Environmental Impacts of Shared Mobility: Potential, Factors, and Assessments

Arbelaez Velez, Ana Maria

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ANA MARÍA ARBELÁEZ VÉLEZ | IIIEE | LUND UNIVERSITY

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Ana María Arbeláez Vélez

LUND UNIVERSITY

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Abstract

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Shared mobility is a demand-side mechanism that has the potential to change travel behavior and vehicle ownership rates among users. This dissertation aims to understand the potential of shared mobility to decrease the environmental impacts of passenger transportation and to understand the factors that might affect this potential. Here I focus on car sharing, with additional attention to ridesharing, bikesharing, and scooter and moped sharing. In this research I design and apply assessments using life-cycle analysis and multiregional input and output analysis to evaluate the environmental potential of shared mobility. My findings add to our knowledge and understanding of the potential of shared mobility. This study also adds to environmental assessments methods by applying multiregional input and output analysis in a novel way.

Changes in both travel behavior and expenditures influenced the impacts of car sharing. Greenhouse gas (GHG) emissions from passenger transportation may either decrease or increase after people engage in car sharing. People who give up private vehicle ownership and shift to active, public and shared transportation decrease their emissions, while people who increase their solo driving increase them. Changes in travel behavior affect the way people spend their income: for example, decreasing spending on fuel, insurance and maintenance while increasing consumption of other products and services. These changes in spending are related to rebound effects that have the potential to decrease reductions in GHG due to car sharing by 71-80%.

The potential of car sharing to decrease the environmental impacts of passenger transportation is also affected by how it was designed and implemented. Differences in ownership models—i.e., whether shared cars are owned by a company or individuals—are found to have a limited influence on GHG emissions.

The specific context of a car sharing system will determine the best form of implementation and its transformational potential. Contextual factors include variables such as the robustness of public transportation networks, cyclist and pedestrian safety, and the availability of charging infrastructure. Car sharing can be a tool to drive a shift away from car ownership; however, countries that have a higher share of public and active transportation users are more likely to witness a shift away from car ownership with the incorporation of car sharing than countries that have high rates of car ownership and use.

This study suggests that shared mobility does not, by default, lead to a decrease in the environmental impacts from passenger transportation. It instead suggests that shared mobility needs to be designed, implemented and used in a certain way in order to achieve this goal. Shared mobility might be implemented in several contexts as one of several tools to reduce environmental impacts from passenger transportation, and in this work I find that a combination of several tools has the greatest potential to achieve such a reduction.

Key words shared mobility, environmental impacts, sustainable transportation, input and output analysis, life-cycle assessment, transportation assessment, demand-side solutions

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MADE IN SWEDEN

Para mi mamá y mi papá,
que son mi ejemplo de perseverancia y constancia.

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Abstract

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The potential of car sharing to decrease the environmental impacts of passenger transportation is also affected by how it was designed and implemented. Differences in ownership models—i.e., whether shared cars are owned by a company or individuals—are found to have a limited influence on GHG emissions.

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a tool to drive a shift away from car ownership; however, countries that have a higher share of public and active transportation users are more likely to witness a shift away from car ownership with the incorporation of car sharing than countries that have high rates of car ownership and use.

This study suggests that shared mobility does not, by default, lead to a decrease in the environmental impacts from passenger transportation. It instead suggests that shared mobility needs to be designed, implemented and used in a certain way in order to achieve this goal. Shared mobility might be implemented in several contexts as one of several tools to reduce environmental impacts from passenger transportation, and in this work I find that a combination of several tools has the greatest potential to achieve such a reduction.

Popular Science Summary

Greenhouse gas (GHG) emissions from passenger transportation continue to increase globally due to a rise in kilometers traveled and a shift from public and active transportation to car and motorcycle ownership and use. Passenger transportation is associated with other negative environmental impacts in cities, including air pollution, noise, and changes in land use. Thus far, technological solutions such as electric cars have been used to hold down emissions and other environmental impacts from passenger transportation.

Although shifting to electric cars promises some environmental savings, it also presents challenges. For example, rare earth metals need to be extracted to produce electric car batteries, which leads to changes in ecosystems and land use. Even if there is a shift to electric vehicles, the problems of increasing car ownership and kilometers traveled by car remain unaddressed.

We need transportation solutions that allow us to change the way we travel. One of these solutions is shared mobility. Shared mobility means acquiring access to a vehicle or a transportation service for a certain period of time in exchange for a fee, or for free, using apps or the internet.

Shared mobility encompasses various modes, including car sharing, ridesharing, on-demand services, and micromobility sharing. This dissertation focuses on car sharing, ridesharing, and micromobility sharing. Car sharing is when people gain access to a car without a driver. Ridesharing is when people with similar travel destinations share the space in a vehicle—also called carpooling or vanpooling. Lastly, micromobility sharing encompasses the sharing of bikes, scooters, and mopeds. Shared mobility options have the potential to change how people travel. Previous research has shown that it has the potential to change the distances people travel, the transportation mode they use, and the rate of car ownership.

This dissertation assesses how shared mobility changes the environmental performance of passenger transportation and explores how this decrease unfolds. It explores two research questions: What is the potential of shared mobility in decreasing the environmental impacts of personal transportation in urban contexts? And which factors affect the potential of shared mobility to reduce the environmental impacts of personal transportation in urban contexts?

This investigation found that car sharing has the potential to both exacerbate and hold down environmental impacts from passenger transportation. Car sharing can decrease the environmental impacts of passenger transportation when it allows a shift from environmentally impactful transportation modes to ones with lower impacts. For example, when car sharing enables users to abandon car ownership and use public and active transportation in combination with car sharing, impacts are most likely to decrease. In contrast, if car sharing gives non-car-owners greater

access to cars, environmental impacts are likely to increase. However, the decrease in GHG emissions when a person relinquishes car ownership is much greater than the increase in GHG emissions from people who gain access to shared cars. Ridesharing was found to have the potential to reduce environmental impacts from passenger transportation if it leads to an increase in vehicle occupancy due to ridesharing users driving with other passengers instead of driving alone. Micromobility modes were found to increase environmental impacts when people use them to replace walking or the use of private bikes or e-scooters. This increase occurs due to additional operational overhead and equipment that shared micromobility modes require, such as higher rates of maintenance, rebalancing of the fleet, and tracking devices.

Since car sharing has the potential to change how people travel, it also has the potential to change how people spend their income. When car owners shed their cars thanks to the availability of car sharing, their spending on car insurance, fuel, and maintenance drops. However, these "savings" will most likely be redirected to other consumption categories. The reduction in actual environmental savings from car sharing due to increased spending in other categories is known as a rebound effect. In this thesis I find that the initial savings from car sharing may be reduced by 71-81% due to this phenomenon.

In this dissertation I also identify factors that affect the potential of shared mobility to decrease emissions from passenger transportation, distinguishing four types of such factors: changes in travel behavior, the design and operation of shared mobility modes, household spending, and context.

Identifying how shared mobility can decrease the environmental impacts from personal transportation, as well as identifying the factors that affect these impacts, can help governments and sharing organizations develop transportation policies and shared mobility modes that have the greatest likelihood of delivering on the promise of environmental gains. This can facilitate the development of shared mobility modes that can, when combined with strong public transportation networks, support car-free lifestyles in urban areas.

List of papers

Paper I — Arbeláez Vélez, A. M. Environmental impacts of shared mobility: A systematic literature review of life-cycle assessments focusing on car sharing, carpooling, bikesharing, scooters and moped sharing. Under review in: *Transport Reviews*

Paper II — Arbeláez Vélez, A. M., & Plepys, A. (2021). Car sharing as a strategy to address GHG emissions in the transport system: Evaluation of effects of car sharing in Amsterdam. *Sustainability, 13*(4), 2418. https://www.mdpi.com/2071-1050/13/4/2418

Paper III — Arbeláez Vélez, A. M. (2023). Economic impacts, carbon footprint and rebound effects of car sharing: Scenario analysis assessing business-to-consumer and peer-to-peer car sharing. Sustainable *Production and Consumption, 35*, 238-249. https://doi.org/https://doi.org/10.1016/j.spc.2022.11.004

Paper IV — Arbeláez Vélez, A. M., Ivanova, D., & Statler, K. Shared mobility and lifestyles as mechanisms to reduce environmental impacts from transport. Under review in: *Environmental Research Letters*, special edition: Focus on Technology and Global Change.

