	9.9
	More than 4 times per week	25.1	18.2	22.9	20.7	13.1
Frequency of use of private car	Never	25.6	15.6	20.6	22.0	16.2
	Occasionally	25.7	22.3	24.4	19.1	8.5
	1-2 times/week	28.7	22.0	24.7	17.0	7.6
	3-4 times/week	30.2	25.3	23.0	16.2	5.5
	More than 4 times per week	41.6	21.7	18.9	12.0	5.8
Frequency of use of active modes	Never	37.0	20.9	20.0	14.9	7.3
	Occasionally	29.6	23.6	24.2	15.8	6.9
	1-2 times/week	25.2	21.9	25.6	19.7	7.6
	3-4 times/week	25.6	23.1	23.6	19.4	8.3
	More than 4 times per week	30.2	17.8	20.4	18.2	13.4
Frequency of use of shared kick-scooter/bike	Never	33.3	21.0	21.0	16.1	8.7
	Occasionally	12.5	22.3	28.8	26.0	10.3
	1-2 times/week	9.6	19.2	36.5	23.6	11.1
	3-4 times/week	11.0	11.0	39.0	30.0	9.0
	More than 4 times per week	18.0	13.1	21.3	23.0	24.6
Frequency of use of shared car/moped-scooter	Never	34.0	21.0	20.7	15.9	8.6
	Occasionally	15.1	21.7	28.2	23.7	11.2
	1-2 times/week	14.1	20.3	32.7	23.7	9.3
	3-4 times/week	20.1	15.6	33.5	19.6	11.2
	More than 4 times per week	34.8	15.9	18.3	19.5	11.6

According to the data, the largest differences in the perceived capacity to give up car ownership due to shared mobility are associated with travel-related variables. For instance, 42% of individuals living in car-less households agreed with the statement. This level of agreement, although reasonably high, drops sharply for those respondents living in households with one (25.0 %) and two or more cars (19.4%). The relationship between individuals' use of public transport and the perceived capacity to give up car ownership appears to be fully coherent with initial expectations, since the level of agreement increases with the frequency of use. For obvious reasons, the same is observed for the use of shared mobility modes, while the opposite applies for the case of private car use. A share of 41.2% of those who do not use the car believe that they will not need to own a car in the future, while this percentage rises to 63.3% among respondents who use the car more than four times a week.

Figure 9-2 shows the spatial distribution of the mean of respondents' agreement with the statement *"Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future"*, according to the geographical divisions described in Section 3.4. Some spatial clustering can be clearly observed in the data, in the sense that the potential of shared mobility to reduce perceived private car dependency seems to be lower as we move away from the city centre of Madrid (see Figure 9-2a). However, the average values for the municipal area level represented in Figure 9-2b show that, despite the persistence of this decreasing trend, there is variability also within metropolitan rings. Interestingly, the presence of significant spatial autocorrelation among the average responses of individuals has been confirmed by the Moran's I statistical test, conducted for the average values at the municipal area level (Moran's I = 9.098, p-value = 0.000).

4. Methodology: A multilevel ordinal logit

This research explores the explanatory variables determining individuals' perceived vehicle dependency and the role played by shared mobility. Particularly, the variable to be modelled (y) corresponds to the respondents' self-declared level of agreement with the possibility of not needing to own private vehicle ownership in the future given the increasing supply of shared mobility. To that end, we adopt a Multilevel Ordered Logit model (also known as mixed-effects model) for two main reasons. First, the outcome variable has an ordinal nature, since the respondents' level of agreement has been captured through a 5-point Likert scale (see previous comments in Section 3.2). Second, the multilevel component allows to account for the potential lack of independency of observations as it may happen with the responses of individuals living in the same area of the region, overcoming the so-called "atomistic-

fallacy” (Schmidt-Catran & Fairbrother, 2016). In this respect, the literature commonly agrees (see e.g. Ding et al., 2018; Huo et al., 2021) that both car ownership levels and shared mobility usage habits are strongly influenced by the built environment and geographical dimensions. Therefore, the multilevel specification is able to capture potential heterogeneity in the observations derived from hierarchical or nested structure in the data related to the residential location of the individual. A detailed description of multilevel models can be found in e.g. Hedeker (2008).

The proposed framework models a response variable y_{ijk} of ordinal nature and follows a three-level (i – j – k) nested structure, being hierarchically from the highest to the lowest: *metropolitan rings* (level 1, subscript k); *municipal areas* or clusters of municipal areas (level 2, subscript j); and individual respondents (level 3, subscript i). As previously commented in Section 3.4, the model considers the following spatial disaggregation: a total of 4 metropolitan rings, 69 municipal areas and 15,666 individuals. A summary of the levels’ composition and a diagram of the model structure can be found in 8- A. The model includes random effects at both intercepts and certain slope parameters, allowing random variations among metropolitan rings (k) and municipal areas (j), as shown below in a general form. Taking the assumption of proportional odds ratios, the specification for the cumulative probability for each category c is the following:

$$Y_{ijk} = \text{logit}[P(y_{ijk} \leq c)] = \ln\left(\frac{P(y_{ijk} \leq c)}{P(y_{ijk} > c)}\right) = \alpha_c - (x'_{ijk} \beta + z'_{ijk} (u_{jk} + u_k) + \varepsilon_{ijk}) \quad (2)$$

where α_c be the cut points with $c = 1, 2, \dots, C-1$; x_{ijk} the vector of explanatory variables (fixed-effects); β the vector of regression parameters to be estimated; z'_{ijk} the vector of coefficients for the random effects; u_{jk} the random effects for level j nested within level k; u_k the random effects for level k; and ε_{ijk} the common idiosyncratic error term. Random and error terms in the model are considered to be independently distributed. In this respect, a significant random coefficient (intercept and/or slope) at a certain geographical level indicates that divergences between responses are (wholly or partly) due to unobserved differences at this level.

The research conducts three different models depending on the fixed- and random- effects considered in each case:

0. Model 0 (M0), commonly known as the unconditional means model, includes only the random intercepts for level 1 (metropolitan ring) and level 2 (municipal area), with no explanatory variables x_{ijk} . Model M0 aims to test for the presence of statistically

significant differences in individuals' responses between metropolitan rings (level 1) and municipal areas (level 2), thus confirming the suitability of a multilevel framework.

1. Model 1 (M1) includes explanatory variables at the individual level, also known as fixed-effects (socio-economic attributes and mobility habits), as well as the random intercepts for levels with a statistically significant effect. Those explanatory variables that displayed p-values over 0.05 and for which the likelihood-ratio test showed that their inclusion did not significantly improve the explanatory power of the model were excluded.
2. Model 2 (M2) includes, in addition to the explanatory factors considered in M1, a set of geographical variables at the municipal area level, namely a land-use mix indicator, population density and number of public transport access points (metro and rail stations and bus stops) in the place of residence.

5. Modelling results

This section presents the main results and findings obtained from the multilevel modelling. The first sub-section (Section 5.1) provides the results for Model 0 and reflects on the spatial heterogeneity of the data. The second part (Section 5.2) describes the results corresponding to the fixed-effects included in Models 1 and 2. Section 5.3. presents the results for the random-effects and their geographical implications.

5.1. Unconditional means models (Model 0)

Table 8-5 displays the results for the unconditional means models. Model 0.A includes the random intercepts for the two levels considered in the analysis (metropolitan ring level and municipal area level), while Model 0.B only considers random intercepts for the municipal area level. As can be observed, the variance across municipal areas is statistically significant ($p\text{-value} < 0.05$) in both models, thus confirming the presence of spatial heterogeneity in the responses of individuals at the municipal level. By contrast, the random effects for metropolitan rings are not significant in Model 0.A at 95% confidence level. In spite of this result, the Likelihood ratio test indicates that including this level in the model significantly improves its goodness-of-fit. Therefore, both levels have been kept for the construction of the successive models.

Table 8-5: Results for Models 0.A and 0.B

	Model 0.A			Model 0.B		
	Coeff.	Std. Error	p-value	Coeff.	Std. Error	p-value
Fixed effects						
Threshold 1	-0.752	0.171		-0.643	0.042	
Threshold 2	0.139	0.171		0.248	0.041	
Threshold 3	1.119	0.172		1.227	0.043	
Threshold 4	2.400	0.173		2.507	0.048	
Random effects						
var(metropolitan ring)	0.116	0.083	0.165			
var(municipal area)	0.008	0.004	0.046	0.095	0.019	0.000
-2loglikelihood		-23,845.93			-23,886.79	
	Likelihood ratio test (0.B nested in 0.A)			Prob > chi ² = 0.000		

5.2. Fixed-effects – latent, socio-economic and travel-related variables

Table 8-6 displays the modelling results for the fixed-effects included in the analysis, which encompass psychological preferences, socio-economic attributes of the individuals and their households and travel-related variables. The final specification of the model is the result of a process of testing alternative combinations of these factors. Variables that were not significant at the 90% confidence level and which, according to the likelihood-ratio tests, did not improve the goodness-of-fit of the model, were gradually removed from the model to obtain more parsimonious specifications. It should be noted that some coefficients in the final specification of the model in Table 8-6 are duplicated, which reflects that two or more categories within a certain variable have been merged⁸.

The subjective psychological preferences captured by the latent constructs seem to be important determinants of individuals' perspective on the possibility of giving up their private vehicle. According to the modelling results, environmental awareness and tech-savviness increase the probability of respondents declaring that they could forego their private vehicle in the future because of the increasing supply of shared mobility. In this respect, several authors have previously pointed out a strong relationship between a high level of environmental awareness and the willingness to substitute car ownership by shared mobility (Clewlow, 2016; Sopjani et al., 2020).

As for the socio-economic attributes, the modelling results shows that the future perceived need to own a private vehicle is higher among adults between 26 and 55. This results suggests a higher effectivity of shared mobility in reducing car ownership among the youngest generations (under 26 year old), which may be associated with the fact that middle-age adults are more likely to face life cycle events that are often observed to trigger car purchases (e.g., having kids, moving further away from the centre of the city or job changes) as noted by e.g. Clark et al. (2016) or Oakil et al. (2014). Older individuals also seem to be more likely to be

⁸ When two or more consecutive categories of a variable were statistically significant only at the 90% level, a Wald test was performed to check whether those categories were significantly different. If the test did not confirm that they were significantly different, these categories have been merged.

willing to give up private vehicles in the future, probably because after a certain age people give up driving anyway. In this respect, previous results regarding the effect of age on car ownership reduction because of shared mobility are not conclusive. While Cervero et al. (2007) observed a positive effect of age on the probability of shedding a car, Kim et al. (2019) found that individuals over 50 years old were more likely to dispose their cars than younger population groups.

Our modelling results also indicate that individuals with higher levels of education are also more likely to believe they will not need a car in the future, in line with the results obtained by Zhou et al. (2020) or Haustein (2021). While occupation seems to play a marginal role on the willingness to shift to a car-independent mobility, teleworking does appear to have a significant impact, with more flexible arrangements being positively correlated with the perception of a private car not being necessary in the future. As for income, individuals with a monthly income above 2,000€ are more likely to believe they could give up the ownership of a vehicle given the increasing supply of shared mobility. Nevertheless, this effect virtually disappears when the interactions between income level and car use are introduced. In fact, the net effect of income is negative for all the considered interactions except for individuals earning over 3,000 € who use their car on an occasional basis (see modelling results in Table 8-6). That means that individuals with monthly incomes between 2,000 € - 3,000 € are more likely to believe they could give up owning their cars in the future than the lowest income groups, only in the case of those who do not use the private car currently. For individuals with a monthly income over 3,000 €, the same applies for those who do not use their private vehicle or use it occasionally.

According to the modelling results for the travel-related variables, the number of cars owned in the household significantly reduces the probability of considering that owning a car will not be necessary in the future, which is in line with Le Vine & Polak (2019) or Nijland & van Meerkerk (2017). Reasonably, the same effect is observed for individuals commuting outside their municipality of residence. The effect of these two variables makes it clear that car dependent individuals are likely the most reluctant ones to shift to more sustainable mobility options. This is further confirmed by the results for the variables capturing the frequency of public transport and private car use. Those who use their private vehicle 3 or more times per week are less likely to believe they could give up the ownership of a car in the future. As expected, all types of public transport users are more likely to agree with the possibility of giving up owning a car than non-public transport users.

The effect of shared micromobility usage (bike and kick-scooter sharing) allows to confirm the coherence of the model. As could be initially expected, more frequent users of these services

are more likely to believe that they would allow for a transition to a non-car-based mobility in the future. The adoption of carsharing and moped-scooter sharing is also significantly related to greater willingness to forego a car in the future. Nevertheless, in this case the odds of agreeing with the given statement do not increase with frequency of use. Similar results were obtained by Liao et al. (2020) for the case of carsharing in the Netherlands, where they observed that a higher frequency of use of this option was not necessarily correlated with decisions to reduce car ownership. Interestingly, owners of cars that use shared cars or mopeds occasionally are significantly more likely to believe they could give up their car in the future (see interactions between car ownership levels and frequency of use of different transport modes in Table 8-6). In the same trend, the interactions between the adoption of shared-mopeds or shared-cars and the frequency of use of the private car show that those who combine both options in their mobility habits are more likely to consider a car-less lifestyle as a feasible option in the future than those who use neither of them.

Finally, it is noteworthy that some variables that could initially be considered relevant in explaining perceived private car dependency were not found statistically significant in the model. This is the case of the type of dwelling (collective housing or detached house), the declared difficulty of parking around the residence or the possession of a driver's license. The access to shared mobility services within the area of residence did not have a significant explanatory power either, which is reasonable given that the statement took the increasing expansion of shared mobility as a condition for the possible relinquishment of car ownership.

Table 8-6: Modelling results for the fixed-effects (Models 1 and 2)

Ordinal response variable: Level of agreement with the statement: Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future.	
	Coeff. (Std. Error)
LATENT VARIABLES	
Tech-savviness	0.060** (0.023)
Environmental awareness	0.638*** (0.022)
COVID-19 preventive behaviour	--
SOCIOECONOMIC ATTRIBUTES	
Age (16 – 25 years old)	
26 – 35 years old	-0.100*** (0.034)
36 – 45 years old	-0.100*** (0.034)
46 – 55 years old	-0.100*** (0.034)
56 – 65 years old	--
Over 65 years old	--
Education (base: Primary education)	
Lower-secondary education	--
Vocational training	--
Baccalaureate	0.131*** (0.046)
University education	0.102*** (0.037)
Occupation (base: Employed)	
Student	--
Student and part-time employed.	--
Unemployed	-0.173** (0.064)
Retired	0.129** (0.052)
Teleworking regime (base: No teleworking)	
I cannot choose the day I work/study from home.	0.144*** (0.040)
I choose the days in which I want to work/study from home among some pre-established days.	0.155** (0.055)

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I choose the days in which I want to work/study from home.	0.275*** (0.041)
Monthly HH income (base: Less than 1,000 €)	
1,000 € - 1,500 €	--
1,500 € - 2,000 €	--
2,000 € - 3,000 €	0.259*** (0.078)
More than 3,000 €	0.317*** (0.090)
I prefer not to answer	--
Number of individuals aged over 65 in the HH	-0.033** (0.014)
MOBILITY HABITS	
Cars in the HH (base: 0 cars)	
1 car	-0.473*** (0.049)
2 or more cars	-0.653*** (0.054)
Most frequent trip within the urban area of residence (base: Yes)	
No	-0.089** (0.033)
Frequency of use of private car (base: Never)	
Occasionally	--
1-2 times/week	--
3-4 times/week	-0.138** (0.070)
More than 4 times per week	-0.317*** (0.052)
Frequency of use of public transport (base: Never)	
Occasionally	0.138*** (0.042)
1-2 times/week	0.302*** (0.053)
3-4 times/week	0.250*** (0.060)
More than 4 times per week	0.300*** (0.050)
Frequency of use of shared kick-scooter/bike (base: Never)	
Occasionally	0.352*** (0.078)
1-2 times/week	0.391*** (0.126)
3-4 times/week	0.430** (0.176)
More than 4 times per week	0.577** (0.233)
Frequency of use of shared car/moped scooter (base: Never)	
Occasionally	0.170* (0.099)
1-2 times/week	0.170* (0.099)
3-4 times/week	0.170* (0.099)
More than 4 times per week	--
INTERACTIONS	
	Coeff. (Std. Error)
Interactions Monthly HH income # private car use	
2,000 € - 3,000 €#Occasionally	-0.407*** (0.106)
2,000 € - 3,000 €#1-2 times/week	-0.613*** (0.105)
2,000 € - 3,000 €#3-4 times/week	-0.500*** (0.132)
2,000 € - 3,000 €#More than 4 times per week	-0.278** (0.101)
More than 3,000 €# Occasionally	-0.271** (0.114)
More than 3,000 €#1-2 times/week	-0.463*** (0.110)
More than 3,000 €#3-4 times/week	-0.360** (0.132)
More than 3,000 €#More than 4 times per week	-0.249** (0.106)
Frequency of use of shared car/moped scooter # Cars in the HH	
Occasionally#1 car	0.201* (0.113)
1-2 times/week #1 car	0.201* (0.113)
Occasionally #2 or more cars	0.286** (0.126)
1-2 times/week#2 or more cars	0.286** (0.126)
Adoption of shared car/moped scooter# Frequency of use of private car	
Shared car/moped adopted#1-2 times/week	0.188** (0.087)
Shared car/moped adopted#3-4 times/week	0.188** (0.087)
Shared car/moped adopted#More than 4 times per week	0.188** (0.087)
Threshold 1	-0.809*** (0.114)
Threshold 2	0.170*** (0.114)
Threshold 3	1.245*** (0.114)
Threshold 4	2.621*** (0.116)

***p-value < 0.005, **p-value < 0.05, *p-value < 0.1

5.3. Random effects and municipal area variables

Table 8-7 shows the modelling results for the random intercepts obtained in Model 1 and Model 2, as well as the coefficients for the geographical variables at the municipal level. As explained in Section 5.1, the introduction of the random intercepts at the metropolitan ring level were not statistically significant in the unconditional means model (M0), but the log-likelihood ratio test showed that their introduction improved the model. Nevertheless, after introducing the fixed-effects, the variance across metropolitan rings virtually disappears (it takes a value of $4.01e-22$) and the log-likelihood ratio suggests that their introduction does no longer improve the goodness of fit of the model. These results show that variability of individuals' opinions across the metropolitan rings is largely explained by the individual-level variables. Consequently, the metropolitan ring level has been removed from the final specification of the multilevel model (indicated in Table 8-7 with italics), leaving random intercepts at the municipal area level as the only random effect in Model 1.

After confirming the presence of spatial heterogeneity in the data at the municipal level, the analysis also tested the potential presence of spatial autocorrelation of the random intercepts previously calculated. To that end, Moran's I statistical test was performed, which confirmed that the random intercepts are capturing spatial effects (see Table 8-7). In order to explain these effects, geographical variables, namely population density and land-use mix of the individuals' municipal area of residence, have been incorporated in Model 2 (for more details, see Section 3.3). Other geographical variables capturing public transport supply were removed from the analysis due to collinearity problems with land-use entropy. As can be observed in Table 8-7, both population density and land-use entropy have a positive effect on individuals' expected willingness to give up private car ownership in the future as a consequence of shared mobility provision, which is in line with previous contributions (Clewlow, 2016; Mishra et al., 2015). These results also reflect the higher private car dependency and car use in less densely populated areas concluded by Bassolas et al. (2019). In addition, the introduction of these two variables leads to a remarkable loss of statistical significance of the variance of intercepts across municipal areas and the disappearance of spatial autocorrelation across random intercepts. This ultimately means that the built environment characteristics capture much of the geographical variability previously observed at the municipal level, which is supported by the lack of significance of the Moran's I statistical test for the random intercepts in Model 2. For illustrative purposes, the spatial distribution of random intercepts calculated in Models 1 and 2 have been graphically represented in Appendix 8-C..

Table 8-7: Modelling results for the random-effects and geographical variables at the municipal area level

	Model 1	Model 2
MUNICIPAL AREA VARIABLES	Coeff. (Std. Error)	Coeff. (Std. Error)
Land use entropy	n/a	0.463*** (0.021)
Population density (1,000 inhabitants/km2)	n/a	0.095*** (0.149)
RANDOM INTERCEPTS	Var (Std. Error)	Var (Std. Error)
Metropolitan ring	4.01e-22 (3.95e-10)	n/a
Municipal area	0.009 (0.004)	0.004 (0.003)
GOODNESS OF FIT		
Log-Likelihood	-22,775.64	-22,765.57
Log-Likelihood Ratio Test	10.36 (p-value = 0.001)	3.21 (p-value = 0.037)
SPATIAL AUTOCORRELATION		
Moran's I for the level 1 random intercept	3.177	0.272
p-value	0.001	0.393

The analysis also explores potential spatial heterogeneity in the impact of individual-level variables on the expected need to own a vehicle in the future across municipal areas. To this end, random slopes for some of the most relevant explanatory factors (e.g. current car ownership, private car and public transport frequency of use, etc.) were added in the modelling specification. Unfortunately, the variance was not found statistically significant for the tested variables. Nevertheless, in order to further explore the spatial heterogeneity in the effect of some explanatory variables under study, the AMEs (Average Marginal Effects) at the municipal level have been computed for four relevant variables: car ownership level, private car use, teleworking regime and use of shared micromobility.

Figure 8-1a shows the AMEs of owning 2 or more cars on the probability of agreeing with the given statement. In the figure it can be observed that the districts that conform the centre of Madrid display a darker color, which means that people living in these areas and owning two or more cars are less likely to disagree with the statement regarding the possibility of not needing a private car in the future. Therefore, these individuals would be potentially more inclined towards future car independence. It is noteworthy that many of the municipalities located in the outermost ring also display low AMEs, which might hint towards a high potential of shared mobility to reduce the number of cars in the household also in sub-urban and rural areas. As for the effect of the variable capturing private car use (Figure 8-1b), it seems to be more homogeneously distributed throughout the Region of Madrid, although again with some rather low AMEs among the more peripheral municipalities. Thus, frequent car users living in rural areas are more prone to car-independent behaviour than frequent users living in municipalities around the city of Madrid.

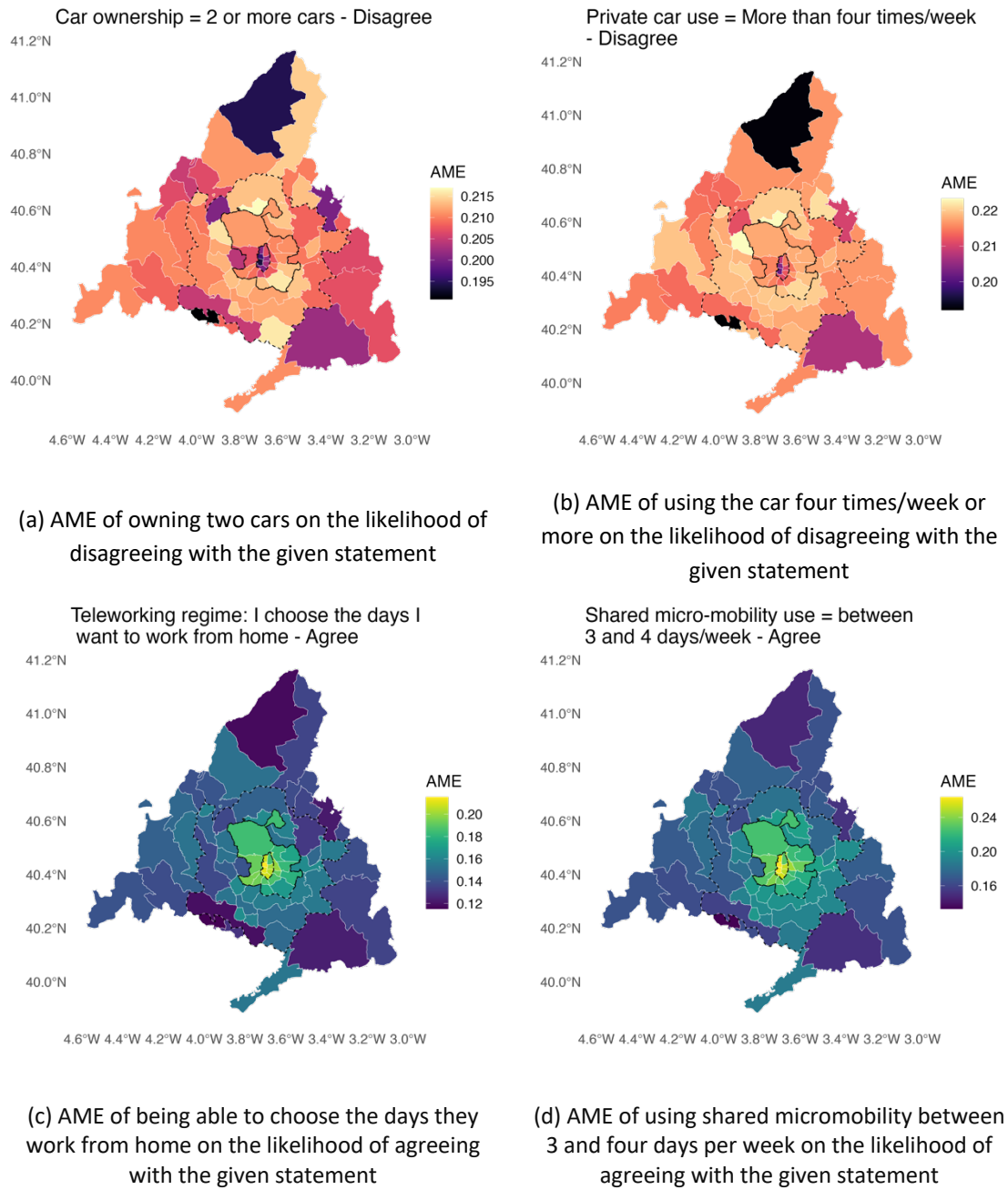


Figure 8-1: AME by municipal area for some relevant explanatory variables

Figure 8-1c shows the geographical distribution of the AMEs on the probability of considering giving up vehicle ownership as a feasible option for the variable capturing whether the individual enjoys a fully flexible teleworking regime. It can be observed that the effect of flexible teleworking on the expected feasibility of giving up car ownership greatly varies throughout the region. The municipality of Madrid, an especially its city centre, shows very high AMEs that rapidly decrease as we move further away. This might be due to the fact that, even if individuals commute less frequently, those who bear longer commuting distances

(such as workers living in the periphery often do) may be less likely to believe they could give up private car ownership in the future. Finally, Figure 8-1d shows the effect of using shared micromobility (bikes or e-scooters) on the probability of agreeing with the statement. As can be observed, AMEs show a very similar distribution to the ones estimated for teleworking. Nevertheless, the declining effect of the use of shared micromobility seems to be rather gradual, with municipalities around Madrid displaying reasonably high AMEs even if no shared vehicles can be found in most of them.

6. Discussion and policy recommendations

The analysis of the survey together with the interpretation of the modelling results allow us to point out some relevant findings regarding the potential of shared mobility to reduce vehicle ownership in big cities and their surroundings, where a variety of shared mobility services are rapidly expanding.

First, the preliminary analysis of the sample suggests a high potential of shared mobility to reduce motorisation rates, since around 25% of the whole sample agreed that owning a car will not be needed in the future, given the increasing supply of this kind of services. This percentage rose to 42% among car-less individuals, suggesting that shared mobility can be more effective preventing individuals living in car-less household from purchasing a car than leading car owners to relinquish them. This idea is confirmed by the modelling results, which indicate that the number of cars in the household decreases the probability of considering that the ownership of a car will no longer be a necessity in the future.

Additionally, it can be concluded that the implementation of flexible teleworking arrangements can further support the reduction of private car dependency, as those who enjoy this kind of benefits are more likely to see shared mobility as a convenient option to substitute car ownership in the future. This suggests that the combination of policy instruments that reduce travel demand with policies that encourage modal shift for the remaining trips can be especially successful reducing vehicle ownership. In this regard, the role of employers promoting sustainable transport practices among their employees, e.g. by implementing or extending their teleworking schemes and providing vouchers for public transport and/or shared mobility for travel-related and commuting trips, could be crucial.

It is especially relevant to mention that the adoption of carsharing or moped-sharing has been observed to moderate the perceived private car dependency of car owners and intensive car users, who are the most reluctant groups to believe they could give up car ownership in the future. This shows that encouraging car dependent individuals to adopt this kind of shared mobility services can significantly reduce their attachment to cars, potentially facilitating a transition to a less car dependent mobility. At this point, it should be mentioned that even if shared cars and private cars are in broad terms the same mode, their environmental and social impacts differ substantially (Yoshizawa et al., 2023, Martin & Shaheen, 2016). Apart from the different advantages of shared vehicles, regarding a higher utilisation rate, lower life cycle-emissions or better air quality that were mentioned in the introduction, the non-intensive usage of carsharing as a natural element of shared mobility ecosystem can hardly be considered a car dependent behaviour. It is unrealistic to assume that individuals can completely stop using cars, since there are some activities (such as doing the groceries, giving rides to children or persons with reduced mobility or carrying heavy goods) that specifically require the use of a car. However, the usage of cars could be limited to cases in which it is actually the best option and avoided when another mode is a cheaper and more sustainable alternative. We argue that this way of using cars is considerably more likely to occur if individuals do not own a private car.

Additionally, these findings are reinforced by the positive effect of shared micromobility usage on the perception of being able to live without a car in the future. Taken together these results would allow to conclude that the use of shared mobility can indeed reduce the perception of needing to own a private car in the future. In this regard, combining an appropriate provision of shared mobility, with car circulation restrictions, such as road pricing and Low Emissions Zones, that force individuals to seek alternative modes (e.g, shared mobility) can be especially effective reducing car dependency.

Considering the spatial analysis, the AMEs allow to conclude that intensive car users and owners of two or more cars who live in the city centre are less reluctant to give up the private vehicle in the future, than car dependent individuals living outside of Madrid. This is likely a consequence of the higher supply of alternative mobility options (public transport and shared mobility) in city centres and hints towards a significant potential incidence of shared mobility on car ownership in areas where the negative effects of car ownership and use are especially

problematic (i.e., lack of public space for active modes or high levels of air pollution) and the potential of deploying shared mobility services is bigger.

However, our study also shows that a non-negligible share of residents in the sub-urban areas of the region believe they would not need to own a car in the future given an increased supply of shared mobility services (see Figure 9-2), which suggests a remarkable potential of shared mobility to substitute private vehicles in these areas. Although this expansion could be hindered by the low cost-effectiveness of shared mobility services in less densely populated areas, this problem could be mitigated by a better connection of shared mobility with the public transport system, along with a strategical design of operational areas.

7. Conclusions, limitations and further research

This work has explored how shared mobility might impact the perception of individuals -either users or not of this kind of services- on their need to own a car in the future provided the increasing supply of shared services in urban areas and its surroundings. The analysis was conducted for the case study of the Region of Madrid (Spain) and focused on understanding the different variables explaining the impact of shared mobility on the respondents' perceived dependency on private cars. In this respect, building a model that simultaneously accounts for both individual preferences and spatial effects adds value to the literature by exploring how the effect of shared mobility on car ownership varies across segments of the population and geographic areas. Given the rapid expansion of shared mobility beyond the city centre, understanding the impact of fleet expansion to sub-urban areas, could be key to exploit its potential to reduce car ownership levels.

The analysis results suggest that shared mobility has potential to reduce private car ownership in the future, being particularly effective in preventing individuals living in car-free households from acquiring one. Remarkably, the analysis has also shown that encouraging individuals to adopt shared mobility can significantly reduce their perceived need to keep the property of a car. Even among highly car dependent individuals, the adoption of carsharing or moped-sharing significantly reduces their perception on a private car being a necessity in the future. Furthermore, the effect of shared mobility on reducing car dependency is strengthened when it is accompanied by other measures such as promoting flexible teleworking.

Even though the study has some limitations, it can be used as a starting point for further research to explore elements not covered here. First, while this article explores the long-term potential of shared mobility understood as a system, in car ownership reductions, further studies should study this phenomenon using revealed information. Second, it would be valuable to explore the impact of additional latent variables so as to capture e.g. the concept of "car pride". Such variables could account for the positive emotions that some individuals experience when owning and driving cars, which extends beyond the mere mobility needs. Thus, the potential impact of shared mobility on the willingness of these individuals to relinquish car ownership would be more accurately assessed. And third, while this research confirms that the spatial aspects of urban mobility do influence the uptake of share mobility, incorporating more detailed geographical variables, such as household accessibility to public transportation or proximity to retail establishments or leisure activities could potentially improve the understanding of causality. A more disaggregated analysis of the role of the built-environment on car ownership reductions due to the availability of shared mobility systems would allow to further explain some of the spatial trends that were observed in this work.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

EU disclaimer

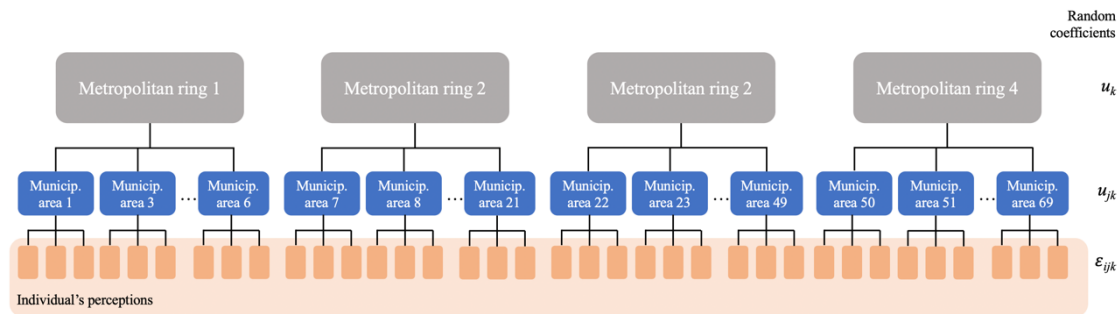
The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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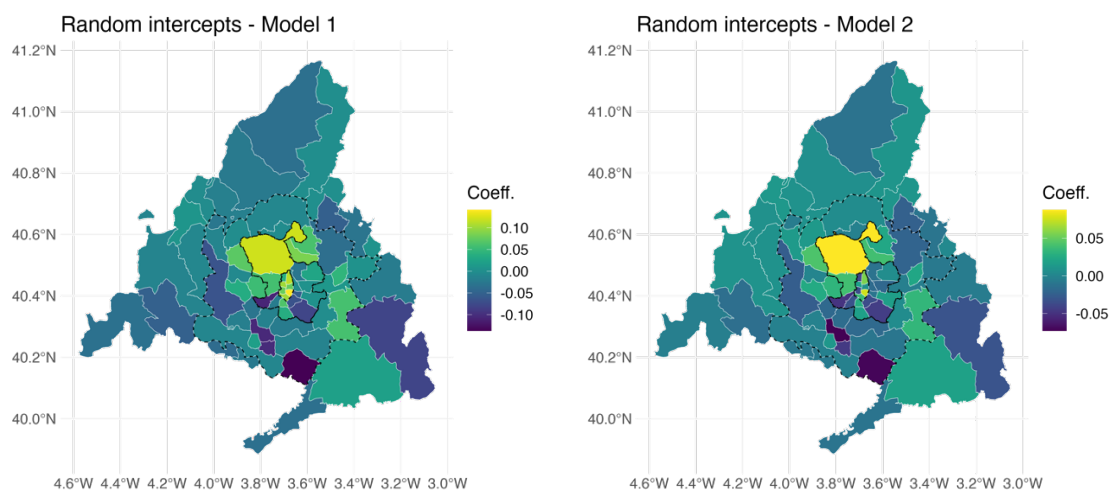
Appendix 8-A: Hierarchical structure of the multilevel model



Appendix 8-B: Summary statistic of the two geographical levels

Group variable	Number of groups	Observations per group		
		Min	Average	Max
Metropolitan ring	4	2,335	3,916	4,744
Municipal area	69	94	227	755

Appendix 8-C: Graphical representation of the random intercepts for Model 1 and Model 2



8.2. Analysing individuals' use of moped-sharing and their perception about future private car dependency

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Abstract

Moped-scooters are one of the latest services coming into the shared mobility ecosystem, which is why scientific contributions devoted to this actor are still scarce. This research explores two main questions. First, it analyses the determinants of the frequency of use of e-moped-sharing among adopters of these services. Second, it examines whether the use of e-moped-sharing may affect the individuals' perspective of the need to own a private vehicle in the future. To achieve this goal, we conducted a survey campaign in the four main cities of Spain (Madrid, Barcelona, Valencia and Seville) which gathered 3897 valid responses. This data was employed to build a Generalised Structural Equations Model that accounts for the influence of a variety of factors, including socio-economic characteristics, stated travel behaviour and psychological preferences of the individuals. The results show that the frequency of use of electric shared mopeds is higher among wealthier younger individuals and residents in the city centre. The modelling concludes that more frequent use of shared electric mopeds is negatively correlated with the belief that private vehicles will remain a necessity in the future. This effect seems to be more pronounced among high-income groups and those that combine e-moped-sharing with other shared services.