Contribution to papers

Paper 1 — A.M.A.V. developed the idea and research design. A.M.A.V. collected the data and conducted the literature review. A.P. and O.M. reviewed drafts of the literature review and provided feedback. A.M.A.V. answered peer-review comments.

Paper 2 — A.M.A.V. developed the idea and research design. A.M.A.V. collected data and conducted the LCA. A.P. was consulted during the process. A.M.A.V. wrote the paper, and A.P. and O.M. commented on the draft. A.M.A.V. answered peer-review comments.

Paper 3 — A.M.A.V. developed the idea and research design. A.P. was consulted during the process. A.M.A.V. collected data and conducted the MRIO analysis, and A.P. was consulted along the process. A.M.A.V. wrote the paper, and A.P. and O.M. commented on the draft. A.M.A.V. answered peer-review comments.

Paper 4 — A.M.A.V., D.I. and K.S. developed the idea and research design. A.M.A.V. collected data and conducted the MRIO analysis. D.I. and K.S. were consulted during this process. A.M.A.V. wrote the paper, and D.I. and K.S. commented on the drafts. All authors will take care of the peer-review process.

Other publications

Mont, O., Voytenko Palgan, Y., Plepys, A., & Arbeláez Vélez, A. M. (2022). Urban sharing in Melbourne. City report no. 4. https://static1.squarespace.com/static/581097b4e3df28ce37b24947/t/63355959dd415e557c79cab8/1664440667717/Melbourne+_2021_FINAL_220818.pdf

Plepys, A., & Arbeláez Vélez, A. M. (2021). Chapter 15: The environmental implications of car-sharing In T. Sigler & J. Corcoran (Eds.), *A modern guide to the urban sharing economy*. Edward Elgar Publishing. https://doi.org/10.4337/9781789909562

Mont, O., Plepys, A., Voytenko Palgan, Y., Curtis, S., Zvolska, L., & Arbeláez Vélez, A. M. (2020). Urban sharing in Shanghai. City report no. 3. https://static1.squarespace.com/static/581097b4e3df28ce37b24947/t/6055e1a72998f4194fe73111/1616241064945/Shanghai+report-komprimerad.pdf

Mont, O., Plepys, A., Voytenko Palgan, Y., Curtis, S., Zvolska, L., & Arbeláez Vélez, A. M. (2020). Urban sharing in Toronto. City report no. 2. https://static1.squarespace.com/static/581097b4e3df28ce37b24947/t/5f0c1d23792782130c6c4883/1594629426451/Toronto+report_FINAL_web.pdf

Mont, O., Plepys, A., Voytenko Palgan, Y., Singh, J., Curtis, S., Zvolska, L., & Arbeláez Vélez, A. M. (2019). Urban sharing in Amsterdam. City report no. 1. ISBN: 978-91-7895-321-9https://static1.squarespace.com/static/581097b4e3df28ce37b24947/t/5da46c7b6b739e6f84c8528a/1571056875497/Cityreport1Amsterdam.pdf

Arbeláez Vélez, A. M. (2019). Quantifying the sustainability impacts of sharing economy at a city level. Working paper, IIIEE at Lund University. Working+paperVelez.pdf (squarespace.com)

Preface

This research was conducted at the International Institute for Industrial Environmental Economics (IIIEE) at Lund University. The IIIEE is known for its inter- and transdisciplinary research that involves several societal actors and its focus on solution-oriented investigations.

This dissertation was part of the Urban Sharing project that was funded by the European Research Council under the European Union's Horizon 2020 research and innovation program (grant number 771872). The project aims to test, and advance knowledge about urban sharing organizations from the perspectives of sustainability, business model design, and institutionalization. These different perspectives have been studied by professor Oksana Mont, senior lecturer Yuliya Voytenko Palgan, lecturer Andrius Plepys, postdoctoral fellow Jagdeep Sigh, and PhD students Lucie Enochsson, Steven Curtis, and Ana María Arbeláez Vélez. These team members represent different disciplines, creating an interdisciplinary research group using a combination of methods, including mobile research labs, case studies, interviews, observation, expert panels, modeling exercises, and on-site fieldwork. This broader project focused on five cities: Amsterdam, Seoul, Melbourne, Toronto, and Shanghai. Including different cities in the project allowed researchers to compare urban sharing in different city contexts.

Abbreviations

GHG	Greenhouse gases
CO_2	Carbon dioxide
NO_x	Nitric oxide
ICV	Internal combustion vehicle
EV	Electrical vehicle
ICT	Information and communication technologies
B2B	Business-to-consumer
P2P	Peer-to-peer
LCA	Life-cycle assessment
MRIO	Multiregional input and output
WTW	Well-to-wheel
PSS	Product service systems
B2B	Business-to-business
TBL	Triple bottom line
IOA	Input and output analysis
IOT	Input and output tables
TAU	Transportation as usual
ASI	Avoid-shift-improve
ASI + ST	Digitalization and social transformation
$PM_{2.5}$	Particulate matter 2.5

1 Introduction

Since the Industrial Revolution, greenhouse gas (GHG) emissions levels have increased due to human activity, as well as the rate of extraction of natural resources such as minerals, wood and water (Lamb et al., 2021). This trend has generated unprecedented pressure on the environment and has led to changes that are unsustainable. Global actions are being taken to reduce these negative environmental impacts: for example, the Paris Agreement, in which the international community agreed to reduce emissions in order to limit the temperature rise to “well below” 2°C. Transportation is one of the sectors with the highest growth in emissions, which—despite these efforts—have increased globally by 1.9% each year, from 7.3 Gt CO_2eq in 2010 to 8.5 Gt CO_2eq in 2018. Almost three-quarters of these emissions come from freight and passenger road transportation (Lamb et al., 2021). Passenger transportation emissions have increased due to a rise in transportation activity and a shift to higher-emitting transportation modes (European Commission, 2019; Hansen & Nielsen, 2017; SLoCaT, 2018).

Sustainable consumption and production is the 12th UN Sustainable Development Goal, with the aim of building systems that efficiently uses resources and developing solutions to reduce harmful environmental impacts from human activity (United Nations, 2002). Production solutions—also referred as supply-side solutions—have focused on improving energy efficiency, shifting to renewable energy sources, and developing cleaner forms of production (DeSimone & Popoff, 1997; IPCC, 2022; World Business Council for Sustainable Development, 1996). Consumption solutions—also called as demand-side solutions—have focused on changing how people consume through changes in lifestyles and behaviors enabled by new systems of provision and new socio-technological schemes (Méjean et al., 2019; Wachsmuth & Duscha, 2019). Studies have found that demand-side solutions have high mitigation potential in the passenger transportation sector, such as shifts to car-free lifestyles and decisions to buy more efficient cars (Ivanova et al., 2020; Wynes & Nicholas, 2017). However, fewer researchers have looked at the mitigation potential of demand-side solutions (Creutzig et al., 2018; Wachsmuth & Duscha, 2019).

One demand-side solution for passenger transportation is shared mobility. Shared mobility gives users access to a vehicle or transportation service for a limited amount of time, either in exchange for a fee or for free (Shaheen & Cohen, 2018).

Shared mobility encompasses a variety of transportation modes, from traditional forms such as public transportation to more novel ones such as car sharing, ridesharing, and bikesharing. Shared mobility modes have been found to change the way people travel by changing travel distances, modal shares, car ownership rates, and car purchase motivation (Gleave, 2017; Martin & Shaheen, 2011; Namazu & Dowlatabadi, 2018; Shaheen et al., 2019).

In this chapter I first present the environmental challenges posed by passenger transportation, then introduce the concept of shared mobility and its potential to change travel behavior, as well as the consequences of these changes on environmental impacts from passenger transportation. Finally, I discuss existing gaps in our knowledge on this subject and how this thesis aims to cover them, as well as further detailing the scope of the dissertation and presenting in a summarized manner the papers included in this thesis.

1.1 Passenger transportation: A growing problem

Passenger and freight road transportation accounts for almost three-quarters of all transportation emissions globally and is the largest source of transport emissions in all regions of the world (Figure 1-a and Figure 1-b). The increase in GHG emissions from personal transportation is associated with an overall increase in passenger transportation, rising car ownership, and a shift to more emissions-intensive transportation modes.