1. Introduction

Climate change, drastic levels of air pollution and increasing concentration of the population in urban areas are leaving policy makers no option but to transform car-centric cities and promote the use of more efficient means of transport (UITP, 2021). Meanwhile, three main revolutions —shared mobility, vehicle electrification and automation— are turning the urban transportation landscape inside out (Fulton, 2018). Additionally, the rise of mobile applications to plan and manage mobility as well as the expansion of telematic activities and remote working are driving the transition to an increasingly virtual mobility (Ozbilen et al, 2021; Mouratidis et al., 2021). In the middle of this transition, the rapid and wide expansion of shared mobility services is a reality that is increasingly changing travel behaviour in urban areas. Shared mobility is an innovative mobility service that allows users to have on-demand short-term access to transport modes through the utilisation of mobile apps and without the intervention of any intermediary (Invers, 2022; Shaheen et al., 2015). The potential of shared mobility to reduce private car ownership and use, improve the accessibility to public transport systems, achieve a more efficient use of public space and improve air quality in urban areas is undeniable (Baek et al., 2021; Shaheen & Cohen, 2018). Nevertheless, when putting it into practice, some relevant negative effects have also been observed. For instance, some studies point out a significant substitution of public transport and walking trips (Liao & Correia, 2020), concerns for the safety of both riders and pedestrians when shared mobility is not adequately regulated (Badeau et al., 2019; Maiti et al., 2022) or conflicts regarding the parking of shared vehicles on sidewalks as they reduce city walkability (Brown et al., 2020; Gössling, 2020).

Moped scooters are one of the latest options that have been incorporated into the shared mobility ecosystem. They are in between cars and micromobility vehicles (bikes, kick-scooters). On the one hand, they circulate on the road and can reach speeds that are similar to those of cars in urban centres. On the other hand, they occupy significantly less public space, barely generate noise pollution as they are electric and consume less energy than electric cars both in the operational phase and in their whole life cycle (Schelte et al., 2021). Like to other shared mobility services, shared-mopeds are subjected to the debate on whether their net effect on the sustainability of urban transport is positive or negative. This is in addition to the continued growth of this shared mode in the past few years since its initial expansion. In 2021, 87 different operators managed moped-sharing services (MSS from now on) in 175 cities worldwide. Notably, Spain is one of the main hotspots for this kind of services, with Madrid and Barcelona being two of the top three cities with the largest fleets in Europe. Overall, Spain has the second-largest fleet of shared-mopeds worldwide (Invers, 2022).

In contrast to the increasing penetration of MSS around the world, the number of scientific contributions devoted to this new actor in urban mobility is still scarce. Particularly, further analysis is needed to understand the adoption and usage patterns of this shared mode in order to develop effective regulations and governance frameworks that maximize its environmental and social potential. For instance, it should be further explored the extent to which the large-scale deployment of shared-mopeds fleets can affect individuals' preferences and long-term mobility behaviour in urban areas (e.g., private vehicle ownership and use).

In this regard, this paper aims to address two main research questions: i) identify the explanatory factors that influence the frequency of use of electric shared-mopeds among individuals who already use these services; and ii) explore whether the use of MSS may affect the perception of individuals regarding their expected need to own a private vehicle in the future. To that end, this paper develops a Generalised Structural Equations Model (GSEM, from now on) based on the information collected from an extensive survey campaign conducted among electric moped-sharing users in Spain. The model controls for the potential influence of individuals' psychological preferences, together with other traditional explanatory factors such as individual and household socio-demographics, stated travel behaviour and built-environment characteristics. The analysis is conducted for the case of Spain, the country with the second-largest fleet of shared-mopeds worldwide after Taiwan.

After this introductory section, this paper is structured as follows. Section 2 reviews the existing literature for the different shared mobility services, putting special attention on research works dealing with MSS. Section 3 includes a brief description of the case study, as well as the data employed for this research. Section 4 presents the methodology and structure of the model that has been proposed, together with the factor analysis employed to build the latent psychological variables. Section 5 includes the modelling results for the GSEM approach and compares them with previous findings in the scientific literature. Section 6 discusses the results previously exhibited with the aim of drawing conclusions and making policy recommendations. Finally, Section 7 outlines the main contributions and limitations of this paper and suggests avenues for further research.

2. Literature review

The literature devoted to shared mobility has grown exponentially in the past few years in parallel to the advent of these services in many cities around the world. Existing research works address many different aspects of these new urban mobility forms. For instance, a first group of contributions covers the assessment of the social, economic and environmental impacts of shared mobility implementation (Wortmann et al., 2021; Baptista et al., 2014).

Other authors aim to understand the spatiotemporal dynamics of the use of this type of services (Arias-Molinares et al., 2021; Böcker et al., 2020; Hu et al., 2021). An alternative approach to the topic, which is the one followed in this paper, focuses on characterizing the user profiles and identifying the factors driving the adoption and frequency of use of shared mobility services (Blazanin et al., 2022; Efthymiou et al., 2013; Lee et al., 2021). Unlike other shared mobility services, research works dealing with shared moped scooters are still relatively scarce, as the cities where shared mopeds are available are not as numerous as those with e.g., shared kick scooters or shared bikes. Hereafter, we review all the existing works, to the best of the authors' knowledge, related to moped sharing.

Wortmann et al. (2021) focused on the potential of moped sharing to substitute private cars in meeting mobility demand in the city of Berlin (Germany). Their findings would indicate that as the fleet of shared mopeds grows, a larger amount of car trips could be replaced, but fleet occupation rates gradually decrease. Bach et al. (2023a) compared regulatory frameworks for mopeds in different EU cities through surveys with experts, concluding that the preferred scenario for stakeholders is to avoid limitations to the number of licenses or operators and achieve efficient management of the service by close dialogue between public institutions and private operators. With a similar approach, Méndez-Manjón et al. (2021) provided a comparison of the characteristics of the different services offered in Spanish cities. Through a life-cycle assessment, Schelte et al. (2021) provide interesting insights on the effect of shared-mopeds fleets on carbon emissions. Their work concludes that the volume of greenhouse emissions through the entire life cycle of a shared moped, when managed efficiently, is comparable to that of public transport vehicles. Life-cycle assessments were also performed by de Bortoli (2021), who compared moped-sharing services and their private equivalents and by Felipe-Falgas et al. (2022), who assessed the environmental performance of three shared mobility modes, including moped-sharing.

An important share of research works dealing with MSS analyses the spatial distribution and spatiotemporal dynamics of these services. For instance, Arias-Molinares et al. (2021) conducted a spatiotemporal analysis by exploiting origin-destination data of electric shared-mopeds from seven Spanish cities. City-level attributes such as land-use distribution and average neighbourhood income were found to have a significant impact on the dynamics of use. They also identified a strong seasonality in the use of MSS. More recently, Arias-Molinares et al. (2022) used GPS records for bike-sharing, kick-scooter-sharing and moped-sharing in Madrid to study how the COVID-19 pandemic affected the use of these services and their relationships with land use. Interestingly, they found that shared mobility services have been far more resilient than public transport in the context of the pandemic. Additionally, MSS are

the preferred shared mode during the morning peak hours and they seem to better maintain demand levels during vacations compared to other transport services. Similarly, Fiorini et al. (2022) explored the influence of built-environment characteristics on moped-sharing flows across the city of Milan (Italy). From a different perspective, Bach et al. (2023b) built a model to predict the probability of each cadastral parcel of the city of Barcelona (Spain) being served by MSS. Their findings point out that MSS are still far from being a net contributor to transportation justice and spatial equity. In addition, Pérez-Fernández et al. (2021) evaluated the impact of determining suitable parking places for shared-mopeds on the efficiency of the service.

The most interesting set of contributions for the purpose of this research is the one that assesses MSS users' characteristics and preferences. The work by Aguilera-García et al. (2020) employed a generalised ordered logit to model the adoption of electric moped-sharing in major Spanish urban areas, using a survey carried out in 2018 that collected 430 responses. Their results indicate that young male adults are in general more likely to use these services, as well as students and individuals with university education. It is also noted an increased adoption of moped sharing among middle-aged adults in Spain. Using the same survey, Aguilera-García et al. (2021) conducted an exhaustive descriptive analysis of usage patterns and perceptions of moped-sharing users. Their findings reinforced that the use of these services is more frequent among young adults, males, well-educated individuals and city centre residents. Higher levels of mobility were also found to have a positive effect on the frequency of use of electric shared mopeds. In the same line, Gilibert & Weymar (2022) confirm previous findings regarding the profile of MSS users by carrying out a survey among 210 users of these services in Barcelona (Spain) in 2020. It also shows that moped-sharing users are more likely to use public transport than non-users, but they are unlikely to combine moped-sharing for multimodal trips. The conclusions by Bartkowiak et al. (2021) for the case of Poland are similar to those obtained in previous contributions regarding users' socio-economic characteristics. They also highlight the convenience of the service and the possibility of avoiding parking costs as the main reasons behind the use of electric shared mopeds.

Moreover, Loudon et al. (2023) conducted a Panel Mixed Logit model to explore the mode choices between private cars, bikes and shared mopeds, based a survey with 191 valid responses in the Netherlands. The results showed that it is possible to substitute the private car by shared mopeds under specific regulatory frameworks and pricing schemes. A series of discrete choice models were also employed by van Kuijk et al. (2022) to analyse individuals' willingness to use different shared mobility services—including shared-mopeds—as first/last mile option to reach public transport, based on a survey campaign with a total of 499

respondents. Finally, the works of Eccarius & Lu (2020), Van Veldhoven et al. (2022) and Chen et al. (2021) proposed Structural Equations Models based on different behavioural theories to explore how latent constructs impact the individual's intention to use moped sharing. These three works utilized sample sizes under 500 individuals.

This paper builds upon the results obtained in previous research works reviewed above and provides some innovative aspects. Firstly, as has been shown above, sample sizes employed so far in the scientific literature on shared mopeds from a travel behaviour perspective are somewhat small. Taking advantage of larger samples, as this paper does, allows for calibrating more complex econometric models and obtaining more robust conclusions. Strongly linked to this point, this paper explores the impact of latent psychological variables on individuals' frequency of use of shared-moped and the consequent potential reduction in car ownership. Previous works considering such variables to analyse intended behaviour, found that they play an important role in the willingness to adopt moped-sharing services. Therefore, understanding how they affect stated choices regarding frequency of use can be a valuable contribution to the literature. Third, previous research has analysed the extent to which car ownership may affect moped-sharing adoption and frequency of use. In that respect, Loudon et al. (2023) concluded that a substitution of private car by shared-mopeds is possible under certain circumstances, but to date it has not been approached how the usage of moped-sharing may affect future vehicle decisions (through e.g. individuals' perception of the necessity to own a private vehicle in the future). This point is particularly relevant in a post-COVID-19 scenario, given the current preferences of individuals towards private transport modes, as noted by Vega-Gonzalo et al. (2023). Finally, it is needed to provide an updated overview of the usage of MSS in Spain in the post-pandemic era, which has been observed to significantly affect the use of shared mobility services to cover mobility needs in urban areas (Awad-Núñez et al., 2021; Rahimi et al., 2021).

3. Case study and data collection: moped-sharing users in four Spanish cities

3.1. Moped sharing in Spain

Moped sharing firstly appeared in Spain in the city of Barcelona as of 2013. This service had an almost negligible presence and demand until around 2018, when it spread out throughout the country, not only inside big cities (Madrid, Barcelona, Valencia, etc.) but also in medium-sized cities (e.g., Murcia, Córdoba, etc.). Although some operators have recently ceased their operation in medium-sized cities due to the effects of the COVID-19 pandemic, Spain, with

around 18,000 vehicles in operation, is currently the nation with the second-largest fleet of shared-mopeds worldwide after Taiwan, (Invers, 2022).

Moped-sharing operators in Spain provide standard electric mopeds, whose batteries can be switched without moving the vehicle. These mopeds are operated in a free-floating system and have capacity for one or two passengers. MSS users book the service through a mobile application that allows them to know the location of available mopeds nearby them. Riding this kind of vehicle is allowed in Spain for all those who have held a car driving license for more than three years or for those who own a motorbike/moped driving license.

Acciona Movilidad is currently one of the most important operators of MSS services in Spain. They operate fleets of electric shared mopeds in Madrid, Barcelona, Valencia and Seville, and interestingly its technological platform allows the use of the service in an integrated way in all these four cities. Although the mopeds can be used in the whole metropolitan area of these cities, trips can only start and end in defined areas, which are referred to as service areas. Registration is free for the user and the price of the service is established on a per-minute basis depending on the speed of the vehicle. MSS users have the option of paying for the service each time they use it (prices range between 0,33 and 0,44 €/minute) or buying different types of subscriptions, which provide reduced prices (prices range between 0,19 and 0,26 €/minute). Additionally, it is worth noting that, when the service was re-started after the COVID-19 lockdowns, sanitary kits were provided with some wipes and hydro-alcoholic gel to clean the handlebar, the helmet and the sit. The governance and regulation of MSS differs across the four cities in which the company operates. In Barcelona and Valencia there is no limit to the number of operators, but the number of licenses is capped at 7,000 and 2,000, respectively. In contrast, in Seville there is no limit to the fleet of shared mopeds, but the number of service operators has been restricted to two by the local government. Finally, in Madrid there are no limitations to the supply of these services and its regulation is based on a close collaboration between the operators and the local institutions (Bach et al., 2023a).

3.2. Data collection: a survey campaign among MSS users

This paper employs data collected from a survey campaign targeted at users of *Acciona* electric shared-mopeds during March and April 2022. The dissemination of the survey was done through personal emails to all the registered users of the company, so all respondents in the sample have already adopted moped-sharing. The geographical coverage includes the four Spanish cities where the operator offers its services, which are also the biggest cities in the country: Madrid, Barcelona, Valencia and Seville. A total of 3,897 valid responses were collected. The questionnaire gathers information regarding four main areas: i) socio-economic

characteristics of the individuals and their households (e.g., gender, level of education, annual household income and structure, etc.); ii) travel and mobility-related variables (e.g, private vehicle availability, number of trips in weekdays and non-weekdays, frequency of use of moped-sharing, frequency of use of alternative shared modes available such as bike-sharing and kick-scooter-sharing, etc.); iii) detailed information on the last trip made on a shared moped; and iv) personal attitude and lifestyle preferences. This last aspect was captured through the inclusion of a set of eighteen attitudinal indicators following a five-point Likert scale. Through the indicators, the respondents could rate their level of agreement with several statements related to different psychological attitudes, namely: environmental awareness, comfortability with the use of technology in their daily life, willingness to share and subjective fear of contagion with COVID-19. Further input concerning the latent constructs is provided in Section 4.

Table 8-8 displays the distribution of the first two groups of variables in the sample. Since this survey campaign was only targeted to users of moped sharing, the sample does not necessarily provide an accurate representation of the global population of Spanish cities.

The distribution of the sample shows an unbalanced profile of shared-moped users in terms of gender and education, with 85.5% of respondents self-identifying as men and 69.5% having university studies. According to INE (2021), around 40% of Spanish citizens had this level of education in 2021. The sample distribution is coherent with the analysis of moped-sharing adoption previously done in Spain by Aguilera-García et al. (2020), who observed that the most frequent socio-economic profile for MSS users is that of a middle-aged, educated and full-time employed man. Noticeably, respondents in our sample are evenly distributed across the income segments. Regarding the travel-related variables, it is worth mentioning that the percentage of households in the sample who have access to at least a car (85.1%) is ten points higher than the average of this rate among the Spanish population (74.4%), according to the latest data available. Additionally, almost half of the respondents in the sample (42.7%) own a private moped, suggesting that the shared and private versions of this mode complement each other.

Most of the adopters of electric shared-mopeds reported to use these services on a rarely basis (35.9%) or less than once a week (40.9%), so they can be considered infrequent or occasional users. Only 3.7% of respondents declared using moped-sharing on a daily basis. This distribution of the frequency of use of MSS among adopters is in line with previous studies on other shared modes (see e.g Aguilera-García et al., 2021; Arias-Molinares et al., 2021; Gilibert & Weymar, 2022). We can observe that the adoption of kick-scooter- sharing and bike-sharing among MSS users is rather low. According to the data collected, only 11.2% and 19.9%

of respondents reported to have ever used kick-scooter-sharing and bike-sharing, respectively. Interestingly, we should note that 53.5% of the sample considers that owning a private vehicle will no longer be necessary in the future given the increasing provision of shared mobility services.

Table 8-8: Sample distribution for the socio-economic and travel-related variables.

SOCIO-ECONOMIC VARIABLES			TRAVEL RELATED VARIABLES		
Variables	Categories	Relative freq. (n = 3,897)	Variables	Categories	Relative freq. (n = 3,897)
Gender	Male	85.5%	Public transport card	No	41.4%
	Female	14.5%		Multi-personal reloadable card	47.5%
Age	18-24	4.7%		Monthly/Annual season ticket	11.1%
	25-34	28.7%	Vehicle ownership	Regular access to a car	85.1%
	35-44	30.8%		Regular access to a moped/motorcycle	42.7%
	45-54	26.7%		Regular access to a e-scooter	9.6%
	55-64	8.0%		Regular access to a bike	38.3%
	65 or above	1.1%		Regular access to a van	5.8%
Education	Non university	30.5%	Weekday mobility	Zero trip	13.3%
	University	69.5%		1 - 2 trips	57.0%
Annual income	Less than 21,000 €	16.0%		3 or more trips	29.7%
	21,000 to 29,999 €	11.5%	Non-weekday mobility	Zero trip	14.3%
	30,000 to 40,999 €	12.9%		1 to 2 trips	45.0%
	41,000 to 59,999 €	13.3%		3 or more trips	40.7%
	60,000 € or more	13.0%	Frequency of use of moped sharing	Infrequent user (rarely)	35.9%
	Without own income	1.9%		Occasional (less than once a week)	40.9%
Occupation	DN/DWA	31.4%		Weekly (1-4 times a week)	19.5%
	Employed	79.0%		Daily (5 or more times a week)	3.7%
	Student	3.2%	Need to own a vehicle in the future	It will remain a necessity	46.5%
	Part-time employee/student	11.8%		It will no longer be necessary	53.5%
	Retired	2.4%	Residence within a MSS service area	No	37.2%
	Other (homemaker. unemployed)	3.6%		Yes	62.8%
Household size	1 person	12.5%	Frequency of use of e-scooter sharing	Never	88.8%
	2 people	28.4%		Infrequent user (rarely)	8.4%
	3 people	26.7%		Occasional (less than once a week)	2.3%
	4 people or more	32.4%		Weekly (1-4 times a week)	0.4%
Minor children in the household	No minor children	80.1%		Daily (5 or more times a week)	0.1%
	1 minor	16.1%	Frequency of use of bikesharing	Never	81.1%
	2 minors or more	3.8%		Infrequent user (rarely)	9.8%
Residence location	City centre	32.1%		Occasional (less than once a week)	5.1%
	Municipal area	49.9%		Weekly (1-4 times a week)	2.9%
	Metropolitan area	18.0%		Daily (5 or more times a week)	1.1%
City of residence	Seville	29.7%			
	Valencia	13.8%			
	Barcelona	17.8%			
	Madrid	38.7%			

3.3. Zip code level variables

Respondents were asked to provide the zip code of their residence in order to have approximate information on the characteristics of the zone where they live. The users of *Acciona MSS* live not only in the major cities under study but also in outlying towns within their metropolitan areas, so the zip codes represent an appropriate spatial level to capture the characteristics of the built environment of the residential location. Given that fact, zip code level variables have been incorporated into the model to capture the land-use mix (percentage of the zip code surface dedicated to collective housing, single-family housing, parking, commercial, industrial and offices) and the provision of public transport (density of urban and interurban bus stops and density of stations of rail services: metro, tram and sub-urban train). Spatial variables have been calculated for each zip-code division in the region where the cities are located. The coordinates of the public transport infrastructures have been obtained from the official open data platforms of each of the four regions and/or cities and thereafter, spatially intersected with the geographical specification of the zip codes. On the other hand, the land-use variables have been directly downloaded at the zip-code level from the Urban Real Estate Cadastre Statistics (Anuario Estadístico Catastral, 2022). The mean and the standard deviation of the zip code level variables can be found in Table 8-9. The built-environment variables have been included for the sake of completeness, given that they have been found to play an important role when modelling shared mobility demand (see e.g. Duran-Rodas et al., 2019; Huo et al., 2021; Wang & Chen, 2020).

Table 8-9: Summary statistics of the zip code level variables

ZIP CODE LEVEL VARIABLES	Mean (sd)
Density of urban bus stops (no./km ²)	20.64 (15.8)
Density of metro/tram stations (no./km ²)	1.8 (3.0)
Density of interurban bus stops (no./km ²)	6 (17.1)
Density of sub-urban train stations (no./km ²)	0.16 (0.44)
Density of collective housing area (m ² /km ²)	18.0 (19.8)
Density of single-housing area (m ² /km ²)	105.5 (173.8)
Density of parking area (m ² /km ²)	10.1 (91.6)
Density of commercial area (m ² /km ²)	39.35 (103.1)
Density of industrial area (m ² /km ²)	141.9 (343.5)
Density of offices area (m ² /km ²)	74.0 (117.5)

3.4. Exploratory analysis of the trip-level variables

As mentioned before, respondents reported travel details of their last trip using MSS. Specifically, the questionnaire collected: the purpose and the duration of the trip, the mode with which moped sharing was combined and the mode that would have been used if MSS had not been available (mode substitution). Hereafter, a brief exploratory analysis of this set

of questions has been done, with the sample distribution for the trip-level characteristics displayed in Table 8-10.

The most common trip purpose is leisure (44.1%) followed by commuting (25.1%) and shopping or running personal errands (15.1%). The comparison of these data with the distribution of trip purposes provided by city travel surveys reveals some differences between the general mobility trends and the patterns observed for electric shared-mopeds. For instance, the share of leisure trips is considerably lower for all cities than in the sample (it ranges from 6.0% in Madrid to 19.7% in Seville). For the case of commuting, the opposite is observed, as the share of trips to the workplace or place of study ranges from 39.9% in Seville to 50.0% in Valencia (Ayuntamiento de Sevilla, 2019; CRTM, 2018; IERMB, 2022; Generalitat Valenciana, 2018). This high prevalence of leisure trips is in line with previous research on both shared-mopeds (see e.g., Aguilera-García et al., 2021 for Madrid and Barcelona) and shared kick-scooters (see e.g., McKenzie, 2019 for Washington D.C.).

Regarding trip duration, almost three-quarters of the sample (73.2%) declared that their last trip lasted between 5 and 15 minutes and up to 79% of the respondents did not combine the use of a shared moped with any other transport mode in their last trip. This seems reasonable given that MSS are free-floating services in Spain, so they are well suited to reach the users' final destination without the need to combine with another mode for a last-mile connection.

The sample analysis also shows that electric shared-mopeds mostly substitute public transport (32.7%), private vehicles (23.5%) and walking (17.3%). In addition, only 2% of respondents declared that they would not have made that trip in case moped-sharing had not been available, which ultimately reflects the ubiquitous accessibility provided by the high provision of public transport services in Spanish cities. Interestingly, it can be observed that 40.0% of moped-sharing trips have been captured from more sustainable modes (public transport + walking). All these preliminary results concerning trip-level attributes are to a large extent aligned with previous findings in the field of MSS (Aguilera-García et al., 2021; Arias-Molinares et al., 2021; Gilibert & Weymar, 2022).

Table 8-10: Sample distribution for the characteristics of the last trip using MSS.

Variables	Categories	Relative freq. (n = 3,897)
Purpose of the last trip using MSS	Commuting	25.1%
	Leisure	44.1%
	Shopping or running errands	15.1%
	Work-related trips	5.7%
	Visiting family or friends	6.2%
	Other	4.0%
Estimated duration of the last trip	Less than 5 minutes	3.6%
	5 to 10 minutes	34.6%
	10 to 15 minutes	38.6%
	15 to 20 minutes	16.9%
	20 to 30 minutes	4.6%
	More than 30 minutes	1.7%
Mode with which MSS was combined in the last trip	No combination	78.6%
	Private car or moped	11.6%
	Other shared mobility services	8.2%
	Public transport	1.6%
Mode substitution	Walking	17.3%
	Private vehicle	23.5%
	Taxi or ride-hailing	14.0%
	Other shared mobility services	9.7%
	Public transport	32.7%
	I would not have made the trip	2.0%
	Other	0.8%

In order to explore how trip-level characteristics vary across the different types of MSS users, the distributions of trip purpose and mode substitution have been plotted in Figure 8-2 and Figure 8-3, respectively. Interestingly, shows a direct relationship between the reported frequency of use of MSS and the probability of using them for commuting purposes. For instance, 54.5% of daily users of MSS declared that their last moped-sharing trip was for commuting purposes, while this percentage drops to 22.7% and 19.1% for infrequent and occasional users, respectively. At the same time, those who use electric shared mopeds less often, seem to choose them mostly to carry out leisure trips or to a lesser extent, for shopping or running errands. As can be observed in Figure 8-2, leisure represents 48.2% and 45.5% of the last trip among infrequent and occasional users, but only 21.4% for the case of daily users.

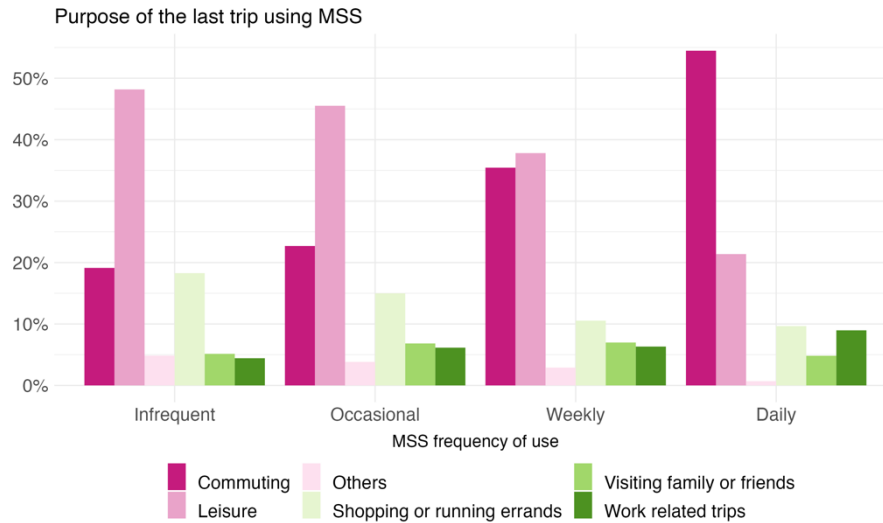


Figure 8-2: Distribution of the purpose of the last trip made by MSS for the different types of users

Regarding the mode substitution for the different user profiles, it can be observed that the more frequently MSS are used, the less likely is that this mode substitutes the private vehicle. As can be observed in Figure 8-3, the percentage of last trips that substituted the private car is around 24% for both infrequent and occasional users, while this percentage is lower (20%) among daily users of moped sharing. Inversely, the probability that electric shared mopeds substitute public transport is higher for daily users (37.9 % of their last trips reported) than for the other profiles. The substitution effect with respect to walking seems to be similar for all types of moped-sharing users.

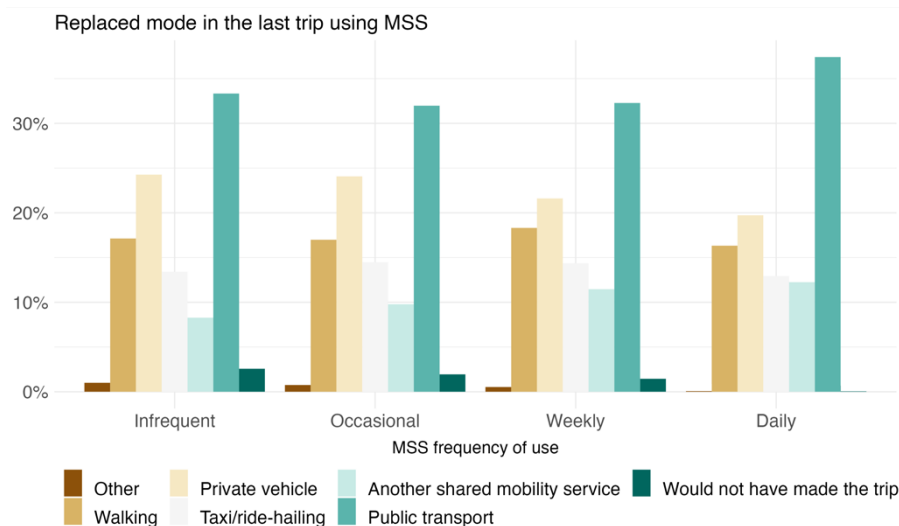


Figure 8-3: Distribution of mode substitution in the last trip made by MSS for the different types of users

4. Methodology: a Generalised Structural Equation Model (GSEM)

A GSEM framework has been chosen as the most suitable methodology for the purpose of this research. This econometric technique, widely used in the field of transport behaviour modelling, allows to simultaneously account for the interrelationships between explanatory variables of a different nature: socio-economic attributes, psychological latent variables and travel behaviour parameters. Interestingly, GSEM incorporates the estimation of the latent variables within the model, also introducing them as determinants of the endogenous variables through indicator variables of the constructs collected in the questionnaire. This leads to a parsimonious joint estimation and dependence structure among all endogenous variables in the model. Thus, it constitutes a valuable tool to investigate drivers of shared mobility adoption and usage, given that travel choices in these modes seem to be noticeably influenced by individuals' beliefs and perceptions as much as by socio-economic characteristics (see e.g., Aguilera-García et al., 2022 for carsharing; or Wang & Chen, 2020 for bike-sharing).

Next, we comment on the overall structure of the modelling adopted, followed by a description of the latent psychological constructs included and modelled in the research.

4.1. Model structure

The GSEM is made up of two main parts. The structural part, also known as SEM, accounts for the relationships between the latent variables and the socio-economic attributes. In the measurement (MEM) part, the influence of the latent constructs and all exogenous explanatory parameters on the outcome (endogenous) variables is estimated. GSEM models generalise traditional SEM models in that they allow the introduction of different types of link functions (logit, Gaussian, gamma, etc.) between the exogenous and endogenous variables. As a result, this makes it possible to model dependent variables other than those of a continuous nature, such as ordinal, nominal or binary responses⁹.

Figure 8-4 shows the overall structure of the model developed in this research, which includes three types of variables:

- **Exogenous variables:** they include i) socio-economic and household attributes; ii) ownership of different types of vehicles (car, moped, e-bike, etc.); iii) stated frequency of use of bike-sharing and kick-scooter-sharing; and iv) zip code variables capturing

⁹ In this study, the GSEM has been implemented using the *gsem* command of the STATA version 17.0 software.

land-use mix and public transport provision, as previously commented in Section 3.2. It is worth mentioning that the city-level variables have been interacted with a binary variable that captures whether the individual lives within the MSS area of the operator or not. This interaction was introduced to control for the potential fact of neighbourhood characteristics having a different effect on MSS usage. The full list of explanatory variables included in the model can be found in Figure 8-4. It should be noted that the model takes into account the covariances between the exogenous variables, with their values being taken as given by the software.

- **Latent variables:** A factor analysis has been implemented to build these latent variables from the indicators included in the survey. These latent variables capture the subjective lifestyle or psychological preferences of the individuals that may affect their travel choices regarding electric shared mopeds.
- **Endogenous variables:** the variables modelled at the individual-level in this research include weekday and non-weekday mobility rates, frequency of use of shared-mopeds and the subjective perception of whether owning a private vehicle would be necessary in the future given the increased provision of shared mobility services. The first three co-endogenous variables follow an ordinal logit specification, while the last variable has been modelled as a binary logit response.

The structure of the GSEM is displayed in Figure 8-4. First, the arrow in the upper part of the Figure 8-4 indicates that the latent variables explain the Likert-scale indicators included in the survey (see Section 3.2 for more details). Second, the latent variables are assumed to be intercorrelated through a covariance term, which is indicated by the two-way arrows that connect them. Third, a set of regressions has been included in the model in which the latent variables are modelled as a function of the socio-economic attributes. This aims to capture the effect that the characteristics of an individual may have on his/her attitude and lifestyle preferences. These sub-models are represented in the figure by the arrow that connects the socio-economic attributes with the latent variables. Third, the latent variables together with all the exogenous variables are introduced as explanatory factors in the sub-models of the four co-endogenous variables.

The causal specification that is displayed in Figure 8-4 is the one for which the best data fit was obtained. This specification considers weekday and weekend mobility rates influencing MSS frequency of use and these three endogenous variables finally impacting the subjective perception of the need to own a private vehicle in the future. In this regard, the authors would like to highlight that this model specification does not assume a direct substitution effect between MSS and the private car. The hypothesis put forward is that the usage of a specific

shared mobility service may affect individuals' perception of the possibility of being able to fulfil their daily mobility needs without the need of a car at a certain point in the future.

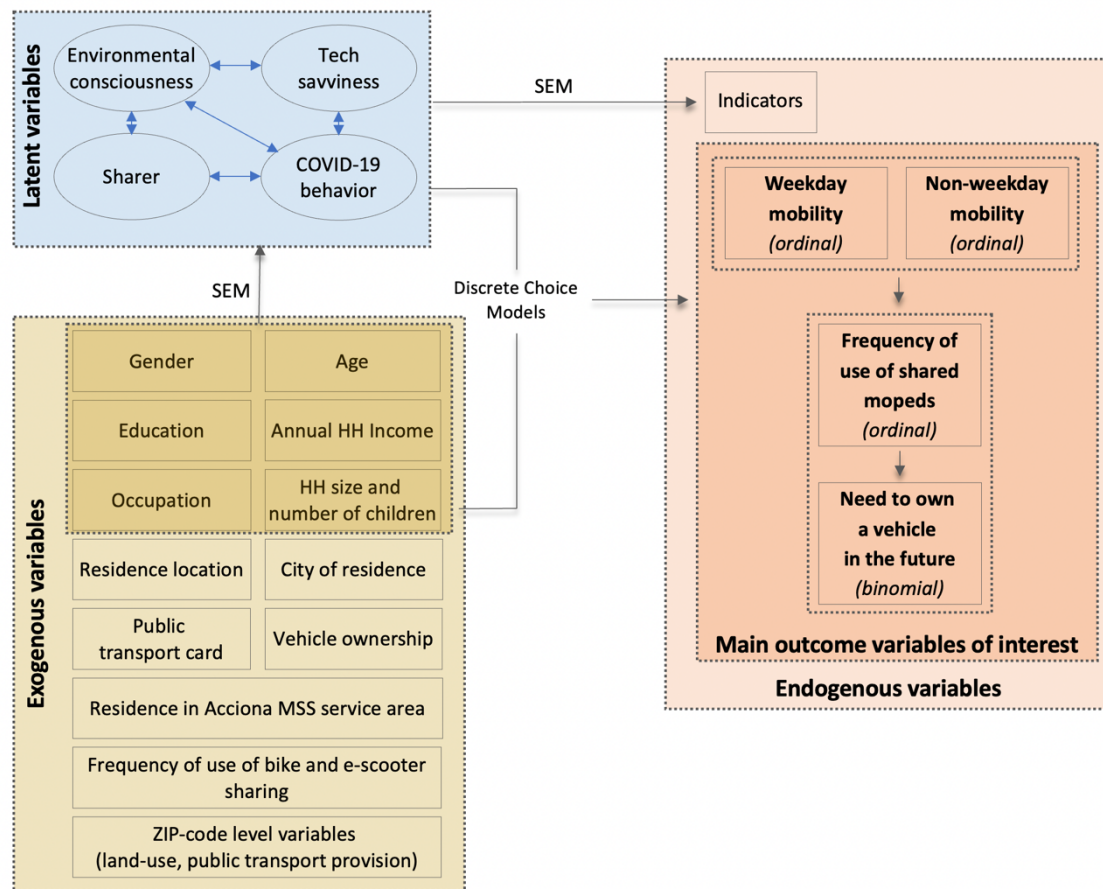


Figure 8-4: Structure of the GSEM

4.2. Building the latent variables: Factor analysis

As mentioned in Section 3, the survey included a set of eighteen 5-point Likert scale indicators that capture personal attitudes and lifestyle preferences of the respondents, which were previously observed to influence the usage of MSS and shared mobility in general (Aguilera-García et al., 2022; Van Veldhoven et al., 2022). The complete list of indicators included in the survey can be found in Appendix 8-E. Factor Analysis has been employed to build latent variables that group related indicators and provide a consistent scale to measure psychological constructs, ultimately affecting individuals' travel-related choices.

First, an Exploratory Factor Analysis (EFA) was applied to gain understanding on the correlation between indicators and put forward a hypothesis regarding the possible latent factors that could be extracted from the sample. This hypothesis was thereafter tested through a Confirmatory Factor Analysis (CFA), which provided the final weights of each indicator for each factor and allowed to obtain information on the goodness-of-fit of the

factorial model later introduced in the GSEM. For a detailed description of both EFA and CFA, the reader is referred to Heck (1998). Next, we describe the intermediate and final results that have been obtained for the factor analysis, as well as the results of the statistical tests carried out to ensure the suitability of this technique for the purpose of this analysis.

The KMO test yields a value of 0.74 which shows that there is a common variance across the indicators included in the study. As for Barlett's test of sphericity, a null p-value was obtained, proving that the covariance matrix is significantly different from the identity matrix. Both tests validate the use of the factor analysis technique for the construction of latent variables based on the indicators included in the survey. Thereafter an EFA was carried out to examine the relationships between indicators and factors. The factor loadings for the attitudinal indicators that were kept in the analysis (factor loadings higher than 0.5) as well as the squared multiple correlation coefficients obtained in the CFA can be found in Table 8-11.