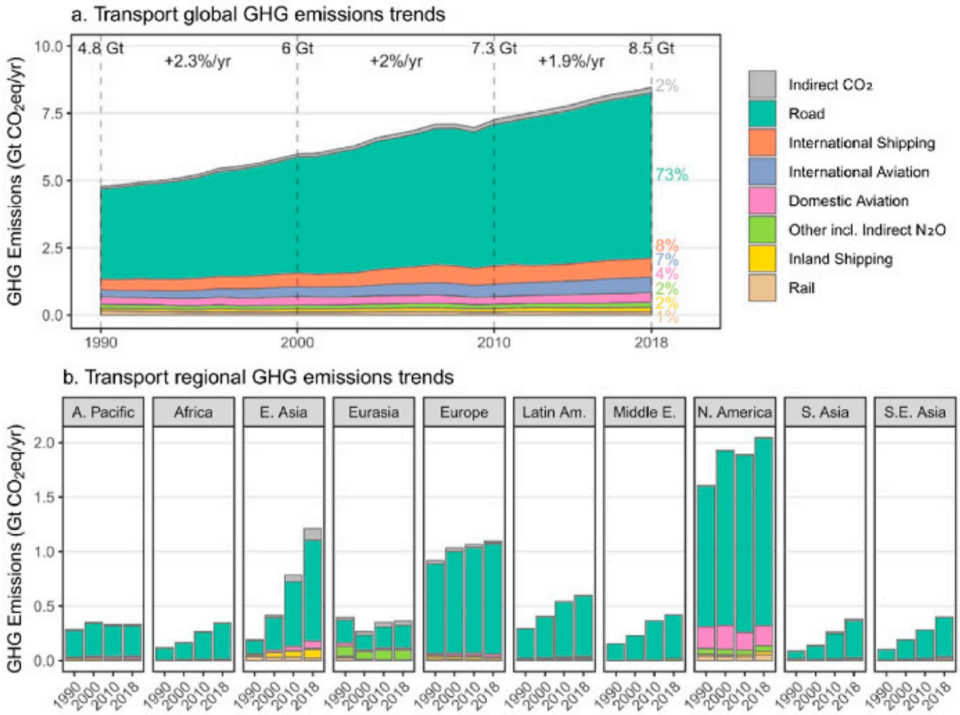

Figure 1 – Global and regional GHG emissions, 1990-2018. (From Lamb et al. (2021)

Passenger transportation activity is increasing in all regions of the world: In Europe, activity increased by 40% compared with 1990 levels, and Asia presents the fastest growth doe to increase in motorcycle ownership (Eurostat, 2022; Lamb et al., 2021; Sims R. et al., 2014). Some of the socioeconomic factors driving increasing travel distance include growth in household disposable incomes (linked to the increase in per capita GDP) and total population, changes in household composition, and urbanization (Ding et al., 2017; Jong & Riet, 2008; Lamb et al., 2021; Oakil et al., 2016a).

Car ownership has risen in all regions of the world, a trend that is forecasted to continue (Dargay et al., 2007; European Research Agency, 2012). In 2020, there were 651 cars per 1000 inhabitants in North America, 483 in Europe, 136 in Latin America, and 26 in India (European Research Agency, 2012). Researchers have predicted that car ownership rates in Latin America and India could reach 317 and 105 cars per 1000 inhabitants, respectively, by 2050 (European Research Agency, 2012). This growth in car ownership is driven by growing household incomes and changes in household composition and the built environment, among others (Ding et al., 2017; Jong & Riet, 2008; Oakil et al., 2016a). This rise in car ownership shows that society is not shifting away from car dependence, in part due to barriers such as tensions between established industries, societal/cultural norms, and the current systems of provision (Mattioli et al., 2020).

A shift in the modal split from public and active transportation to more emissions-intensive transportation modes such as motorcycle or car ridership is also linked to emissions increases (Lamb et al., 2021; Sims R. et al., 2014). Car driving is one of the highest-emitting transportation modes per kilometer travelled. Direct emissions from passenger cars range between 90 and 250 g CO_2eq per kilometer, and motorcycle emissions range between 75 and 225 g CO_2eq per kilometer, while rail ranges between 40 and 110 g CO_2eq per kilometer and buses between 25 and 125 g CO_2eq per kilometer (Sims R. et al., 2014). The rise in per capita GDP has been linked to a shift from lower- to higher-emitting transportation modes (Gota et al., 2019; Matas & Raymond, 2008; Pendyala et al., 1995).

Despite the environmental impacts of car driving and ownership, car use is an important transportation alternative for people who live in lower-population areas who cannot access public transportation, as well as for people with special mobility needs. Recognizing that transportation solutions vary depending on factors such as the built environment, personal health, and geographical location is key to developing transportation systems and policies that cater to everyone’s transportation needs.

Passenger vehicle fleet electrification is one supply-side solution to decreasing passenger transportation emissions. When both direct and indirect emissions are included, internal combustion vehicles (ICV) can emit up to 32.7 t CO_2eq compared to electric vehicles (EVs), which emit 26.2 t CO_2eq (a value that depends on the energy mix used to charge the car) (Ellingsen et al., 2016; Ivanova et al., 2020). In addition to this, EVs also promise to improve local air quality and decrease fuel depletion during the use phase (Lin et al., 2020; Soret et al., 2014).

Although evidence points to potential environmental benefits from EVs in some cases, other studies have identified that EVs have the potential to exacerbate negative environmental impacts. Bauer et al. (2015) reported that out of all vehicle types, EVs had the highest impact on human toxicity potential, terrestrial acidification, and particulate matter formation. Their study found that all these impacts could be mitigated by using clean energy sources to charge vehicles—a key variable if EVs are to deliver on their emissions savings potential in the use phase. Studies by Burchart-Korol et al. (2018) and Bicer and Dincer (2018) yielded similar results. Depletion of scarce metals such as lithium and cobalt has also been identified as a potential impact from battery manufacturing (de Souza et al., 2018; Van Mierlo et al., 2017). Passenger fleet electrification cannot deliver its expected carbon savings if vehicles are powered by high-carbon energy sources (Marmiroli et al., 2018; Tran et al., 2012).

Moreover, fleet electrification also presents certain social and technological challenges, such as increased demand on the already-overloaded energy system or the need to build charging infrastructure. Fleet electrification does not address all the driving factors for rising emissions from road transportation, such as increasing per capita travel distances and growing size and weight of the fleet (Lamb et al., 2021; Sims R. et al., 2014). Moreover, passenger fleet electrification does not contribute to the move away from car dependent societies and instead helps to perpetuate it.

This dissertation explores how demand-side solutions, specifically shared mobility, can contribute to building a transportation system that offers a robust and flexible alternative to car ownership.

1.2 Shared mobility

Shared mobility emerged as a transportation alternative in which access to a transportation service or vehicle is provided for a determined amount of time, either in exchange for a fee or for free (Shaheen & Cohen, 2018). The various forms of shared mobility can be divided into traditional and innovative services. Traditional modes include public transportation, taxis, shuttles, car rentals (short-term leasing), and paratransit (Shaheen & Cohen, 2018). Innovative shared mobility includes bikesharing, car sharing, carpooling, ride-hailing, and scooter and moped sharing. Traditional modes differ from innovative modes because the latter are accessed using information and communication technologies (ICT) (Shaheen & Cohen, 2007). Because the focus of this thesis is on innovative shared mobility, references to shared mobility in the remainder of the text should be understood to refer to this category of shared mobility.

Shared mobility modes include car sharing, ridesharing, on-demand ride services, and micromobility sharing (Figure 2). In car sharing, users gain access to a car (sans driver) for a short time in exchange of a fee or for free; both business-to-consumer (B2C) and peer-to-peer (P2P) systems exist (Shaheen et al., 2015). In the case of B2C, cars are owned by the sharing organization, while in P2P, cars are owned by individuals. Ridesharing is when people with similar routes and travel times travel together using either cars or vans (Chen et al., 2017). On-demand ride services provide users with a car and driver for hire and include both ride-hailing, where passengers travel alone, and ride-splitting, where passengers with similar destinations travel together and share the cost of the trip (Gupta et al., 2019). On-demand ride services are similar to taxis in how they work. Lastly, micromobility modes refer to short-term access to shared micromobility vehicles such as scooters, mopeds, or bikes. This dissertation focuses mainly on car sharing but spends some time looking at the impacts of micromobility and ridesharing as well. In this study I did not include on-demand ride services due to their similarity to taxi services, the environmental impacts of which have been researched extensively (d'Orey et al., 2012; Kinsella et al., 2023).