Table 8-11: Results for the Factor Analysis

Latent variable	Attitude statements in the survey	Factor loading (EFA)	Squared multiple correlation
Environmental consciousness	I try to choose environmentally sustainable modes of transport.	0.796	0.608
	I usually recycle the waste at home.	0.697	0.177
	In general, I am willing to pay more for a product whose production process has a lower environmental impact.	0.823	0.521
Tech savviness	I regularly use online tools to ease my daily tasks (banking services, online shopping, e-mail, etc.)	0.775	0.391
	Trying new mobile applications and learning how to use them is easy for me	0.815	0.207
Willingness to share	I regularly use shared economy applications (second-hand clothes applications, Airbnb, Ebay, etc.)	0.844	0.275
	I occasionally buy second-hand items (clothes, furniture, etc.)	0.823	0.633
Preventive COVID-19 infection behaviour	To avoid infection with COVID-19, I have decided to restrict my social activity with acquaintances and leave the house as little as possible.	0.882	0.710
	I avoid crowded places (public transport, gym, shopping centres, etc) due to COVID-19	0.905	0.528
Overall Squared Multiple Correlation			0.989

As can be observed, four factors were extracted and linked with four psychological constructs based on the nature of the indicators associated with each of them. The first factor, named "Environmental consciousness", includes indicators related to the importance given by individuals to environmental sustainability when making consumption decisions. The second factor, "Tech savviness", is associated with indicators that capture the level of comfortability of the respondents with the use of technology. The "Willingness to share" construct is made up of indicators concerning the use of shared economy applications and the purchase of second-

hand items. The last construct, "Preventive COVID-19 infection behaviour", captures the fear of the individuals to be infected by COVID-19 through their tendency to change their behaviour to avoid it.

The latent constructs, that have been proposed based on the EFA results, were subsequently tested using CFA. The confirmatory analysis allows testing whether these factors provide a good representation of the data. The following goodness-of-fit indexes were obtained: Root Mean Square Error of Approximation (RMSEA) = 0.056, Comparative Fit Index (CFI) = 0.956, Tucker Lewis Index (TLI) = 0.925, Standardized Root Mean Square Residual (SRMR) = 0.039, Goodness of fit index (GFI) = 0.9517. According to the recommended cut-offs in previous literature (Akaike, 1987), these values show a good fit of the model and support the validity of the latent constructs as good measures of the unobserved attitudes and beliefs we captured. Additionally, the likelihood ratio test between the final model and the saturated model yields a value of $\chi^2 = 284.1$, which allows to reject the null hypothesis and consider that the final specification of our model fits the data better than the saturated model.

5. Modelling results

This section provides the results obtained from the GSEM calibration to explore individuals' frequency of use of MSS and their subjective perception of the need to own a private vehicle in the future. The regression coefficients that are displayed in Tables 5 and 6 represent the direct effects of the independent variables on the dependent variable. The final specification of the model is the result of a process of testing alternative combinations of explanatory factors. Those variables that were not significant at the 90% level were gradually removed from the model to obtain a more parsimonious specification, since the likelihood-ratio tests proved that they did not improve the goodness-of-fit of the model. This procedure has been widely adopted in the field of transport research (see e.g., Alemi et al., 2018; Aguilera-García et al., 2020). Additionally, some coefficients in the final specification of the model are duplicated, which reflects that two or more categories within a certain variable have been merged¹⁰.

5.1. Structural model: socio-economic determinants of the latent constructs

Table 8-12 displays the results for the regression of the socio-economic variables on the psychological latent constructs (SEM part). The environmental consciousness construct is mainly influenced by gender and age, with females and adults aged between 44 and 65 years

¹⁰ When two or more consecutive categories of a variable were statistically significant only at the 90% level, a Wald test was performed to check whether those categories were significantly different. If the test did not confirm that they were significantly different, these categories were merged.

old showing higher pro-environmental attitudes. These results are in line with previous findings in the field of sociological research (see e.g. Franzen & Vogl, 2013; Sundblad et al., 2007). In Spain, a positive correlation between age and environmental consciousness was also observed by Aguilera-García et al. (2022). As for tech-savviness, according to the model, it increases with income and level of education and, as expected, decreases for older adults (55 years old and above). These relationships have been observed in previous contributions analysing the drivers of technology adoption (Abu-Shanab, 2011; Magotra et al., 2016).

Table 8-12: Modelling results - socio-economic determinants of the latent variables

Variable (<i>Reference</i>)	Environmental consciousness	Tech-savviness	Willingness to share	Preventive COVID-19 infection behaviour
	Coeff. (std. error)	Coeff. (std. error)	Coeff. (std. error)	Coeff. (std. error)
Gender (<i>Male</i>)				
Female	0.150*** (0.034)	0.029** (0.014)	0.088*** (0.026)	--
Age (18-24)				
25-34	-0.147*** (0.030)	--	--	--
35-44	--	--	--	0.164*** (0.038)
45-54	0.060** (0.028)	--	-0.043** (0.021)	0.176*** (0.041)
55-64	0.060** (0.028)	-0.067*** (0.018)	-0.271*** (0.035)	0.253*** (0.059)
65 or more	--	-0.186*** (0.049)	-0.419*** (0.100)	0.253*** (0.059)
Education (<i>Non-university</i>)				
University	--	0.052*** (0.011)	--	-0.120*** (0.033)
Annual HH income (< 21,000 €)				
21,000 to 29,999 €	--	0.045*** (0.016)	0.077*** (0.029)	--
30,000 to 40,999 €	--	0.072*** (0.016)	0.050** (0.021)	-0.076* (0.045)
41,000 to 59,999 €	--	0.071*** (0.016)	0.050** (0.021)	-0.127*** (0.044)
60,000 € or more	--	0.112*** (0.016)	--	-0.232*** (0.046)
Without own income	0.202** (0.088)	--	--	0.248** (0.109)
Occupation (<i>Employed</i>)				
Student	--	--	--	--
Part-time employee/student	--	--	0.051* (0.028)	0.090** (0.046)
Retired	--	--	0.148** (0.067)	0.250** (0.100)
Other (homemaker, unemployed)	--	-0.062*** (0.027)	--	0.137* (0.078)
Household size (<i>1 person</i>)				
2 people	--	--	--	0.086** (0.037)
3 people	--	--	--	0.108*** (0.037)
4 people or more	-0.050* (0.026)	--	--	--
Minor children in the HH (<i>No</i>)				
1 minor	--	--	--	0.095** (0.044)
2 minors or more	-0.139** (0.064)	--	--	--
Constant	0.032 (0.171)	-0.07*** (0.010)	-0.007 (0.015)	-0.075** (0.043)
CORRELATIONS BETWEEN LATENT VARIABLES				
Environmental consciousness	1.000			
Tech-savviness	0.050*** (0.010)	1.000		
Willingness to share	0.204*** (0.023)	0.040*** (0.014)	1.000	
Prevent. COVID-19 behaviour	0.283*** (0.021)	-0.124*** (0.013)	0.069*** (0.016)	1.000

***p≤0.001, **p≤0.050, *p≤0.100

Willingness to share tends to be higher among women and individuals living in middle-income households (21,000 – 59,999 €/year). Reasonably, adults above 45 are less likely to show a sharing behaviour. Previous research works in the field of travel behaviour confirmed that older adults are less likely to adopt services from the sharing economy sector (Aguilera-García et al., 2022; Gomez et al., 2021). Finally, having a preventive COVID-19 behaviour is positively correlated with age, which could be initially expected given that age has been a well-known

risk factor for the disease. Additionally, people living in households with many family members are more likely to be cautious when putting themselves in risky situations regarding the spread of COVID-19, likely due to the fear of transmitting the disease to other members of the family. On the other hand, higher levels of education (university studies) and belonging to middle-high- and high-income households, are associated with a lower COVID-19 preventive behaviour.

5.2. Weekday and non-weekday mobility rates

The results for the weekday and non-weekday mobility rates can be found in Appendix 8-F. Weekday mobility among users of MSS is mainly determined by age and income. Age positively influences the number of weekday trips, with individuals aged above 34 travelling more often. Although old adults move less than younger adults (Metz, 2000), we do not notice that effect in our sample, likely because there are few old adults among adopters of MSS. As for income, the modelling results show that individuals with higher levels of income tend to move less on weekdays, which may be due to e.g. the wider adoption of teleworking among these socio-economic groups, particularly after COVID-19 lockdowns, as noted by López-Soler et al. (2021). Regarding non-weekday mobility, younger and wealthier users of electric shared mopeds make more trips, in contrast to what was observed for weekday mobility.

Concerning the influence of mobility-related variables, we can observe that the ownership of other modes of transport, such as vans, kick-scooters or mopeds, is associated with higher mobility rates both for weekdays and non-weekdays. As seems reasonable, holding a monthly/annual public transport card leads to higher mobility rates on weekdays, since these individuals can enjoy unlimited rides at a fixed or reduced price. No statistically significant differences in mobility rates are found for car ownership, again reflecting the ubiquitous accessibility provided by the high supply of public transport services in major Spanish cities. Finally, we should note that no statistically significant results were found for other explanatory variables such as gender, city of residence or household structure.

5.3. Frequency of use of shared mopeds

This section discusses the modelling results regarding one of the variables of special interest in this research, which is MSS frequency of use. As with other shared mobility services, latent constructs have been shown to play an important role when explaining the use of electric shared mopeds. For instance, environmental consciousness has a positive and significant effect on the frequency of use, in line with previous findings for other shared mobility services (Blazanin et al., 2022; Chen et al., 2021). This may indicate that fully electric shared mopeds

are perceived as environmentally friendly modes by intensive users of this transport option. In contrast, the preventive COVID-19 behaviour construct is negatively correlated with higher frequency of use of MSS, even after controlling for its effect on general mobility rates. This result shows that, despite ensuring social distance and the efforts of the operator to make the service safer (see Section 3), using a shared vehicle with other unknown travellers keeps COVID-19-concerned individuals from using these urban mobility services more often. The positive effect of the tech-savviness construct is coherent with the fact that riding MSS in Spain requires the use of a mobile application.

As for the influence of socio-economic attributes, they are largely in line with the previous literature for MSS and other shared mobility services. Wealthy young (under 34) individuals and with higher levels of education are the population segment that displays higher frequencies of use (see e.g. Aguilera-García et al., 2020, 2022; Böcker et al., 2020). Interestingly and in contrast to what has been observed in many other studies exploring shared mobility usage, gender does not seem to influence the frequency of use of MSS in this case. Nevertheless, we should remind that MSS users are mostly men (see Table 8-8). It is somewhat surprising that no statistically significant differences are found between the city of residence, despite the fact that the cities surveyed range in size from 0.7 million inhabitants (Seville) to 3.2 million (Madrid).

Table 8-13: Modelling results - frequency of use of MSS and perception of vehicle ownership as a necessity in the future

	Variable (<i>Reference</i>)	Frequency of use of MSS (ordinal)	Need to own a vehicle in the future (base: it will remain a necessity)
		Coeff. (std. error)	Coeff. (std. error)
Latent variables	Environmental consciousness	0.164*** (0.048)	0.505*** (0.056)
	Tech-savviness	0.218* (0.113)	--
	Willingness to share	--	0.276*** (0.068)
	Preventive COVID-19 infection behaviour	-0.166*** (0.041)	-0.108** (0.041)
Individual and household characteristics	Gender (<i>Male</i>)		
	Female	--	-0.297*** (0.098)
	Age (<i>18-24</i>)		
	25-34	--	--
	35-44	-0.144** (0.069)	0.254*** (0.086)
	45-54	-0.144** (0.069)	0.563*** (0.093)
	55-64	-0.290** (0.118)	0.594*** (0.137)
	65 or above	-0.290** (0.118)	0.893** (0.354)
	Education (<i>Non-university</i>)		
	University	0.249*** (0.070)	--
	Annual HH income (<i>Less than 21,000 €</i>)		
	21,000 to 29,999 €	--	0.149* (0.081)
	30,000 to 40,999 €	--	0.149* (0.081)
	41,000 to 59,999 €	0.185*** (0.071)	--
	60,000 € or more	0.185*** (0.071)	0.339*** (0.106)
	Without own income	--	0.492* (0.267)
	Occupation (<i>Employed</i>)		
	Student	--	-0.416** (0.211)
	Part-time employee/student	0.183* (0.095)	--
	Retired	--	--
	Other (homemaker, unemployed)	--	-0.341* (0.181)
	Household size (<i>1 person</i>)		
	2 people	--	--
	3 people	--	--
	4 people or more	--	-0.217*** (0.076)
	Minor children in the HH (<i>No</i>)		
	1 minor	--	--
	2 minors or more	--	0.464** (0.187)
Place of residence	Residence location (<i>City centre</i>)		
	City outskirts	-0.344*** (0.084)	--
	Metropolitan/suburban area	-0.555*** (0.100)	--
	City of residence (<i>Seville</i>)		
	Valencia	--	--
	Barcelona	--	--
	Madrid	--	--
	Residence within MSS service area	0.504*** (0.000)	--
Mobility-related attributes	Public transport card ownership (<i>No</i>)		
	Multi-personal card (10-journey and single ticket)	--	--
	Monthly/Annual season ticket	--	--
	Regular access to a car	-0.410*** (0.088)	-0.414*** (0.101)
	Regular access to a moped/motorcycle	-0.501*** (0.062)	--
	Regular access to an e-scooter	--	--
	Regular access to a bike	-0.169*** (0.064)	--
	Regular access to a van	--	--
Zip code variables	Density of urban bus stops	0.011*** (0.004)	--
	Density of urban bus stops#Residence within MSS service area	-0.010** (0.005)	0.007** (0.003)
	Density of sub-urban train stations#Residence within MSS service area	0.125* (0.075)	--
	Land-use percentage: offices#Residence within MSS service area	-0.002** (0.001)	--
	Land-use percentage: collective housing	--	0.005* (0.003)
	Land-use percentage: parking#Residence within MSS service area	--	-0.030** (0.011)
Endogenous variables	Weekday mobility (<i>Zero trips</i>)		
	1 to 2 trips	0.367*** (0.092)	--
	3 or more trips	0.409*** (0.134)	--
	Non-weekday mobility (<i>Zero trips</i>)		
	1 to 2 trips	--	--
	3 or more trips	--	--

Frequency of use of MSS (<i>Infrequent user</i>)		
Occasional	n/a	0.209** (0.081)
Weekly	n/a	0.348*** (0.095)
Daily	n/a	0.348*** (0.095)
Frequency of use of MSS# Frequency of use of bikesharing		
Infrequent user of MSS#Occasional user of bikesharing	n/a	0.816*** (0.285)
Infrequent user of MSS#Weekly user of bikesharing	n/a	0.816*** (0.285)
Infrequent user of MSS#Daily user of bikesharing	n/a	0.816*** (0.285)
Occasional user of MSS#Daily user of bikesharing	n/a	1.782* (1.066)
Frequency of use of MSS# Frequency of use of e-scooter sharing		
Infrequent user of MSS#Infrequent user of e-scooter sharing	n/a	0.434** (0.195)
Infrequent user of MSS#Occasional user of e-scooter sharing	n/a	0.434** (0.195)
Infrequent user of MSS#Weekly user of e-scooter sharing	n/a	0.434** (0.195)
Infrequent user of MSS#Daily user of e-scooter sharing	n/a	0.434** (0.195)
Constant	n/a	0.040 (0.135)
Threshold 1	-0.790*** (0.178)	n/a
Threshold 2	1.131*** (0.179)	n/a
Threshold 3	3.267*** (0.193)	n/a
Goodness of fits statistics		
Log-Likelihood (model)	-28,045.36	AIC 56358.71
Log-Likelihood (null)	-28,727.69	BIC 57142.18
LR test	$\chi^2 = 1326.67$	

*Only the statistically significant zip code variables were included in the table. ***p<0.001, **p<0.050, *p<0.100

According to the modelling results, both residents in the city centre, with good accessibility to public transport services and residents within the moped-sharing service areas, are found to use electric shared-mopeds more often than residents in other areas. This means that the possibility of making door-to-door trips without any additional first- and/or last-mile connection, encourages users to choose MSS more often. Additionally, for the whole sample, the density of urban bus stops in the zip code of residence increases the frequency of use of MSS, an effect already observed by Huo et al. (2021) for kick-scooters in five US cities. However, the negative coefficient for the interaction between the density of urban bus stops and the binary variable that captures whether the individual lives within the *Acciona* MSS area, suggests that the complementary relation between urban buses and MSS weakens when individuals are able to use electric shared-mopeds as a door-to-door transport option.

Concerning travel-related attributes, we observe that frequency of use is higher among those who do not have access to a private car or moped, in line with what was found for the adoption of MSS by Aguilera-García et al. (2020). This indicates that MSS allow car-less individuals to satisfy urban mobility needs that may require a private vehicle without assuming the economic burden of owning it. Finally, there is a positive relationship between weekday mobility rates and frequency of use of MSS, an effect previously observed for electric shared-mopeds (see e.g., Aguilera-García et al., 2021).

5.4. Expected need to own a private vehicle in the future

Finally, this section presents the modelling results for the variable that captures MSS users' opinion on whether the ownership of a private vehicle will still be a necessity in the future given the increasing provision of shared mobility. As in the case of MSS frequency of use, latent psychological constructs were found to have a noticeable explanatory power and their results are fully in line with what would be initially expected. Higher pro-environmental attitudes, a greater willingness to share and less concern about being infected by COVID-19, are negatively correlated with the belief that private vehicles will no longer be a necessity in the future.

The results for the socio-economic variables yield some interesting results. While the previous sub-model (Section 5.3) did not reveal gender differences regarding the frequency of use of MSS, in this regression women are more likely to have answered that that owning a vehicle will still be necessary notwithstanding the rise of shared mobility. This could be due to the greater burden of child and family care tasks that women in general carry, difficult to make without a private vehicle (Gauvin et al., 2020; Singh, 2019). Individuals older than 35 years old show a higher probability of thinking that giving up vehicle ownership will be a feasible option. However, when interpreting the modelling results for age, we should take into account that our sample only includes actual users of MSS, which is far from being the rule compared to the general population. Surprisingly, the results show that a higher level of income and the presence of two or more minor children are correlated with a higher probability of considering a feasible option to give up owning the private vehicle in the future. The positive effect of income and children on the willingness to reduce car ownership as a consequence of shared mobility usage was also observed by Liao et al., 2020 for the case of The Netherlands and Kim et al., 2019 in Seoul, Korea.

Reasonably, already having access to a car is positively correlated with thinking that owning a vehicle will still be necessary despite the increasing provision of shared mobility services. According to the modelling results, individuals already owning a private vehicle in their household are 54.6% more likely to consider that vehicle ownership will remain a necessity in the future. This result hints towards MSS being more successful in preventing car-independent individuals from switching to a more car dependent mobility than in making car owners giving

up their vehicles, which is aligned with what was observed in Le Vine & Polak (2019) for the case of car-sharing in London.

The modelling results for the frequency of use of MSS indicate that the use of these services is correlated with a higher probability (compared to infrequent users) of considering that the fulfilment of daily mobility needs without a private vehicle could be a feasible option in the future. The model also shows that occasional users are, *ceteris paribus*, 23.3% more likely to consider that owning a private vehicle will no longer be a necessity in the future. For weekly and daily users this percentage rises up to 41.6%. In addition, the interactions between this variable and the frequencies of use of bike-sharing and kick-scooter-sharing, allow to capture the impact of these shared modes on perceived future vehicle dependency among infrequent users of MSS. Those who use shared-mopeds rarely, but use bike-sharing occasionally or more often, are more likely to believe that they could become vehicle independent. The model yields similar results for all kinds of users of shared kick-scooters. Altogether, these findings suggest that the frequency of use and the combined use of different shared modes is positively correlated with the belief that owning a private vehicle will not be that necessary in the future. Finally, the fact that the place of residence (city centre/outskirts of the metropolitan area; within/outside the MSS area, etc.) is not statistically significant, suggests that the potential effect of MSS may not be restrained to residents in the city centre, where shared mobility is most accessible.

5.5. Mediation effects

In order to analyse potential mediation effects in the model, the research employed the method proposed by Buis (2010). This method allows to disentangle the observed direct and indirect effects on binary variables considering one mediation variable. In our case, the mediation variable is the frequency of use of shared-mopeds and the co-endogenous binary variable is the perceived need of the individual of owning a car in the future. Table 8-14 displays the direct, indirect and total effects of the exogenous observed variables that were found statistically significant in the model for both variables. It should be noted that the direct effects that are computed through this method do not coincide with the direct effects estimated by the model. This is due to the fact that these coefficients are obtained through the estimation of a logistic regression that considers the endogenous binary variable, the

mediation variable and the set of explanatory variables, the effects of which are under study. For more details on the methodology followed to estimate the mediation effects, the reader is referred to Buis (2010).

For the case of age, the direct and the indirect effect of the perceived need to own a car in the future have opposite signs. While the direct effect of being older than 35 years old on the probability of believing that a car would not be needed in the future is positive, the indirect effect through the mediation of the frequency of use of shared mopeds is observed to be negative for these groups. This result suggests that even though people over 35 years old seem to be more willing to give up their cars as a consequence of the increasing supply of shared mobility, the fact that this groups display lower frequencies of use of shared mopeds might be slightly reducing this willingness to reduce car ownership. As for the level of income, we can observe that both the direct and indirect effect are positive and significant for high-income households (above 40,000€ per year). Nevertheless, the size of the indirect effect constitutes a small fraction of the total effect, suggesting that the mediation role of the frequency of use of shared mopeds on the effect that income has on the perceived need to own a car in the future is statistically significant but limited in practice. Finally, the coefficients for the direct and indirect effects of car availability show that all effects are significant and negative. Therefore, the mediation effect of the frequency of use of shared mopeds seems to be strengthening the negative effect of having access to a car on future perceived car independency.

Table 8-14: Total, direct and indirect effects on the perceived need to own a car in the future

Variable (Reference)	Need to own a vehicle in the future (base: it will remain a necessity)		
	Total effect	Direct effect	Indirect effect
	Observed coefficient (std. error)	Observed coefficient (std. error)	Observed coefficient (std. error)
Age (18-24)			
25-34	--	--	--
35-44	0.301*** (0.065)	0.313*** (0.065)	-0.011** (0.005)
45-54	0.301*** (0.065)	0.313*** (0.065)	-0.011** (0.005)
55-64	0.412*** (0.070)	0.432*** (0.070)	-0.020*** (0.007)
65 or above	0.412*** (0.070)	0.432*** (0.070)	-0.020*** (0.007)
Annual HH income (Less than 21,000 €)			
21,000 to 29,999 €	--	--	--
30,000 to 40,999 €	--	--	--
41,000 to 59,999 €	0.182*** (0.061)	0.168*** (0.061)	0.013** (0.007)
60,000 € or more	0.182*** (0.061)	0.168*** (0.061)	0.013** (0.007)
Regular access to a car	-0.462*** (0.094)	-0.426*** (0.096)	-0.036** (0.015)

***p≤0.001, **p≤0.050, *p≤0.100

6. Discussion and policy recommendations

The joint analysis of the results for the sub-models included in the GSEM allows to draw interesting findings that help us suggest policy recommendations on how to harness MSS to reduce perceived dependency on the private car:

This research shows that a noticeable percentage of MSS users (on average, 53.5% for the whole sample and 51.8% among those who currently have access to a car) consider that owning a private vehicle will no longer be a necessity in the future. This is remarkable given the high presence of individuals in the sample who own a private car (85.1%). These results suggest that car owners believe that the supply of shared mobility could, together with other aspects such as life-cycle events or place of residence, enter the considerations they face when making decisions regarding their car ownership levels. This would emphasize the potential of shared mobility to encourage individuals to shift to car-independent mobility habits, thereby avoiding the environmental, social and economic costs of private cars (Gössling et al., 2022). As for those who do not have access to a car, it is noteworthy that the sub-model for the frequency of use of MSS shows that they tend to use shared mopeds with a higher frequency of use than those who do not own a car. These results are in line with previous results for car-sharing (see e.g., Mouratidis, 2022 or Ye et al., 2019) and show that shared services are supporting the mobility of those who do not have access to a private car, which in some cases will have a positive effect on social equity. Additionally, the fact that the sub-model for future perceived car-independency yields a positive correlation between the lack of access to a private car and the belief that a car will not be necessary, highlights even further the potential of shared mobility to prevent zero-car individuals from purchasing one.

The exploratory results mentioned above are supported by the fact that the modelling results show a negative correlation between the frequency of use of MSS and the perceived need to own a vehicle in the future. Moreover, our findings show that the combined adoption and use of different shared modes decreases even further this perception. This reinforces the idea of shared mobility services being a useful tool to reduce private car ownership in urban areas. The reductions in the number of cars that are motivated by an increasing use of shared mobility are likely to ultimately lead to a reduction in car usage, as previous contributions have observed (see e.g., Cervero et al., 2007 or Martin & Shaheen, 2016). In addition, the lack of significance of the variables controlling for city of residence, despite the notable differences in terms of population and urban size, supply of public transport services, etc., would imply that the benefits of shared mobility for the reduction of vehicle ownership can be leveraged across urban areas of diverse nature.

While the place of residence has a significant effect on the frequency of use, with residents living in the city centre and within the MSS area riding electric shared mopeds more often, it is surprising that the place of residence within the metropolitan area does not affect the perception of whether a private vehicle will remain a necessity in the future. This fact suggests that shared mobility users living in the urban outskirts believe, as do those living closer to the city centre, that in the future they will be able to take more advantage of the benefits of shared mobility, perhaps relying on the future expansion of the service area. According to this hypothesis, encouraging operators to expand their services to areas further away from the city centre may be an effective way to benefit from the potential of MSS to substitute private car ownership, especially in lower density areas where accessibility to public transport is low and car ownership levels are often high. In this regard, some kind of support from local governments would be advisable, given that the provision of services in these areas may not be attractive for private operators due to the lower turnover use of mopeds. However, the results for the place of residence should be taken with caution, as the division into postcodes is a rather limited level of spatial disaggregation, which may prevent the model from capturing all existing spatial effects.

The exploratory analysis of the trip-level variables shows that daily users of electric shared-mopeds are the most likely ones to use them for trips that would have been done by public transport. These findings suggest that, in general, daily users of MSS would need incentives to shift to public transport or to combine it with MSS. Given that daily users are also more likely to declare that they use MSS for commuting purposes, implementing regulation schemes that penalize trips during peak-hours and foster integration with public transport, could help mitigating this substitution effect.

The modelling results concluded a negative relationship between general mobility rates during weekdays and income, which is probably due to a wider adoption of teleworking regimes among these socio-economic groups (López-Soler et al., 2021). Moreover, individuals living in high-income households are more likely to use MSS frequently. These results hint towards MSS being a suitable transport option for high-income workers that benefit from more flexible travelling dynamics and need lower levels of mobility due to the uptake of teleworking. Additionally, the results show that, among MSS users, being part of a high-income household is positively correlated with considering that giving up private vehicles in the future would be feasible given the increasing supply of shared mobility services. Consequently, once individuals are familiar with the service, MSS appears to be an important driver for future reduction in car ownership levels among households that generally show higher levels of car ownership and use, compared to other segments of the population.

7. Conclusions, limitations and further research

This paper explores the factors that determine the frequency of use of MSS among adopters of these services, as well as users' expectations about the possibility of not needing a private vehicle in the future because of the increasing provision of shared mobility. To that end, we adopted a GSEM model that accounts for the influence of socio-economic attributes, subjective beliefs and preferences, mobility behaviour and city-built environment variables, on the frequency of use of MSS and perceptions of the future need to own a vehicle. One of the main strengths of this research is the large sample (3,897 individuals) gathered through the survey campaign, which allowed for the construction of an exhaustive modelling framework and provided an extensive overview of MSS usage. The analysis allowed to draw relevant conclusions regarding the role of shared mobility in urban transport systems, which is crucial given the relative shortage of research addressing shared mopeds.

Interestingly, the research has shown that a significant share of MSS users considers that owning a private vehicle will no longer be a necessity in the future and that the probability of declaring this belief is positively correlated with the frequency of use of these services. Furthermore, the model points out that the combined use of different shared modes is positively correlated with considering a private-vehicle-independent lifestyle as a feasible option in the future. These findings highlight the potential of shared mobility to reduce the current levels of private vehicle ownership in urban areas. In particular, the results show that the use of MSS may be more effective dissuading individuals without a car from buying one than convincing those that already own one or more vehicles to get rid of them. In addition, the lower or lack of explanatory power of some of the variables controlling for residential location (city of residence and place of residence within the metropolitan area) suggest the potential of shared mobility to reduce car dependency regardless of the characteristics of the neighbourhood of residence and its location within the city.

As for the main limitation of the study, it should be noted that the use of a sample that only includes users of a specific shared mobility service could restrict the scope of some results. For instance, when analysing the effects of socio-economic attributes, such as age and gender, it should be considered that the adoption of MSS is wider among young men. In the same fashion, the specific pricing scheme of *Acciona* services may attract certain socio-economic profiles. In this regard, as main avenue for further research we suggest enriching the analysis by comparing changes in responses coming from different companies and services. Given that each operator may differ in terms of e.g., fares applied or area served within the city, it would be of great interest to analyse potential differences in trip dynamics or frequency of use of

different electric shared-mopeds services. Additionally, it would also be insightful to jointly model shared mobility usage choices for different modes. Such analysis would allow gaining a deeper understanding on how the existing modes of the shared mobility ecosystem interact and how each of them contributes to the achievement of more sustainable and integrated urban transport systems. Moreover, safety considerations have been observed to play a key role in the adoption and usage patterns of certain shared mobility services such as kick-scooters (see e.g., Kopplin et al., 2021 or Pourfalatoun et al., 2023). However, this topic has not yet been addressed in the scientific literature for the case of shared moped-scooters. In this regard, investigating the extent to which this concern may be a factor limiting the expansion of these services is a broad avenue for further research. Finally, in the present study some information from the individuals' zip-code of residence was incorporated into the model, as those were the most accurate indicators available of the built-environment characteristics. Nevertheless, future studies would benefit from the inclusion of lower-level spatial characteristics and more details regarding the access of individuals to public transport (e.g., whether they can reach it by walking or need to rely on other modes).

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

EU disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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Appendix 8-D: List of questions included in the survey

Question	Options provided
SOCIO-ECONOMIC INFORMATION	
Age	< 18; 18 – 24; 25 – 34; 35 – 44; 45 – 54; 55 – 64; > =65
Gender	Male; Female; I do not want to answer
What is the highest level of education you have completed?	Primary education; Secondary education or vocational training; University education; I do not want to answer
Occupation	Student; Employee; Studying and working; Retired; Unemployed; Entrepreneur/Self-employed; Housewife; I do not want to answer
Zip-code of residence	<i>Open answer</i>
Including yourself, how many people live in your household?	<i>Open answer</i>
How many of them are minors?	<i>Open answer</i>
For purely statistical purposes, could you please indicate what was the gross income level of your household last year?	Less than 12.000€; between 12.000€ and 18.000€; between 18.001€ and 21.000€; between 21.001 and 30.000€, between 30.001€ y 41.000€, between 41.001€ y 60.000€, between 60.001€ and 100. €. More than 100.000€; No income of my own: I depend on my family's income; I do not know/I do not want to answer.
FREQUENCY OF USE OF SHARED SERVICES	
Indicate how often you usually use the shared motorbikes/moped-scooters	Rarely, Less than once a week, Between 1 and 4 times per week, More than four times per week.
Indicate how often you usually use shared kick-scooters.	Rarely, Less than once a week, Between 1 and 4 times per week, More than four times per week.
Indicate how often you usually use shared bikes.	Rarely, Less than once a week, Between 1 and 4 times per week, More than four times per week.
INFORMATION REGARDING THE LAST TRIP WITH SHARED MOPED SCOOTERS	
What was the purpose of the last ride you can remember on a shared motorbike?	Going to/returning from my place of work or school/university; Attending a work meeting (outside my place of work); Going to/returning from leisure or recreational activities; Going to / returning from shopping or personal business; Going to / returning from visiting family or friends; Getting to/from a bus station, train station or airport; Other purpose (please specify); I do not know/I do not want to answer.
What was the approximate duration of this trip?	Less than 5 minutes; Between 5 and 10 minutes; Between 10 and 15 minutes; Between 15 and 20 minutes; Between 20 and 30 minutes; More than 30 minutes.
Did you combine that last trip with another mode of transport?	With a private car or moped; With other shared services; With public transport; No, I did not.
What means of transport would you have used if bike sharing had not been available?	On foot; Private vehicle; Taxi or ride-hailing; Public transport, I would not have made the trip; I would have been taken by a family; Bike-sharing, Car-sharing; I do not know.
GENERAL MOBILITY HABITS	
On your last WORKING day, excluding walking trips, how many trips did you make (e.g. consider round trip as two trips)?	<i>Open answer</i>
On your last NON-WORKING day, excluding walking trips, how many trips did you make (e.g. consider round trip as two trips)?	<i>Open answer</i>
Indicate the total number of cars in the household.	<i>Open answer</i>
Indicate which of the following vehicle(s) are available in your household and of which you can make personal use on a regular basis	Car; Moped scooter or motorcycle; Kick-scooters; Bike; Van; None
Do you purchase any kind of season ticket/card that allows you to use public transport?	No; Multi-personal reloadable card; Monthly/Annual ticket.
Given the rise of shared mobility, do you think car ownership will still be a necessity in the future?	Yes/No

Appendix 8-E: List of attitudinal indicators included in the survey following a five points Likert-scale structure

Indicator	What is your level of agreement with the following statements?
I try to choose environmentally sustainable modes of transport.	Strongly disagree Disagree Neutral Agree Strongly agree
I usually recycle the waste at home	
In general, I am willing to pay more for a product whose production process has a lower environmental impact.	
I regularly use social media (Facebook, Twitter, Instagram, Snapchat, etc.)	
I regularly use online tools to ease my daily tasks (banking services, online shopping, e-mail, etc.)	
Trying new mobile applications and learning how to use them is easy for me	
I regularly use shared economy applications (second-hand clothes applications, Airbnb, Ebay, etc.)	
I occasionally buy second-hand items (clothes, furniture, etc.)	
I shy away from using/wearing items that have been used by many people before me.	
When a new product comes out, I like to try it before anyone else does.	
I think it is important to get out of the routine and have new experiences.	
Safety is a key issue when choosing a means of transport.	
I only cross a street at a green light and/or at a zebra crossing.	
It is essential to comply with the rules on occupational risk prevention.	
To avoid infection with COVID-19, I have decided to restrict my social activity with acquaintances and leave the house as little as possible.	
I avoid crowded places (public transport, gym, shopping centres, etc) due to COVID-19	
Since the COVID-19 vaccine has become available, I have relaxed precautions related to wearing masks, social distance, reducing my travel, etc.	
Doing a variety of activities and taking certain risks is important to me.	

Appendix 8-F: Modelling results for the weekday and non-weekday mobility rates sub-models

Modelling results for the weekday and non-weekday mobility rates sub-models

Variable (<i>Reference</i>)		Weekday mobility (ordinal)	Non-weekday mobility (ordinal)
		Coeff. (std. error)	Coeff. (std. error)
Latent variables	Environmental consciousness	--	--
	Tech-savviness	--	--
	Willingness to share	0.151*** (0.056)	0.246*** (0.055)
	Preventive COVID-19 infection behaviour	--	-0.059* (0.034)
Individual and household characteristics	Gender (<i>Male</i>)		
	Female	--	--
	Age (<i>18-24</i>)		
	25-34	--	--
	35-44	0.335*** (0.074)	--
	45-54	0.335*** (0.074)	--
	55-64	0.456*** (0.121)	-0.339*** (0.108)
	65 or above	0.456*** (0.121)	-0.339*** (0.108)
	Education (<i>Non-university</i>)		
	University	--	--
	Annual HH income (<i>Less than 21,000 €</i>)		
	21,000 to 29,999 €	-0.261*** (0.098)	--
	30,000 to 40,999 €	-0.261*** (0.098)	--
	41,000 to 59,999 €	-0.289*** (0.099)	0.172** (0.070)
	60,000 € or more	-0.289*** (0.099)	0.172** (0.070)
	Without own income	--	--
	Occupation (<i>Employed</i>)		
	Student	--	--
	Part-time employee/student	0.185* (0.100)	--
	Retired	--	--
	Other (homemaker, unemployed)	--	--
	Household size (<i>1 person</i>)		
	2 people	--	--
	3 people	--	--
	4 people or more	--	--
	Minor children in the HH (<i>No</i>)		
	1 minor	0.145* (0.083)	--
	2 minors or more	0.145* (0.083)	--
Place of residence	Residence location (<i>City centre</i>)		
	City outskirts	--	--
	Metropolitan/suburban area	--	--
	City of residence (<i>Seville</i>)		
	Valencia	--	--
	Barcelona	--	--
	Madrid	--	--
Mobility-related attributes	Public transport card ownership (<i>No</i>)		
	Multi-personal reloadable card (10-journey and single ticket)	--	--
	Monthly/Annual season ticket	0.261** (0.101)	--
	Regular access to a car	--	--
	Regular access to a moped/motorcycle	0.252*** (0.064)	0.174*** (0.062)
	Regular access to a e-scooter	--	0.245*** (0.105)
	Regular access to a bike	--	--
	Regular access to a van	0.354*** (0.136)	--
Zip-code variables*	Density of urban bus stops	--	-0.010*** (0.002)
	Density of metro/tram stations	--	0.026** (0.013)
	Thresholds 1	-1.679*** (0.089)	-1.861*** (0.070)
	Thresholds 2	1.102*** (0.095)	0.337*** (0.062)

9. General discussion

In this chapter the most relevant results obtained in the Scientific Publications are jointly discussed to draw cross-cutting conclusions. Section 9.1 presents the main results obtained with respect to latent variables and socio-economic attributes (Section 9.1.1) and current car ownership and declared travel behaviour (Section 9.1.2). Section 9.1.3 presents the results obtained from the spatial analysis of shared mobility's impact on perceived car dependency. In section 9.2, these findings are summarised to provide a succinct answer to the research questions.

9.1. Cross-cutting discussion of the modelling results

This section presents a transversal analysis of the results that were obtained in each of the scientific publications that are included in Chapters 7 and 8.