Shared mobility modes have a variety of differing characteristics, such as the vehicle used, parking and rebalancing strategies, pricing schemes, and vehicle ownership models. Parking strategies are either stationary (in the case of micromobility services, this is referred to as docked) or free-floating (for micromobility services, dockless). Stationary-based modes can be structured in a round-trip format where trips start and end at the same point, or one-way, where trips start and end at different designated parking locations (Machado et al., 2018). Parking strategies are relevant for both car sharing and micromobility systems. Strategies for rebalancing the geographic distribution of fleet vehicles vary in terms of the vehicles used for rebalancing and is a concern mostly for free-floating car-sharing and micromobility systems. Pricing schemes include membership and pay-as-you-go (with rates being either fixed or dynamic). These characteristics influence how these transportation modes operate and are used, as well as how they fit within the existing transportation landscape.

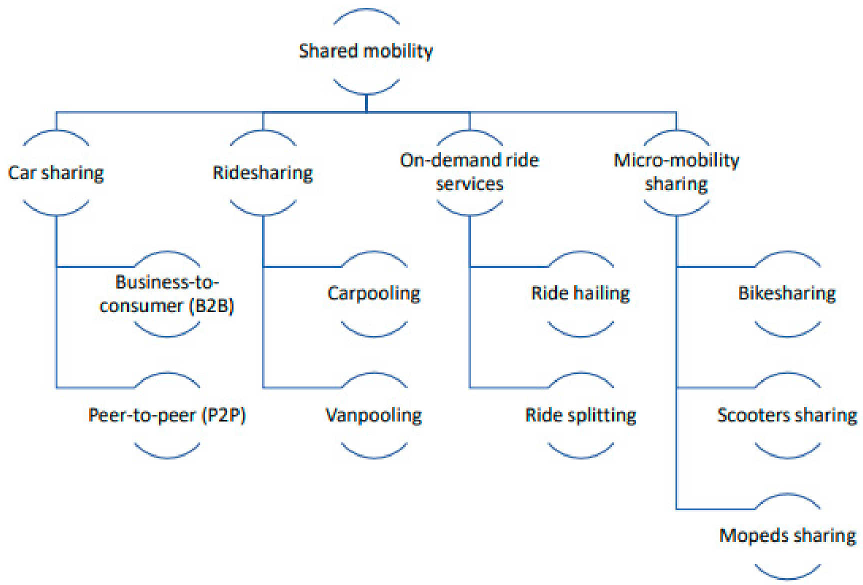

Figure 2 - Share mobility modes. Adapted from Machado et al. (2018). Scooters are also referred to as e-scooters in the literature, and mopeds are sometimes referred to as e-mopeds.

1.3 Changes in travel behavior due to shared mobility

Shared mobility modes have been found to change users' travel behavior by giving them access to a vehicle or a transportation service. Vehicle ownership rates, annual distances traveled, and modal shares have been found to change after people start to use shared mobility options (Gossen et al., 2019; Mi & Coffman, 2019; Shaheen & Cohen, 2019).

Research has found that car sharing can reduce car ownership rates and new car purchases (Gleave, 2017; Martin & Shaheen, 2016; Namazu & Dowlatabadi, 2018). One shared car has been found to replace 7 to 11 privately owned cars. Thus, car sharing allows people to eliminate car ownership, and in some cases, shift their lifestyle from car-dependent to car-free. Car sharing has also been found to potentially decrease new vehicle purchases by 7–55% among users.

Some studies have shown a drop in annual distance traveled after people start using a car sharing service (Cervero et al., 2007; Martin & Shaheen, 2016; Nijland & van Meerkerk, 2017). The magnitude of this drop varies: from moderate reductions of 6–16% to more dramatic reductions reaching 67%. Other studies have found that in some cases, annual travel distance increases, a reflection of the additional trips that car sharing users make due to their access to a shared car (Nijland & van Meerkerk, 2017).

The modal split of car sharing users changes after they start using the service. An increase in solo driving has been reported for car sharing users who did not have access to a car before they started using the service (Martin & Shaheen, 2016; Nijland & van Meerkerk, 2017). For other users, some shared car trips replace public and active transportation trips and other trips replace private car trips (Martin & Shaheen, 2016; Namazu & Dowlatabadi, 2018).

Ridesharing has been reported to increase vehicle occupancy and reduce the number of cars needed to cover transportation demand in specific regions (Caulfield, 2009; Santos, 2018). In the case of micromobility, research on changes in the modal split has mostly found that such services replace public transportation, private micromobility, and pedestrian trips (de Bortoli & Christoforou, 2020).

1.4 Environmental impacts of shared mobility

Assessing the environmental impacts of shared mobility is a complex matter that has been explored from several perspectives. One of these considers the effects that the above-mentioned changes in travel behavior have on environmental impacts from passenger transportation. Other perspectives look at how the design of a shared mobility mode and specific contextual variables affect the mode's environmental impacts. In this section I present evidence from research on emission impacts from shared mobility, followed by a discussion of other environmental impacts such as material depletion or air pollution. I conclude this section with a summary of how these impacts have been assessed.

1.4.1 Emission impacts due to shared mobility

Car sharing has been found to have the potential to decrease carbon dioxide (CO_2) emissions from transportation (Baptista et al., 2014; Migliore et al., 2020). Migliore et al. (2020) found a decrease of 125.57 t CO_2 due to a shift from private car driving to car sharing in Palermo in 2016. This decrease in emissions came from a reduction in car ownership among users with access to a shared car, who then relied more on public and active transportation and also sometimes avoided trips they would have made if they had access to a private car. Another study by Baptista et al. (2014) found savings that ranged between 3.3 and 6.1 t CO_2 due to car sharing in Lisbon, depending on the type of cars used in the shared fleet. Ridesharing, in turn, has been found to have the potential to save 7604 t to 12674 t CO_2 in Ireland (Caulfield, 2009) thanks to increased vehicle occupancy, which allows transportation demand to be covered with fewer vehicles.

Potential emissions reductions has also been found for shared micromobility (Ding et al., 2021). Dockless bikesharing saved 9.23 Mt CO_2eq in Beijing in 2016 due to a modal shift from private cars and public transportation to shared bikes. Emissions savings from scooters have also been reported due to a shift from private car driving to scooter sharing (Luo et al., 2019). Although these results show a decrease, the likelihood of replacing a significant volume of car travel with shared scooter or bike use is questionable.

Although some studies point to a possible reduction in emissions from shared mobility, other research has found the opposite (Kazmaier et al., 2020; Migliore et al., 2020; Nijland & van Meerkerk, 2017; Santos, 2018; Schelte et al., 2021; Sun & Ertz, 2021). Emissions increases following the adoption of car sharing reflect changes in the travel behavior of some users, such as increased solo driving, as well as the technology used in the shared fleet or additional driving needed to rebalance the fleet. Some households increased their emissions by 0.25 t CO_2eq annually after they engaged in car sharing (Martin & Shaheen, 2011). In the case of micromobility sharing emissions increased when there was a shift from private to shared micromobility, or in some cases when there was a shift from public transportation to shared micromobility. Fleet rebalancing and maintenance strategies also influenced this increase in emissions (Kazmaier et al., 2020; Luo et al., 2019; Schelte et al., 2021; Sun & Ertz, 2021). When assessed per kilometer travel, private bike use was associated with 10.5×10^{-6} t CO_2eq in emissions, while emissions from shared bikes with a stationary parking strategy ranged from 57.35×10^{-6} to 68.99×10^{-6} t CO_2eq (Sun & Ertz, 2021).

Much on the research on car sharing has focused on B2C car schemes, with the environmental impacts of P2P car sharing relatively unexplored (Kerr, 2022). B2C car sharing might entail a reduction in environmental impacts due to the newer, more fuel efficient vehicles that typically comprise its fleets compared to the vehicles that comprise P2P car sharing fleets. However, B2C car sharing might also entail higher impacts due to the short service life of vehicles in the shared system, which increases impacts from production. However, research that further explores this phenomenon has yet to be undertaken.

Shared mobility not only potentially changes how people travel but also alters users' spending on transportation and other categories (Gossen et al., 2019; Plepys & Singh, 2019). Potential changes in consumption and rebound effects from shared mobility have received limited scholarly attention, in studies focusing on changes in car purchasing (Ma et al., 2018; Yu et al., 2017). Rebound effects refers to an offsetting of potential environmental savings from shared mobility through consumption in other categories, as users spend the money they save by adopting shared mobility and changing their travel behavior. Existing research on rebound effects from shared mobility has not heretofore looked at impacts related to changes in income and redirection of those resources thanks to changes in travel behavior.