9.1.1. Latent variables and socio-economic characteristics

First, subjective attitudes and preferences seem to play a noticeable role on whether individuals perceive that they will not need a car in the future due to the expansion of shared mobility, among both the general population and shared mobility users. Environmental awareness positively influences this belief in both cases, probably because pro-environmental individuals are more likely to adopt certain shared mobility services (see e.g. Aguilera-García et al., 2022). Additionally, this individual preference has been observed to correlate with less attachment to private cars (Thøgersen et al., 2021). As for tech savviness, it was found to have a positive impact on perceived car independency among the general population but yielded non-significant results for shared mobility users. These differences suggest that the level of comfortability with technology is an essential aspect to consider in the development of a shared mobility as a widespread alternative to private car ownership.

As for the relationship between socio-economic variables and car demand, it is noteworthy that the statistically significant factors seem to coincide across the three-analysis conducted, despite the differences in the directions of their effects. First, the three models yield limited results with respect to gender. The behavioural changes induced by the COVID-19 pandemic with regard to private cars do not appear to differ significantly by gender. As for the role of this factor on shared mobility's impact on car dependency, the only statistically significant results are obtained for the shared mobility users, showing that women are less likely to reduce their car dependency as a consequence of shared mobility. It should be noted that these results are obtained after having controlled for the impact of this variable on shared mobility's adoption and frequency of use.

Interestingly, the results for age diverge between the general population and users of shared mobility. While for the former, the result shows that individuals between 36 and 55 years old are less likely to believe they could give up the car, users of shared mobility older than 35 years old believe they could give up the private car if shared mobility would continue expanding. Taken together, this would suggest that the adoption of shared mobility has the potential to reduce the increase in car ownership usually associated with the life-cycle events that tend to be experienced by young adults (see e.g. Clark et al., 2016; or Oakil et al., 2014). This is especially relevant given that the modelling results in SP1 revealed that young adults

under 25 years old were likely to have increased their car ownership and use as a result of the pandemic.

This work confirms previous results that have observed that the adoption of teleworking regimes has the potential to significantly alter mobility habits (Caldarola & Sorrell, 2022; Silva & Melo, 2017). For the case of perceived car dependency, our analysis for the general population shows that teleworkers are more likely to believe that a car will not be necessary in the future. Moreover, the more flexible the teleworking arrangement is, the higher the intensity of this belief. This effect contrasts with the results observed on the analysis of the new trends on car ownership and use, since full-time and partial teleworkers are respectively 46% and 31% more likely on average to have bought a car due to the pandemic than in-person workers. However, despite this increase in car ownership, teleworkers were more likely to have decreased their car use. This joint analysis of this results suggest that teleworkers are probably reducing their car demand, but due to the increase flexibility their habits may have become less structures, requiring the convenience of a private car, that could be potentially substituted by shared mobility.

With respect to the effect of income, the preliminary study of the new trends in car ownership and use showed that belonging to a high-income group was significantly and strongly correlated with the probability of having reduced the frequency of car use after the start of the pandemic. The odds of decreasing car use among high-income individual are 1.8 times higher than for the lowest income group. Unexpectedly, the analysis of shared mobility's impact on car dependency confirms this trend. It was observed that income had a positive impact on people's perception (both shared mobility users and the general population) about whether living without a car could be feasible. In the case of users of shared mobility, this effect is more pronounced for the highest income group (annual household income above 60,000 €). As for the general population, this effect seems to be further extended to individuals living in households with monthly incomes over 40,000 €. In order to further explore this effect, the income variable was interacted with several travel behaviour variables, but only the interaction with the frequency of use of private car turned out significant. These effects revealed that high-income groups are only more willing to give up the private car than lower-income groups if they use the car occasionally or not at all.

A summary of the most important modelling results regarding the effect of latent and socio-economic factors on shared mobility's impact on car dependency among users and the general population can be found in Table 9-1.

Table 9-1: Comparison between users and general population — latent and socio-economic variables

Explanatory factor	Impact on the likelihood of believing that a car will not be necessary in the future	
	General population	Users of shared mobility
Environmental awareness	+	+
Tech-savviness	+	NS
Willingness to share	N/A	+
Gender - Female	NS	-
Age	-	+
Education	NS	+
Occupation - Student	-	NS
Teleworking	+	N/A
Income	+	+
Household size	NS	+

N/A – the variable was not included in the model; NS – the variable was not significant

*only if car ownership levels are already low

9.1.2. Current car ownership and declared travel behaviour

The access or ownership to private car significantly increases perceived car dependency both for users and for the general population. In fact, among this last sample, the more cars owned in the household, the less likely individuals are to believe that they could give up the ownership of private cars in the future. These results are in line with previous works focusing on the impact of shared mobility on car ownership (see e.g. Le Vine & Polak, 2019 or Nijland & van Meerkerk, 2017). Additionally, for the general population it was found that travelling longer distances in daily life (measured through a variable that captured whether people worked in the same municipality where they live) is associated with a higher probability of believing that a car will be needed in the future. In a similar trend, it has been observed that those who utilize their private vehicles three or more times weekly are less inclined to consider relinquishing car ownership in the future. Finally, individuals who regularly use public transportation reasonably express greater openness to the idea of giving up car ownership in the future. The combined influence of these factors underscores that, as seems reasonable, those who are currently more reliant on cars display less willingness to transition to a car-independent mobility, despite the growing availability of mobility alternatives.

As might initially seem expected (but not obvious), the adoption and frequency of use of shared mobility services has been found of most relevance in explaining the impact these services have on perceived car dependency. Among users of shared mobility, a heavy use of moped scooters reduces the probability of believing that a car will still need be necessary in the future. However, no statistically significant differences were found for lower frequencies

of use (e.g. between weekly and daily use) of this kind of services. Similarly, when considering the whole population, the results show that the adoption of car-sharing and moped-scooter-sharing is also significantly related to greater opinion towards forgoing the car in the future, nevertheless the odds of agreeing with the given statement do not increase in parallel with frequency of use. These results are in line with those obtained for car-sharing in the Netherlands by Liao et al. (2020), who observed that a higher frequency of use was not necessarily correlated with decisions to reduce car ownership. Conversely, the frequency of use of shared micro-mobility significantly decreases the perceived need to own a car in the future.

Aiming to further explore how the combined adoption of different shared modes could influence the impact on perceived car dependency, an interaction between the frequency of use of shared mopeds and the frequency of use of shared micromobility was introduced in the model, yielding some interesting insights. The adoption of bike-sharing or kick-scooter-sharing in combination with shared mopeds, even if the use is infrequent, significantly reinforces the belief that a car will not be needed in the future. These effects allow to conclude that a more multimodal behaviour with respect to shared modes significantly reduces the perceived need of a car being necessary in the future.

Finally, interactions between the adoption of shared cars or mopeds and car ownership and use variables were estimated. The results revealed that car owners who use shared cars or mopeds occasionally are significantly more likely to believe they could give up their car in the future. In the same trend, the interactions between the adoption of shared mopeds or shared cars and the frequency of use of the private car show that those who combine both options in their mobility habits are more likely to consider a car-less lifestyle as a feasible option in the future than those who use neither of them. These observations indicate that the adoption of shared services by travelers that rely heavily on the private car can have a significant effect on their perceived car dependency.

These results have been synthesized in Table 9-2 offering an overview of the aspects related to travel habits that influence the perception of needing a car in the future given the increasing supply of shared mobility.

Table 9-2: Comparison between users and general population — travel habits

Explanatory factor	Impact on the likelihood of believing that a car will not be necessary in the future	
	General population	Users of shared mobility
Car ownership/Access to car	-	-
Frequency of private car use	-	N/A
Frequency of public transport use	+	N/A
Frequency of shared kick-scooters/bike use	+	NS
Frequency of shared car/moped scooter	+	+
Combined use of shared micromobility and moped scooters	N/A	+
Combined use of private car and shared moped-scooter/car	+	N/A

N/A – the variable was not included in the model; NS – the variable was not significant

9.1.3. Spatial context: place of residence and built-environment

This thesis has incorporated a set of variables capturing the characteristics of the built environment in the respondents' area of residence to account for the role that the spatial context might play in the potential of shared mobility to reduce car dependency.

The multilevel model developed to analyse the impact of shared mobility on the perceived car dependency of the general population of the Region of Madrid allowed to prove that there are indeed spatial effects that influence this perception. The random intercepts at the level of the metropolitan ring and the municipal area were statistically significant before the spatial explanatory factors were introduced. These results indicate that the perceptions regarding the need to own a car in the future among individuals living in different municipal areas or districts of the city are heterogeneous. Additionally, the computation of Moran's I for these random intercepts shows that the values of this coefficients are not randomly distributed across the metropolitan rings and municipal areas but rather follow a spatial dependence structure. The random intercepts at the level of the municipal area have been mapped in Figure 9-1. As can be seen, the spatial coefficients are in general smaller in the central districts of the city of Madrid, but there is substantial heterogeneity in areas located in the second (outer districts of Madrid city) and third (sub-urban) metropolitan rings, with some municipalities displaying coefficients similar to those observed for the central area. On the other hand, the coefficients observed in the fourth ring (rural), are mostly negative.

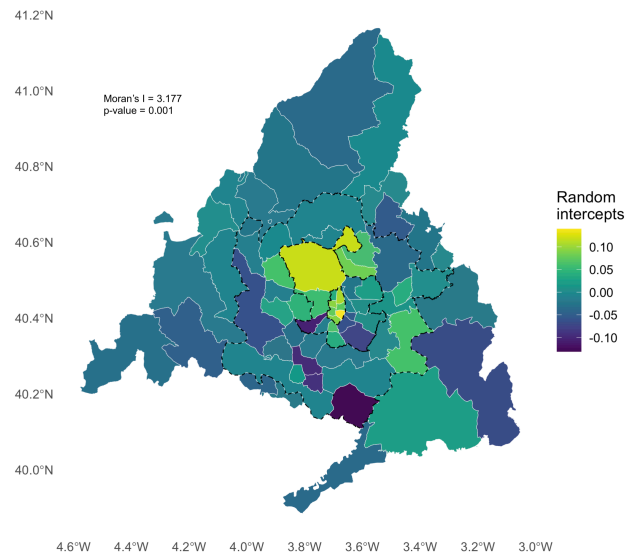
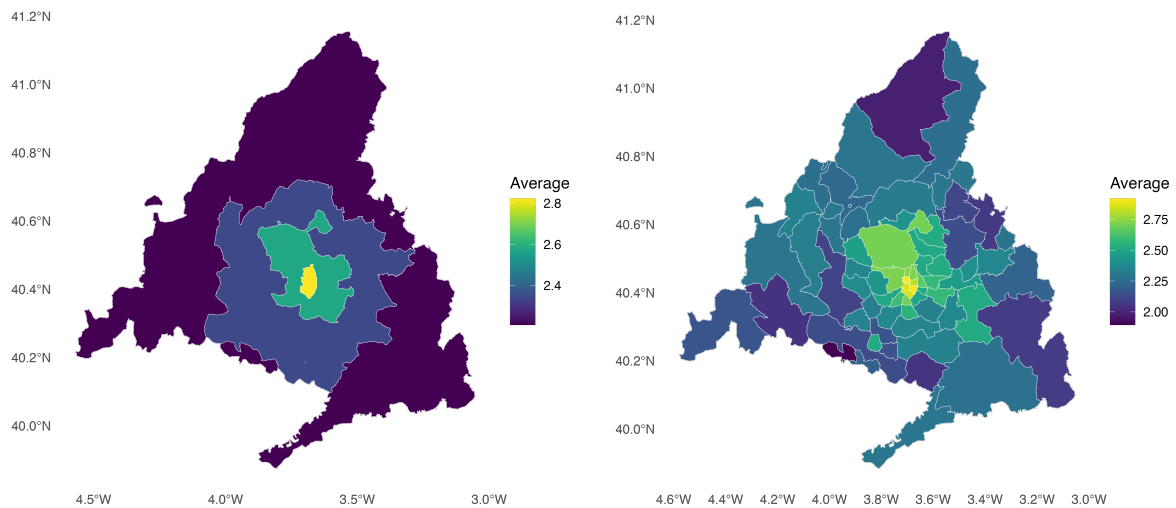


Figure 9-1: Random intercepts of the multilevel model before the introduction of spatial variables
(Source: SP2 - Vega-Gonzalo et al., 2024)

These statistical results, in combination with the map plotting the average responses by metropolitan ring (see Figure 9-2a) and municipal area (see Figure 9-2b), show that the impact of shared mobility happens mainly in the city of Madrid and its surrounding municipalities, that is, in those areas with current availability of shared mobility services. However, the map in Figure 9-2b also presents a non-negligible share of individuals living in the third (sub-urban) and fourth (rural) metropolitan ring who consider that they will be able to live without a car if a sufficient provision of shared mobility service was ensured.

Finally, variables capturing the land use mix and the population density were introduced in the model to account for the spatial variability previously observed. As expected, and in line with previous results, a more mixed land-use pattern and higher population density are correlated with a greater perceived car independency.



(a) Average at the metropolitan ring level

(b) Average at the municipal area level.

Figure 9-2: Average level of agreement with the statement “Given the increasing supply of shared mobility services, I believe that I will not need to own a private vehicle in the future”.

(Source: SP2 - Vega-Gonzalo et al., 2024)

For shared mobility users, living in an area with a higher density of urban buses and collective housing reduces the perceived need to own a car in the future. On the contrary, living in areas with better parking provision reduces the perception of being able to give up the car in the future, presumably because residents face less disadvantages when using the car than those who do not have a good provision of parking around their house. It is especially relevant that for current users of shared mobility, the place of residence within the metropolitan area does not play a statistically significant role on the belief that they will still need a car in the future. This result suggests that the potential effect of shared mobility to reduce car ownership may not be restrained to residents in the city centre, where shared mobility is most accessible. Furthermore, the comparison across respondents from the four biggest cities in Spain reveals that, surprisingly, no statistically significant differences are found between the city of residence, even though the cities surveyed range in size from 0.7 million inhabitants (Seville) to 3.2 million (Madrid).

9.2. Answering the research questions

Building on the key findings obtained in the scientific publications elaborated throughout this thesis, most of which have been discussed in the previous sections, concise answers to each of the three research questions have been formulated. This has been done with the aim of providing a synthesized overview of the main conclusions derived from this thesis.

RQ1 What are the individuals' characteristics, including socio-economic attributes, travel habits, access to modes of transport and city characteristics, that drive car ownership and car use in European urban areas?

The answer to these questions results mainly from the findings obtained in SP1. The analysis of the behavioural patterns of the different car user profiles hints towards a persistence of car usage habits. Individuals display a tendency to stay car independent notwithstanding the occurrence of the sanitary crisis. In the same fashion, those who used the car less frequently prior to COVID have been more inclined to further decrease their car use than those using this mode intensively. Additionally, the analysis of the sample distribution shows that most of the sample have kept the same frequency of use of the private car (55.0%) or decrease it (24.3%). Altogether, these findings suggest that individuals have slightly adjusted their car use according to decrease in mobility rates, but no significant increase in the overall number of trips has been induced.

Despite this positive result, some shifting trends concerning the determinants of car ownership and use ought to be pointed out. On the first place, it is noteworthy that younger adults (under 36) and residents in the cities' core have increased their car use, showing that certain socio-economic segments traditionally observed to rely less often on the car, might have been attracted by this mode after the COVID-19 pandemic. Secondly, the model points to a reduction in car use among high-income, well-educated teleworkers, which proves teleworking to be an effective tool to reduce car use in urban areas. On the contrary, in-person, low-income and low-educated individuals display the lowest probabilities to have reduced car use (pre- vs. post-COVID), which poses concerns regarding the capabilities of these vulnerable groups to cover their mobility needs in an economically and environmentally sustainable way.

The analysis did not reveal any statistical difference in private vehicle ownership and use between cities in different countries, city-level and most of the heterogeneity could be explained by the characteristics of cities. The attributes with a bigger role are the size of the city, the level of urban sprawl and the average performance of the car. Individuals living in

bigger cities with less urban sprawl are more prone to have reduced car use. As for the effect of car performance, a higher accessibility by car was positively correlated with higher car ownership and use before the pandemic and it is negatively correlated with a decrease in car use after the pandemic. These results reinforce the idea that limiting private car accessibility in cities is an efficient measure to reduce car dependency.

RQ2 Does the increasing availability of shared mobility significantly affect perceived car dependency?

The analysis of the sample employed in SP2, which targets the general population of the Region of Madrid, shows that 42.6% of respondents agreed that a car will no longer be a necessity in the future given the increasing supply of shared mobility services. As could have been expected, these percentage increases for the shared mobility sample analysed in SP3. In this case, the analysis of the data showed that, on average, 53.5% of respondents agreed with the feasibility of living without a car in the future.

It is especially interesting to explore how these statistics interact with the access to a private car. In Figure 9-3, it can be observed that those that can currently make use of the private car to cover their mobility needs are less likely to believe they would not need it in the future. Despite this effect, the percentages suggest that shared mobility it is seen by a considerable number of car owners as a feasible alternative. Almost 30% of the sample representing the whole population of the Region of Madrid believes they could live without a car given the increasing supply of shared mobility and this number rises up to more than 50% for users of shared mobility. Therefore, given the increasing expansion of shared mobility, the access to this kind of services would be a factor that, along with other drivers such as life-cycle events or place of residence, may influence car ownership decisions.

An analogue analysis has been done to investigate the incidence of shared mobility on perceived car dependency across the different rings of the metropolitan areas (see Figure 9-4). In a similar fashion, the results show that even outside the core city of the metropolitan area, one quarter of the respondents considers that shared mobility could substitute car ownership in the future. It seems particularly relevant to mention that the percentage of shared mobility users considering a car would not be a necessity in the future displays very limited variations across the different rings. In this regard, the results yielded by the model that showed that the adoption of shared mobility can reduce car dependency in low-density areas are confirmed and hint towards shared mobility as a valuable tool to guarantee accessibility.

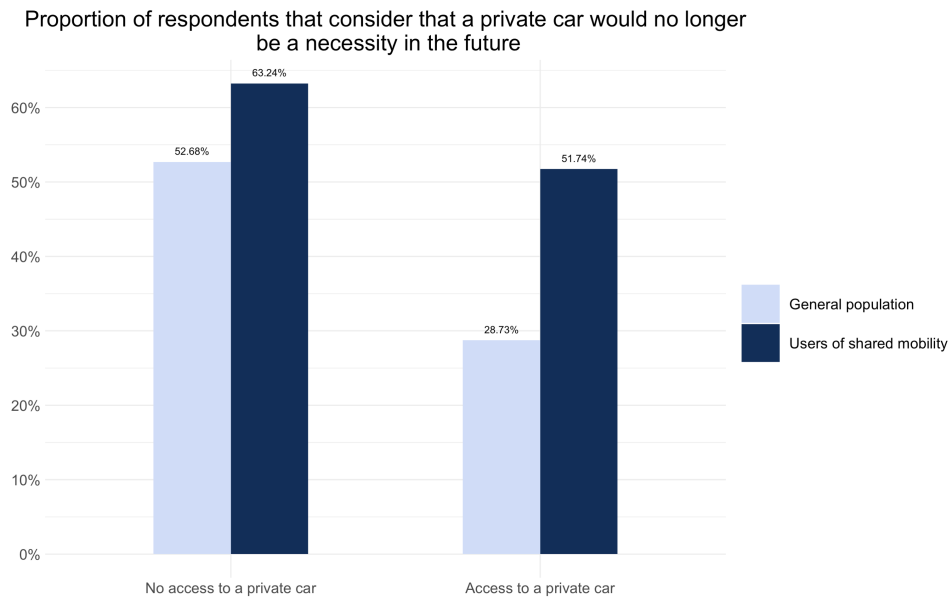


Figure 9-3: Percentage of respondents that believe that car would no longer be necessary in the future, given the increase supply of shared mobility, depending on the access to a private car — users vs. non-users.