1.4.2 Other environmental impacts due to shared mobility

Research on the environmental impacts of shared mobility has also studied its effects on air pollution, land use, energy depletion, and ozone depletion. Studies of air pollution have found that car sharing and carpooling can decrease pollutants if total travel distance is reduced thanks to people sharing rides, as well as in respond to improved technology used in the shared fleet (Migliore et al., 2020; Te & Lianghua, 2019; Zhang et al., 2021). For example, one study found a 25% reduction in particulate matter (PM_{10}) due to the use of car sharing in Palermo (Migliore et al., 2020). Another study in China found that air pollution was reduced when shared micromobility replaced car driving, saving 64 t nitric oxide (NO_x) in Wuhan, Hubei province (Zhang et al., 2021).

A study in China found car sharing reduced land use by 4.68×10^9 m^2 thanks to a drop in car ownership (Te & Lianghua, 2020). Several studies have linked a reduction in energy depletion to all shared mobility modes as a result of changes in travel behavior, such as less solo driving (Te & Lianghua, 2020; Yu et al., 2017; Zhang et al., 2021). For example, one study attributed an energy savings of 1.67×10^9 MJ and a fuel savings of 8358 t to car sharing and bikesharing in China (Te & Lianghua, 2020).

Despite these studies pointing to a possible reduction in air pollution and fuel depletion due to the use of shared mobility, other research has found the opposite (Migliore et al., 2020; Nijland & van Meerkerk, 2017; Santos, 2018). Migliore et al. (2020) found that NO_x emissions increased by 0.012 t in Palermo due to car sharing.

This increase in environmental impacts reflects some users' altered travel behavior, such as increased solo driving, as well as the technology used in the shared fleet and additional driving needed for rebalancing. Shared bikes and scooters consume 1040 and 1310 kJeq of energy per kilometer, respectively, compared to private bike and scooter consumption of 159 and 938–1150 kJeq per kilometer, respectively (de Bortoli, 2021). Material depletion was found to be higher for bikesharing compared to private biking because shared micromobility systems need additional resources to operate, including docking stations, rebalancing vehicles, and tracking equipment, as well as the fact that the shared micromobility fleets requires more maintenance than privately owned vehicles and sometimes have significantly shorter service lives (Moreau et al., 2020; Tao & Zhou, 2021). This

As I have explained in this section, environmental assessments of shared mobility as a whole paint a disparate and fragmented picture (Santos, 2018). This failure to develop a clear understanding of when and how shared mobility delivers environmental gains can hinder future development and implementation of urban transport systems. Understanding the factors that affect the environmental outcomes of shared mobility can contribute to developing systems with a better chance of delivering on their environmental promise in urban areas.

1.4.3 Impact assessment approaches to shared mobility

Assessing how shared mobility changes the environmental impacts from personal transportation is a complex task that can be approached in different ways. Some researchers have used methods that assess impacts from the production side, by evaluating impacts from different types of vehicles or by focusing on assessing the impacts of different parking or rebalancing strategies (Ding et al., 2019; Migliore et al., 2020; Sun & Ertz, 2021). Others approach the question from the consumption side, seeking to understand how shared mobility users change their travel behavior and how these changes reverberate in terms of environmental impacts (Caulfield, 2009; Martin & Shaheen, 2011). Other assessments approach this challenge from both the consumption and production sides (Baptista et al., 2014; de Bortoli, 2021).

Whether environmental impacts are assessed from the production or consumption perspective leads to differences in what is included in the quantification. Assessments that focus exclusively on the production side might focus on impacts from raw material extraction, transportation, and transformation, as well as impacts produced during product manufacturing and at end-of-life. In the case of services, production-oriented assessments might include impacts produced during manufacturing of the goods needed to provide the service, as well as impacts produced during service provision. Such assessments might address impacts in different geographical locations, depending on the global reach of the product's supply chain. Consumption-oriented perspectives generally focus on the use phase: impacts produced when the product is used or when the service is consumed.

Assessments that include both consumption and production analyses look at impacts caused across the entire product life-cycle: from raw material extraction and transformation, to production, use, and end-of-life.

In the case of shared mobility, production-oriented assessments have focused on impacts caused by the production and maintenance of vehicles, as well as impacts caused during the provision of shared transportation services. Some such assessments compare impacts resulting from different shared fleet sizes, as well as different maintenance strategies. Consumption-oriented perspectives have focused on changes in travel behavior and expenditure when people adopt shared mobility. Assessments that approach the question from both production and consumption perspectives have addressed changes in travel behavior, the characteristics of the shared fleet and operational attributes of the shared mobility system.

Looking at how shared mobility can alter environmental impacts from personal transportation during both production and consumption is needed to achieve a systemic understanding that can provide further insights regarding the factors that shape the environmental impacts of personal mobility.

1.5 Knowledge gaps

Shared mobility is perceived as a demand-side solution to decrease the harmful environmental impacts of personal transportation (Mi & Coffman, 2019). It is presented as a tool to decrease emissions and save urban space in cities and is promoted by sharing organizations as sustainable. However, these perceptions and claims are based on disparate and fragmented evidence, as well as assumptions of desired outcomes. Growing evidence, however, points to harmful environmental impacts associated with shared mobility. This body of research suggests that shared mobility does not decrease environmental impacts from passenger transportation by default and that it must instead be designed, put into operation, and used in specific ways if it is to deliver on its environmental promises. Our understanding of how shared mobility can change environmental impacts from personal transportation and the factors that influence these outcomes is limited. In this dissertation I consolidate and review prior research that has assessed shared mobility's environmental impacts and the factors that influence them. I also designed and employed specific assessments to further our understanding of the potential of car sharing to change the environmental impacts from personal transportation.

Assessments of car sharing have focused on B2C models, leaving a gap in our understanding of the environmental impacts of P2P car sharing (Machado et al., 2018; Santos, 2018). A better understanding of the impacts of P2P car sharing will enhance discussions about optimizing car sharing schemes in cities. To fill this gap, here I analyze the impacts of P2P and compare these to B2C impacts.

Given that shared mobility—specifically car sharing—can modify how people travel, it can also change people's spending on transportation (Plepys & Singh, 2019). For example, people who replace their current vehicle with one that is more fuel effective might (paradoxically) increase their spending in fuel by driving farther and more often. Car sharing has been found to decrease vehicle ownership rates or postpone car purchases, but households might re-allocate these budgetary savings towards other consumption categories (Walnum et al., 2014). P2P car sharing also generates income for households who share their cars, increasing their income. We lack studies on how car sharing changes consumption and its consequences on the environmental impacts of transportation and general household consumption. No one has yet looked at rebound effects due to the additional income earned from P2P car sharing, and there is little research that addresses the potential rebound effects due to changes in transportation spending (Walnum et al., 2014). Thus, in this dissertation I look for possible rebound effects from car sharing.

How shared mobility fits within the existing transportation landscape depends on several contextual variables, including the state of the public transportation network, active transportation culture, and the built environment (Ding et al., 2017; Ding et al., 2018). This points to the need to study countries and cities individually to understand how shared mobility fits in their transportation landscape, exploring whether and how it can decrease personal transportation's environmental impacts. This has been explored in different cities (Ding et al., 2019; Raugei et al., 2021; Sun & Ertz, 2021). Nonetheless, this body of research fails to provide narratives that reflect possible pathways through which shared mobility can enable a shift to a more environmentally sound transportation system. Context-specific narratives are relevant when developing national or city transportation policies (Barrett et al., 2022). In this dissertation, therefore, I examine possible transportation narratives and scenarios for three countries that position car sharing as a central element in enabling a shift away from car-dependent societies.

1.6 Research aim and research questions

This dissertation aims to enhance our knowledge about the environmental impacts of shared mobility as an alternative of sustainable consumption and production. To address this aim, two research questions are investigated:

RQ1: What is the potential of shared mobility to decrease environmental impacts from passenger transportation in urban contexts?

RQ2: Which factors affect the potential of shared mobility to decrease environmental impacts from passenger transportation in urban contexts?

I answer these questions by first exploring the existing literature on how shared mobility affects environmental impacts from personal transportation and what factors shape these results. I then explore these questions in greater depth, using environmental assessment tools in a novel application to the case of shared mobility.

1.7 Scope

This dissertation focuses on shared mobility in order to showcase its broader relevance to alternative sustainable consumption and production modes. Shared mobility is a demand-side solution that can potentially either dampen or exacerbate environmental impacts from personal transportation—a sector associated with high environmental impacts (Lamb et al., 2021). I focus mostly on car sharing but also explore impacts from ridesharing, micromobility sharing, and public transportation. I primarily concentrate on GHG emissions but also look at energy and air pollution impacts. I also explore the economic impacts of car sharing, although to a lesser extent than environmental impacts. I do not directly assess social impacts but did consider social aspects of transportation in the assessments; these aspects are also included in the discussion, where I explore the viability of upscaling shared mobility.