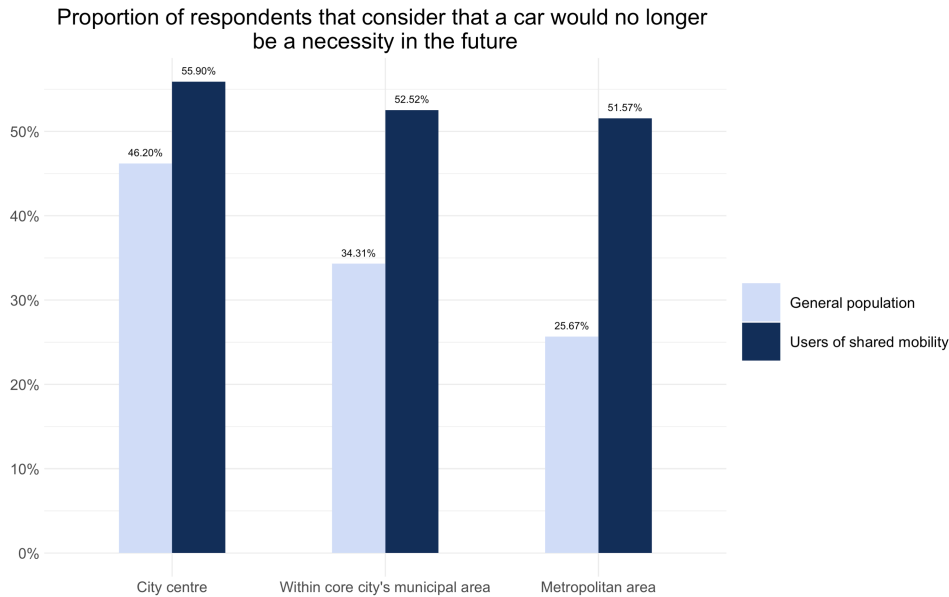


Figure 9-4: Percentage of respondents that believe that car would no longer be necessary in the future, given the increase supply of shared mobility, depending on the place of residence within the metropolitan area — users vs. non-users.

RQ3	Which individual attributes, considering socio-economic variables, subjective attitudes and travel behaviour, are correlated with a higher impact of shared mobility on the individual's perceived car dependency?
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The answer to this question is based on the findings of SP2 and SP3. The joint analysis of the results suggests that the subjective attitudes that determined the perceived need to own a car in the future given the increasing supply of shared mobility are somewhat different between users and non-users. While users' perceptions seem to be mostly influenced by their level of comfortability introducing elements of the shared economy in their daily life, in the case of the general population the lack of technological savviness seems to be a main driver to believe that shared services could substitute the private car in the future. In terms of socio-economic attributes, the analysis suggests that the most common profile to believe that a car would not be necessary in the future given the increasing supply of shared mobility, both among the general population and among users of this services, is that of a high-income teleworker with high levels of education. Specially interesting is to note that the effect of age differs between users and not users. While among those that have already adopted shared mobility, the age is positively correlated with the probability of believing that a car would no longer be necessary in the future, among the general population a negative effect of age is observed.

As for travel behaviour variables, the effect of current car ownership level is particularly strong both for users and non-users. Interestingly, it was found that shared mobility is more likely to prevent non-car owners from purchasing one, that inducing a reduction in car ownership among those that already own one. Finally, it has been observed that the combination of different shared services in the mobility habits of the individual plays a bigger role in reducing perceived car dependency than a high frequency of use of a single service.

RQ4	How does the spatial context affect the potential impact of shared mobility in perceived car dependency?
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The main contributions to this research question come from SP2, although additional insights are also provided by SP3. In general terms, it can be considered that the impact of the spatial context on the reduction of perceived car dependency through shared mobility expansion is smaller than what could have been expected, with the effects of the spatial variables being considerably smaller than those of the individual variables. Within the metropolitan area, residents in the central districts of the core city are more likely to believe that a car will not be

necessary in the future, even after controlling for socio-economic variables and car ownership. However, it is noteworthy that the relative reductions in likelihood for some areas outside Madrid city centre (e.g. outer districts of Madrid and some municipal areas located in the sub-urban ring) are quite limited. This is in spite of the fact that the supply of shared mobility in those areas is still scarce or non-existent. In this regard, the fact that the unexplained variance across areas virtually disappears when introducing spatial variables such as population density and land-use mix, shows that the potential impact of shared mobility on car dependency is determined to a larger extent by the urban development pattern than by the position within the metropolitan area. This conclusion is further supported by the results yielded by SP3, according to which nor the place of residence within the metropolitan area neither the availability of shared mobility around the place of residence significantly influenced the perception of needing a car in the future given the increase in shared mobility supply. Finally, the comparison across cities conducted in SP3 revealed no statistical differences across the perceived need of owning a car of individuals living in urban areas of different sizes and urban forms. The coherence between the results obtained in both publications point to a similar effect of the spatial context for users and non-users of shared mobility services.

9.3. Verification of the research hypotheses

In general terms, the results obtained verify the research hypotheses that were raised in Section 4.4 (Research hypotheses).

The first hypothesis which was related to the changes in car-based mobility induced by the COVID-19 pandemic has been confirmed by the first study of the thesis. The findings indicate that the crisis has indeed influenced several of the primary factors influencing private car-based mobility. It is important to note that, due to the time at which the data for this study was collected, the results do not allow for confirmation of whether these changes persisted after the conclusion of the pandemic. Nevertheless, the findings indicate that changes in car ownership were precipitated among specific population segments that were observed to be relatively independent from private cars before the pandemic. Thus, probably affecting their mid-term mobility habits and choices regarding the use of private cars.

The second hypothesis has been confirmed in the second and third studies. This part of the thesis has shown that the progressive expansion of shared mobility services can impact the perception that individuals have of needing to own a car in the future. However, in accordance with the third hypothesis it was clearly observed that the individual's current travel habits play a central role determining to what extent shared mobility can actually reduce car dependency. In particular, the adoption of shared mobility is clearly correlated with a lower level of future

car dependency. Moreover, the finding that socio-economic attributes were statistically significant explanators of the perceived need to own a car in the future, even when considered within the context of different traveller profiles, lends further support to the validity of hypothesis 2. Finally, the fifth hypothesis may be regarded as the one in which the thesis yields more unexpected results. While the impact of shared mobility on perceived car dependency was observed to undoubtedly have a spatial dimension for the general population, the role of the spatial context, both in terms of area of residence within the metropolitan area and city of residence, was rather limited among users of shared mobility

10. Conclusions, policy recommendations and further research

This chapter first outlines the main contributions of this thesis to the existing literature (Section 10.1). Secondly, Section 10.2 presents the main policy recommendations for harnessing the potential of shared mobility to reduce individuals' car dependency in the mid-term. Finally, Section 10.3 assesses the limitations of the research conducted in this thesis and suggests avenues for further research that could extend the conclusions reached here.

10.1. Contributions

This thesis has explored the interrelationships between the expansion of shared mobility services and perceived car dependency through a series of behavioural analysis. These analyses have employed discrete choice models as methodological frameworks and survey data as main source of information. As shown in the previous chapter (see Section 9.2), the results yielded by these analyses have allowed to provide sound answers to the research questions that were initially raised. Thus, covering the research gaps that were identified and making some valuable contributions to the body of research analysing the relationship between shared mobility and car dependency.

Most of these contributions emerge from the wide variety of explanatory factors that has been considered in the modelling frameworks. The influence of different types of variables has been covered in an integrated manner. On the one hand, individuals' socio-economic attributes, whose interrelations with the impact of shared mobility on car dependency have been largely considered in previous works, have been complemented with subjective attitudes and travel behaviour with respect to a large variety of traditional and shared modes. In this respect, no previous work has modelled how the frequency of use of all available shared services or their combined use with each other and with traditional modes, affects car dependency. The introduction of these interactions has allowed to conclude that the combination of various shared services in the daily mobility habits of individuals has a larger effect on perceived car dependency than a high frequency of use of just one service. In a similar trend, the interactions between current car ownership and car use and the frequency of use of shared mobility have shown that adopting car-sharing or moped-sharing leads heavy car dependent individuals to significantly increase their likelihood of believing that they will not need a car in the future. These findings entail relevant information for the development of mobility policies that profit from the potential of shared mobility to replace private cars.

In addition to the findings on reported travel behaviour, the results on the effect of income provide a relevant contribution to the literature. In contrast with previous works analysing the impact of car-sharing on car ownership (see for instance, Kim et al., 2019 for the case of Seoul, South Korea or Le Vine & Polak, 2019 for London, UK), this thesis' modelling results indicate that high-income groups are more likely to believe that they will not need a car in the future. This divergence hints towards the existence of differences in the socio-economic groups whose car ownership could be affected by shared mobility if the ecosystem is considered as a whole rather than a specific service.

On the other hand, spatial-level drivers have shown a prominent role in explaining car dependency reduction due to the expansion of shared mobility. Previous works have only considered the place of residence within the metropolitan area and, in some rare cases, accessibility to public transport. Aiming to explore this aspect in more depth, this thesis has developed a nested multilevel model that provided insights on the heterogeneity that exists in the interactions between shared mobility and car dependency across the municipalities and city districts of the whole Region of Madrid, including urban, sub-urban and rural community typologies. The consideration of these aspects allowed to observe that, surprisingly, the place of residence within the metropolitan area does not necessarily determine the potential impact of shared mobility on car dependency. In fact, the results reveal that, while the differences across metropolitan rings are not significant, the variance across municipal areas display significant heterogeneity that does not decrease monotonously as we move further away from the city centre.

Finally, the thesis explored the perceptions of both users and non-users of shared mobility to quantify the potential of these services to reduce car dependency, despite their lack of availability in areas outside of city centres and the generally low adoption rates that are currently observed for shared mobility. In this regard, the Spanish urban areas have offered a particularly interesting case study, given the wide expansion of shared mobility, both in terms of variety and fleet size, in combination with a good provision of public transport that can be found in these cities (Fluctuo, 2024). These conditions provide a particularly suitable scenario to analyse how car dependency can be reduced through the deployment of a shared mobility ecosystem. Finally, it is worth highlighting that obtaining robust results for such a wide variety of factors and the development of multilevel models has only been possible through the use of surveys that gathered a high number of responses (10,500; 3,999 and 15,666 respectively) and that were rarely used in previous works analysing the impact of shared mobility on car dependency.

10.2. Policy recommendations

The findings presented in this research can contribute to the development of more efficient sustainable mobility strategies that promote shared mobility as a viable alternative to car ownership. These policy recommendations are exposed hereafter.

- **Shared mobility can be instrumentalized to prevent long-term car dependency among younger generations.** This recommendation is heavily supported by various results obtained through the analysis carried out on this thesis. First, while age seems to be correlated with perceived car dependency among the general population, the

opposite is observed for users of shared mobility. Second, among non-users the main barrier to consider shared mobility as a feasible substitute of the private car seems to be the level of comfort with technology. Third, the results clearly show that those who do not own a car currently show consistently higher tendency to believe they will still not need a car in the future given the increasing supply of shared mobility. Taking together these conclusions, it becomes clear that incentivizing the use of shared mobility among the younger segments of the population, which are in general observed to display higher levels of technological savviness (Magotra, Sharma, & Sharma, 2016) and lower levels of car ownership (Yang et al., 2021), could be an effective way to reduce car dependency in the future. For example, policies could include integrating shared mobility services into youth public transport cards, ensuring an adequate supply of vehicles in university areas or offering discounted fares for young families who opt not to purchase a private car.

- **Combine teleworking arrangements with shared mobility options to further reduce car dependency.** Teleworkers display significantly higher likelihoods of believing that a car will not be necessary in the future as a consequence of shared mobility. This shows that a reduced frequency of commuting in combination with the availability of shared mobility could have a substantial impact on car dependency. Furthermore, the analysis focusing on the changes induced by the COVID-19 pandemic regarding car ownership and use shows a correlation between the adoption of teleworking regimes and decreased car usage, with this correlation being stronger for more flexible arrangements. Consequently, administrations should develop collaborations with employers to find ways of combining the potential of these two policies to reduce car dependency. For instance, offering shared mobility subscription plans for commuting in-person working days.
- **Incorporate equity considerations when utilizing shared mobility as a strategy to reduce car dependency.** The analyses hint towards a larger reduction of car ownership and use among high-income individuals due to new trends in urban mobility that have been considered. On the one hand, while the COVID-19 pandemic has led to a higher reduction of car use among wealthier and more educated individuals, low-income households have been the least likely to reduce their car use, often maintaining similar levels of car mobility. This is presumably due to the lower capacity of these groups to adopt teleworking (Sweet and Scott, 2022) and an increase in the convenience of car as a result of less congestion and more parking availability. Similarly, higher-income groups display lower perceived car dependency resulting from the expansion of shared

mobility services both among users and non-users. This result may be related to the high fares of shared services that make them less appealing to lower-income groups (Brown, 2022). These cross-cutting findings make clear that the transition to a private car-independent mobility system might result in unwanted disfavoured consequences for some socio-economic groups. For instance, low-income groups might be forced to stay car dependent, with the economic burden that this would entail. For this reason, it is essential to find ways to ensure that all population segments can fulfil their mobility needs in an environmentally and economically sustainable way.

- **Modal integration to incentivize variety over frequency in shared mobility services usage.** Introducing various types of shared mobility services in the bundle of mobility choices seems to decrease perceived car dependency to a considerably larger extent than a high frequency of use of just one service. However, in the current situation, shared mobility services are mostly operating individually without any integration strategy that facilitates the access to different services. If shared mobility is to become a realistic alternative to the private car, the different elements of the shared mobility ecosystems should be seamlessly integrated to facilitate access to the mode that best suits the individual's purpose in each case.
- **Encourage car dependent individuals to try shared moped scooter or shared cars.** It has been observed that the adoption of one or both of these shared mobility services significantly increases the likelihood that people consider that they will not need a car in the future given the expansion of shared mobility, even if they currently exhibit extremely car dependent behavioural patterns. Therefore, providing them with incentives to try, even with a very low frequency of use, has great potential to alter their perception regarding the feasibility of reducing car ownership levels.
- **Sustainable urban planning is key to harness the potential of shared mobility as an alternative to the private car in sub-urban areas.** Regardless of the city of residence or the place of residence within the metropolitan areas, increased population density and land-use mix significantly increase the probability of believing that a car will not be necessary in the future, given the expansion of shared mobility. These findings show that shared mobility alone would not reduce the excessive reliance on private cars and its deployment would inevitably require urban development strategies that promote sustainable mobility.

10.3. Limitations and further research

Notwithstanding the relevant contributions and policy insights yielded by this thesis, some limitations have become apparent throughout the course of the research. Rather than undermining the validity of the results, these limitations provide valuable leads for new avenues of research that would enhance the understanding of the role of shared mobility as a tool to achieve more sustainable urban mobility systems.

This work has included latent variables capturing subjective attitudes, such as technological savviness, environmental awareness or willingness to use shared services. Nevertheless, some additional subjective preferences that could significantly affect the perception of individuals regarding the reduced need to own a car given the expansion of shared mobility should be considered in future research. In particular, safety concerns regarding the use of different modes (e.g. mopeds or kick-scooters) should be taken into account, as they have been observed to be a barrier for adoption (see e.g., Kopplin et al., 2021 or Pourfalatoun et al., 2023). Similarly, the symbolic value of cars as demonstration of social status or the positive emotions that some individuals experience when owning and driving cars should be accounted for in order to more accurately assess the potential of shared mobility to reduce car dependency.

As mentioned before, this study had to employ the perceived need to own a car in the future given the expansion of shared mobility as a proxy of the mid-term impact that these services could have on car dependency. This was due to several factors, including the limited adoption and geographical availability of shared mobility services, as well as the relatively short time span since these services were implemented to measure their structural impact on car dependence. However, future studies could employ empirical data from sub-urban and rural areas where different shared mobility services have been already deployed to conduct analogue analysis based on revealed preferences and perceptions.

Additionally, this work has conducted spatial analysis at the level of the city districts (for the case of Madrid), the municipal areas or the zip code area, which has allowed to reach a considerable level of understanding of the role of spatial context in the individual's place of residence on the potential of shared mobility to reduce perceived car dependency. However, non-negligible heterogeneity remains unaddressed within these administrative divisions. For this reason, future research would undoubtedly benefit from a more detailed spatial disaggregation (e.g. census tract) to better characterize the urban environment around the individual's residence. In addition, it would also be interesting to consider the built

environment of the individual's most frequent destination, as this is also likely to influence mobility habits and car ownership decisions.

Finally, analysing the impact of shared mobility on car dependency through stated choice experiments would allow for a more nuanced examination of how different levels of expansion and integration of shared mobility services might lead to different choices of car ownership and use. Such studies would be an interesting complement to the findings of this thesis, which are of a more general nature.

Beyond the consolidations of the results that can be achieved by overcoming the limitations stated above, further research lines opened based on the findings of this thesis. First, the results made clear that a reduction in perceived car dependency is correlated with a more multimodal behaviour. In this regard, the role of integration between shared modes and public transport or private active modes in the sustainable mobility transition should be further explored. First, integrated ticketing systems in which the shared mobility services can be used by a reduced price when being used to access public transport could be explored. Similarly, this topic could be approached from an accessibility perspective, exploring combined fare schemes that allow residents in areas with limited public transport to access key destinations without significantly increasing travel costs. Second, the role of physical integration (for instance via mobility hubs) could facilitate the operation of shared mobility services in low-density areas and its impact on car dependency could yield relevant insights on how to harness shared mobility to mitigate this problem.

Second, the findings of this thesis suggest that shared mobility has potential to reduce car dependency in sub-urban areas, where this problem is more acute. However, in most cases these services have not yet reached these places due to the low cost-effectiveness that offering shared vehicles in these areas entails for companies. In this regard, future research lines should explore strategies to improve the economic sustainability of expanding shared fleets and make their operations outside city centres viable. For this purpose, it could be key to understand how the demand for shared mobility services is associated with the number of vehicles available and how can they be distributed to maximize the turnover in lower-density areas. In addition, the identification of sub-urban neighbours where car dependency intersects with socio-economic inequality could reveal situations in which subsidized shared mobility could complement public transport to increase the access to opportunities among disfavoured groups. An alternative approach to this challenge involves proposing models that re-think shared mobility beyond the capitalistic logic. For instance, the concept of Mobility as a Common (Nikolaeva et al., 2019) proposes the deployment of shared vehicles among communities, rather than operated by private operators.

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