Geographically, my research encompasses cities or urban areas in countries where shared mobility—more specifically car sharing—is available and where research on how it has changed users' travel behavior has been conducted. These geographic locations were also selected based on the availability of other passenger transportation data, such as annual kilometers traveled and modal split. I also selected the included locales with an eye toward representing different passenger transportation landscapes. I therefore look at the Netherlands, the United States, and Sweden, focusing on exploring demand-side solutions for urban areas. My research has also been informed by how shared mobility has been designed and put into operation in Amsterdam, Toronto, Melbourne, and Shanghai—cities that are included in the larger project from which my own research was launched, and where I participated in the Mobile Research Labs.

I selected shared mobility as a case that exemplifies the challenges of assessing the environmental impacts of sustainable consumption and production. The methods I use to analyze environmental impacts from shared mobility were limited to methods that allow the analysis of impacts from a systemic and demand-side perspective. Accordingly, Life-Cycle Assessment (LCA) and Multiregional Input and Output (MRIO) were the two methods I primarily use here. These methods allowed me to analyze impacts from both a production and a consumption perspective, which aligns with the need to understand impacts from both approaches.

1.8 Overview of the papers

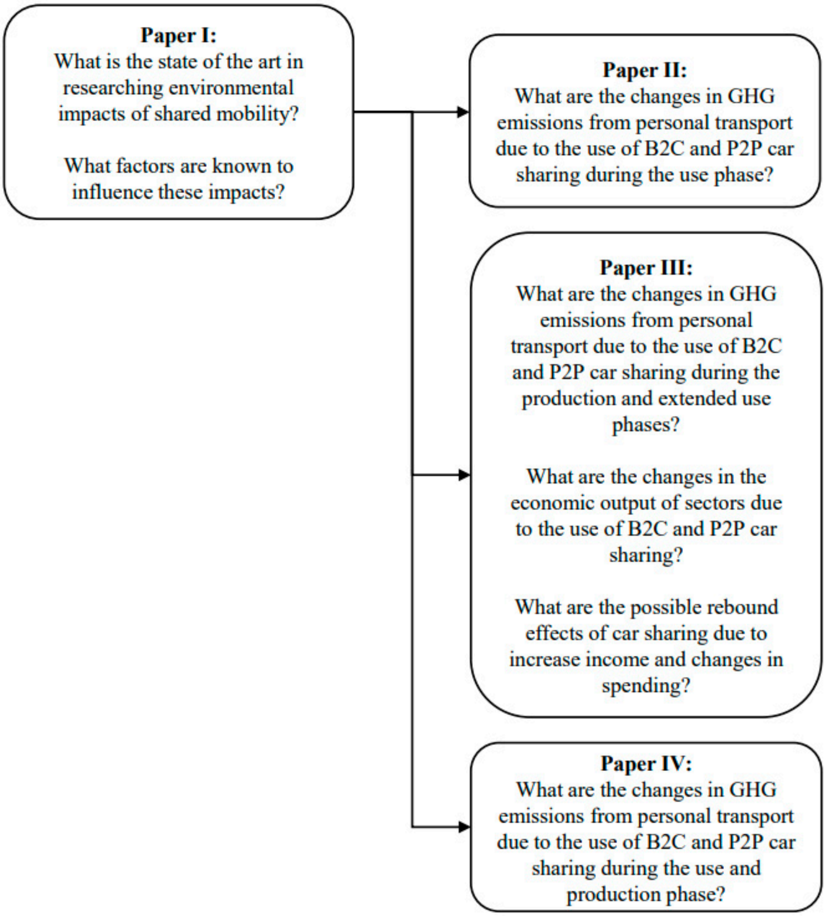

Figure 3. Connection between the papers and specific research questions

This dissertation consists of four papers. Paper I is a qualitative paper presenting a systematic literature review. This paper summarizes the state-of-the-art in evaluating shared mobility's environmental impacts and the factors that influence them. It also identifies gaps in this literature, which I then used as the starting point for the rest of the papers (Figure 3). The three other papers (II, III and IV) are based on quantitative methods. Each paper assesses how car sharing might change environmental impacts from passenger transportation, looking at different characteristics and addressing different questions in a way that offers a unique contribution to the dissertation as a whole. Figure 3 presents the research questions addressed in each paper. Below I present a summary of each paper, including a table that summarizes their characteristics (Table 1).

Paper I: The environmental impacts of shared mobility: A systematic literature review of life-cycle assessments focusing on car sharing, carpooling, bikesharing, and scooter/moped sharing

As I explain earlier in this chapter, assessments of the shared mobility's effect on environmental impacts show mixed and fragmented results. Paper I is a systematic literature review that explores the state-of-the-art in evaluating shared mobility' environmental impacts and the factors that influence them. This paper helps answer both RQ1 and RQ2. The literature review included B2C car sharing, P2P car sharing, carpooling, bikesharing, and scooter/moped sharing. The review was limited to studies that use LCA in their analysis.

This review found that shared mobility modes do not deliver environmental gains in all cases. Instead, certain factors determine whether shared mobility deployment and use has positive or negative effects on environmental impacts. I group the factors determining these outcomes into travel behavior, design and implementation of the shared mobility system, the context, and consumption. Some of the research gaps I identified through this review include a lack of research on the impacts of P2P car sharing, a lack of understanding of potential rebound effects due to car sharing, and a failure to develop specific national pathways for the successful deployment of shared mobility as a strategy to decrease environmental impacts from passenger transportation. This paper includes recommendations for city government and urban sharing organizations.

Paper II: Car sharing as a strategy to address GHG emissions in the transportation system: Evaluation of the effects of car sharing in Amsterdam

This paper is based on one of the research gaps found in Paper I: namely, the lack of research on P2P car sharing. It compares the potential of B2C and P2P car sharing to change GHG emissions from passenger transportation in Amsterdam at both the per-person and city levels. It uses a well-to-wheel (WTW) approach to quantify emissions, which includes both emissions from the extraction of the raw materials used to produce the fuel, and tailpipe emissions from the use of fuel in a car.

At the per-person level, GHG emissions may either increase or decrease when people use car sharing systems. Emissions reductions thanks to users who give up private car ownership when they start car sharing are much greater than emissions increases caused by carless users who gain access to a car for the first time through car sharing. At a city level, this study found a decrease in total emissions. The decrease in GHG emissions was higher when system implementation achieved both fleet electrification and changes in travel behavior. GHG emissions were slightly lower for B2C car sharing than for P2P car sharing. The analysis identified distance travel and travel by car as influential factors that drive GHG emissions levels.

Paper III: Economic impacts, carbon footprint and rebound effects of car sharing: Scenario analysis assessing business-to-consumer and peer-to-peer car sharing

This paper further explores the gap between B2C and P2P car sharing using an assessment that included impacts caused during the entire use phase of these modes, as well as during production. It also looks at possible rebound effects due to increased income or changes in spending due to car sharing. It uses the model developed in Paper II as an input to calculate travel distance and modal split, together with MRIO to assess changes in GHG emissions and the economic output of sectors. This assessment was performed at a per-person level, developing scenarios for implementation in the case country of the Netherlands.

As with Paper II, Paper III found that car sharing has the potential to both increase and decrease GHG emissions from passenger transportation, with the potential decrease being much higher (40%) than the potential increase (0.42–0.70%). The potential decrease resulted from users who shift away from car ownership to public, active and shared transportation. The increase in emissions, in turn, was the result of carless users who gained access to a car through car sharing and therefore increased their solo driving. The rebound effects of car sharing users' due to increased income and reallocated spending have the potential to drastically reduce this potential emissions savings. Once again, differences in emissions from B2C versus P2P car sharing were marginal. This study also found that car sharing has the potential to change the economic output of sectors. Changes in income, distance traveled, and distance traveled by car were found to be the factors influencing GHG emissions levels.

Paper IV: Shared mobility and lifestyles as mechanisms to reduce environmental impacts from passenger transportation

This paper develops possible pathways to decrease environmental impacts from passenger transportation for three countries: the Netherlands, Sweden, and the United States. It considers several drivers in decreasing impacts: namely, shared mobility, digitalization, passenger fleet electrification, and well-being. These drivers allowed changes in travel behavior, such as decreasing distance traveled, shifts to more environmentally friendly transportation modes, and improved emissions characteristics of the fleet. This paper applied the model developed in Paper III to quantify the specific impacts of GHG emissions, air pollution, and energy use.

Environmental impacts from passenger transportation can decrease through the combination of demand- and supply-side actions. The level of actions needed varied and depends on each country's level of car dependency, passenger fleet characteristics, and level of fleet electrification, among other factors: accordingly, the United States will require more extreme demand- and supply-side actions than Sweden or the Netherlands to reduce the analyzed environmental impacts.

Table 1 - Summary of main characteristics of Papers II, III and IV included in this dissertation

	Paper II	Paper III	Paper IV
Unit of analysis	Individual and city	Individual	Country – urban population
System boundaries	Use phase	Use and production phases and non-transportation consumption	Use and production phases
Impacts	GHG emissions	GHG emissions and economic impacts	GHG emissions and energy and $PM_{2.5}$ footprints
Methods	Life-Cycle Assessment	Multiregional Input and Output	Multiregional Input and Output
Geography	Amsterdam	Netherlands	Netherlands, United States and Sweden
Type of impacts	Direct	Direct, indirect and induced	Direct and indirect
Special features	Comparison B2C and P2P car sharing	Comparison B2C and P2P car sharing Calculation of income rebound effects	Comparison of impacts of car sharing in different contexts
The main research questions addressed	RQ1: What is the potential of shared mobility in decreasing the environmental impacts of passenger transportation in urban contexts? RQ2: Which factors affect the potential of shared mobility to decrease the environmental impacts of passenger transportation in urban contexts?		

1.9 Audience

This dissertation's findings about the potential of shared mobility to reduce environmental impacts from personal transportation will be of interest to several actors. Policymakers and sharing organizations can benefit from this research by getting a better understanding of how shared mobility can decrease impacts from personal transportation and the factors that affect this decrease. Moreover, since the dissertation is built on case studies, actors from the countries or cities addressed in these cases can draw insights from it on how shared mobility can fit into their transportation landscape. Researchers and professionals working to develop sustainability assessments can use the results of this dissertation to inform the development of future assessments of consumption and production modes, in particular for shared mobility.

1.10 Dissertation outline

This dissertation comprises six chapters and four appended papers. Chapter 2 explains the framing of this dissertation. Chapter 3 sets out the methods for data collection and analysis, as well as the positioning of this research and the validity and transparency of the results. Chapter 4 details the findings of this dissertation, answering each of the research questions posed in this introduction. Chapter 5 discusses these main findings and considers the possibilities of upscaling shared mobility, along with a reflection about the research methods used. Lastly, chapter 6 summarizes the dissertation's main findings and contributions and offers suggestions for future research.

2 Framing of the dissertation

This chapter positions the dissertation in relation to two fields: sustainable production and consumption and sustainability assessments. I start by explaining where shared mobility is situated in relation to sustainable consumption and production. I then clarify the purposes of sustainability assessments and how I approach sustainability in this dissertation.

2.1 Sustainable consumption and production

Sustainable consumption and production includes a variety of initiatives, including cleaner production, product service systems (PSS), and the circular and sharing economies. In this dissertation I use shared mobility as an example of sustainable consumption and production modes, positioning it as part of both the sharing economy and PSS. In this section I present the definitions of the sharing economy and PSS and explain how shared mobility modes are classified within these two concepts.

2.1.1 The sharing economy

In 2013, the *sharing economy* became a popular term to refer to various innovative businesses that promoted sharing rather than ownership. Academics, practitioners, and policymakers have discussed the term's definition without reaching consensus on a standardized definition (Botsman, 2013; Curtis & Lehner, 2019; Frenken et al., 2015; Oh. S & Moon, 2016). Table 2 summarizes the various definitions of *sharing economies*, and Table 3 provides an overview their characteristics.

Table 2 – Definitions of Sharing Economy

Author	Definition
Frenken et al. (2015)	”[C]onsumers (or firms) granting each other temporary access to their under-utilized physical assets ('idle capacity'), possibly for money.”
Curtis and Lehner (2019)	The semantic properties of sharing economy are “ICT-mediated, non-pecuniary motivation for ownership, temporary access, rivalrous and tangible goods”
PricewaterhouseCoopers (2015)	“[S]haring economy uses digital platforms to allow customers to have access to, rather than ownership of, tangible and intangible assets”
Rinne (2017)	”[F]ocus on the sharing of underutilized assets, monetized or not, in ways that improve efficiency, sustainability and community”

Here I use the definition that Curtis and Lehner (2019) propose: that the sharing economy entails sharing the idle capacity of assets (such as cars, bikes, or tools), granting others temporary access to them. This temporary access may be free of charge or in exchange of a fee. ICT platforms connect assets owners and users. Curtis and Lehner also clarify that in a sharing economy, assets are rivalrous: i.e., no other user can access them when they are shared. The fact that the sharing economy is ICT mediated means that markets can be two-sided or multisided. Users and owners connect to one another via a platform that regulates interactions between them and shapes how sharing takes place. Platforms devise conditions and have pricing schemes for owners and users (Curtis & Mont, 2020; Huefner, 2015).

Sharing economy transactions can take the form of P2P, B2C, business-to-business (B2B), or crowd platforms. Not all B2C models can be classified as sharing, however. Curtis and Lehner's definition excludes B2C offerings that acquire assets to be shared (such as Uber or Jump) and generate a profit.

The sharing economy is present in several sectors, including accommodation, mobility, and assets. Under the definition I adopt here, examples of organizations within the sharing economy include GoMore (the Netherlands, Sweden, and elsewhere), Nabobil (Norway), and Hygglo (Sweden). In the case of Airbnb, rentals of property that is vacant because the owner-occupants are away, or second homes that are rented when the owners are not using them, belong to sharing economy; however, rentals of properties bought for the purpose of renting out for profit do not and are instead classified as a case of a PSS, discussed in more detail below.

Table 3 - Semantic properties of various definitions of the sharing economy

	Idle capacity	Temporary access	Peer-to-peer	ICT meditated	Assets	Rivalrous
Frenken et al. (2015)	x	x	x		x	
Curtis and Lehner (2019)	x	x	x	x	x	x
PricewaterhouseCoopers (2015)	x	x	x	x	x	
Rinne (2017)	x				x	

2.1.2 Product-Service System

The satisfaction of needs with services rather than products has been a topic of discussion since the 1990s. Giarini and Stahel (1993) proposed the service economy as an alternative to the industrial economy. The service economy focuses on a product's or service's performance or results over time, in contrast to the industrial economy, which focuses on the exchange of products and services more than on their utility. Giarini and Stahel (1993) argued that this shift in the economy could reduce resource consumption, since the service economy supports long service lives for products due to better maintenance and service providers' whole lifecycle perspective. The service economy is one of the inspirations for the concept of PSS.

The first definition dates to 1999, when Goedkoop et al. (1999) referred to PSS as "a marketable set of products and services capable of jointly fulfilling a user's need." Thus, PSS allows for a dematerialization of the economy, with a focus on satisfying needs with services rather than products (Goedkoop et al., 1999; Mont, 2002). Mont (2002) definition of PSS includes the need to have "networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models."

The shift to PSS entails changes for customers, producers, and service providers. The most obvious change for customers is the shift from buying products to buying services and system solutions. This supposes that users will no longer have ownership rights over the products they use (Mont, 2002). For producers and service providers, it entails the need to have a whole lifecycle understanding of the product or service they sell. This means that producers or service providers might have ownership rights over the product (Mont, 2002).

PSS was initially promoted as a way to reduce environmental impacts by closing material cycles, reducing consumption, and increasing product utilization rates (Giarini & Stahel, 1993; Goedkoop et al., 1999; Mont, 2002). These benefits would be achieved by devising networks that allow the economy to work like an interconnected system (Mont, 2002).

PSS includes a variety of business alternatives. Products may be replaced by services, such as B2C car sharing or public transportation. Another example is if old products are repaired using a maintenance service rather than being replaced with new products, or material components are recovered when products reach their end-of-life (Mont, 2002).

2.1.3 Shared mobility in sustainable consumption and production

Having clarified the definitions of the sharing economy and PSS I will be using, it is now pertinent to discuss where shared mobility modes are situated with respect to these concepts. Both the sharing economy and PSS promote access to services in place of product ownership, thus emphasizing temporary access (Table 4). However, they differ in that the sharing economy is limited to services that give access to idle capacity, while in a PSS, capacity can vary depending on demand. Thus, PSS includes B2C organizations, while the sharing economy does not. At the same time, PSS also includes the sharing of both goods and services Thus, in PSS, use is not rivalrous (Table 4).

Table 4 - Characteristics of PSS and the Sharing Economy

Characteristic	PSS	Sharing Economy
Capacity	Capacity varies according to demand.	Limited to idle capacity in the system
Access	Temporary	Temporary
Type of business	P2P, B2C, B2B, and crowd platform models.	P2P, B2B, and crowd platform models.
ICT meditated	Not necessarily	Yes
What is included?	Tangible and intangible goods and services	Tangible goods
Rivalrous	No	Yes

I use PSS and the sharing economy in this dissertation because they encompass the types of organizations that organize shared mobility services, including B2C, P2P, and B2B forms. Shared mobility organizations that support the sharing of idle capacity belong to the sharing economy: for example, the car sharing organization GoMore, which allows car owners to share their cars' idle capacity. Organizations where capacity varies to satisfy demand are classified as PSS: examples include Uber, Lyft, and Hertz.

2.2 Sustainability assessments

Sustainable consumption and production systems are implemented with the hope that they will reduce harmful social, environmental, and economic impacts, as well with the hope that they will maximize social, environmental, and economic benefits. Sustainability assessments of sustainable consumption and production systems are key in indicating whether the desired outcomes are achieved and also can point to relevant aspects of systems that could be improved.

In the framework of this dissertation, sustainability assessments are tools and methods that provide policymakers, organizations, and consumers with a quantification of economic, environmental and social impacts that can be used to support decision-making to improve sustainability (Pope et al., 2004). Sustainability is broadly understood to include environmental, economic, and social outcomes, but sustainability assessments often focus on only one of these dimensions. This dissertation primarily focuses on environmental sustainability assessments.

Sustainability assessments include lifecycle and system thinking. Lifecycle thinking is an approach that seeks a holistic understanding of the impacts a product or service produces, from cradle to grave (Mont & Bleischwitz, 2007). Systems thinking is an approach where the entire system within which the product is inserted is analyzed and understood, and not just the product by itself; this approach can include analysis of the relationships between variables, such as rebound effects or feedback mechanisms (Onat et al., 2017).

Assessments may be designed from the top down, from the bottom up, or through a combination of top-down and bottom-up approaches. Bottom-up assessments focus on product, company or per-person level, relying on detailed data that describe how the process works (Feng et al., 2011). Top-down assessments instead focus on macroeconomic level (Feng et al., 2011).

2.2.1 Assessing sustainability

Sustainability encompasses economic, environmental, and social dimensions—more commonly known as the triple bottom line (TBL). The TBL was proposed by Elkington (2004) in seeking to understand the environmental and social consequences of economic activities.

Economic sustainability

Economic sustainability concerns the efficient use of resources and the maintenance or growth of economic capital (Goodland, 1995). Economic sustainability is linked to the idea of a sustainable income: "the amount one can consume during a period and still be as well off at the end of the period" (Hicks, 1975). Thus, economic sustainability includes consumption as one key element.

Environmental sustainability

Environmental sustainability means the maintenance of natural capital, entailing a balance between two main environmental services: source (renewable and non-renewable services or materials extracted from nature) and sink (the environment's capacity to assimilate environmental impacts). The balance between source (input) and sink (output) is determined by the existing reservoirs of resources and the rate at which they are depleted and disposed of. This rate is determined by the scale at which resources are extracted and used (Goodland, 1995). This means that sources of materials and services should be used at a rate that is within the limits of their capacity, and waste and pollution should be generated at a rate that considers the assimilation capacity of the planet. This definition refers solely to biophysical capacity and considers both the planet's resources and its absorption capacity to be limited (Goodland, 1995).

Social sustainability

Social sustainability relates to the satisfaction of human needs, for instance, literacy, education, and values of community and belonging. It emphasizes the systematic participation of all individuals in social, democratic and other processes for society to function in an equitable manner (Goodland, 1995).

Although this dissertation focuses on environmental sustainability, I consider all three dimensions of sustainability—economic, social, and environmental—to be necessary. Sustainability in this broad sense was considered when analyzing the possible trade-offs involved in the solutions proposed in the specific papers and when developing potential transportation scenarios.

2.2.2 Sustainability assessments of shared mobility

The impacts of shared mobility have been assessed from different sustainability perspectives (Roukouni & Homem de Almeida Correia, 2020). Research from an economic perspective has focused on employment, while studies of social impacts have looked at health impacts and transportation equity. Environmental impacts that have been analyzed include air quality, GHG emissions, and energy consumption. Other aspects that have been evaluated include impacts on traffic conditions or parking availability in urban areas (Roukouni & Homem de Almeida Correia, 2020). These aspects of sustainability have been studied to different extents, using different methods.

Assessing how shared mobility changes environmental impacts from personal transportation is a complex issue, given that it involves numerous variables (Zhu et al., 2022). To capture these impacts systemically, both supply and demand perspectives must be understood and considered (Zhu et al., 2022). From a supply perspective, shared mobility organizations determine, for example, fleet size, parking and rebalancing strategies, and the parameters that influence how shared mobility is deployed and used. All of these factors have the potential to influence how shared mobility alters environmental impacts from passenger transportation. From a demand perspective, consumers experience different changes in their travel behavior, which influences the environmental impacts of passenger transportation.

The research questions and aim of this dissertation thus call for assessments methods that can capture both supply and demand aspects. In this dissertation I use LCA and MRIO analysis as methods for the environmental assessments. These methods allow an understanding of environmental impacts that considers both the supply and demand sides and allow for a more systemic understanding of how shared mobility alters the environmental impacts of passenger transportation. In the following section I present these methods in detail and discuss how I applied them in my work.

3 Research design and methods

This chapter explains the author's research positioning. This is followed by a presentation of the methods used to collect and analyze data. At the end of the chapter I offer some reflections about the validity and reliability of the results.

3.1 Research approach

3.1.1 Research positioning

This dissertation is framed by a post-positivist approach. I believe that reality exists, but human understanding of this reality is not perfect due to methodological limitations and knowledge gaps (Guba & Lincoln, 1994). A post-positivist also believes that knowledge can evolve and change over time as it is tested and reviewed. Knowledge is formed by two types of statements: universal and specific. Theories are universal statements that can be generalized, while specific knowledge is bounded to specific contexts. Specific knowledge is the forming blocks of universal knowledge (Lincoln et al., 2011; Popper, 2002).

The methods used in this dissertation primarily align with a positivist perspective, given the quantitative nature of three of the included papers. However, this research was also informed by qualitative methods, including interviews and literature reviews. Thus, in this dissertation I also apply post-positivist methodological approaches (Lincoln et al., 2011).

This dissertation is interdisciplinary in nature (environmental science, economics, transport and behavioral studies), focusing on real-world problems analyzed from two perspectives: sustainable consumption and production and sustainability assessments (Stock & Burton, 2011; Strijbos, 2017). These fields were combined to generate new knowledge to understand better the sustainability impacts of sustainable consumption and production models. Additionally, this dissertation was part of a larger interdisciplinary project (for example, social, environmental, political and behavioral sciences), where perspectives such as governance, institutionalization, and business models informed my work.

3.2 Methods for data collection

3.2.1 Literature review

As part of this dissertation research I conducted several literature reviews. Paper I presents a systematic review of papers that assess the environmental impacts of shared mobility, focusing on the results of these assessments and the factors that influenced these results. To do so, I used Web of Science and Scopus to identify papers for inclusion and followed the ROSES guidelines—which address issues such as establishing research questions and article screening in a way tailored for systematic literature reviews in environmental science—to select the final papers for review (Collaboration for Environmental Evidence, 2013).

Papers II, III, and IV contain narrative literature reviews that explore the state of the art with respect to the specific research questions that frame each paper. The results of these reviews are included in the background sections of each paper and helped inform my research process.

3.2.2 The Mobile Research Lab

The Mobile Research Lab is a collaborative research process where an interdisciplinary group of researchers studies a specific question in a certain urban context. The research is done using ethnographic methods that combine site visits with stakeholder interviews of company employees, city officials, NGO staff, and others. The diversity of stakeholders allows researchers to achieve a holistic understanding of the situation in the specific context and also allows them to identify possible solutions (Mont, 2018).

In this dissertation, I participated in the Mobile Research Lab in Amsterdam and was involved in the remote Mobile Research Labs in Toronto, Shanghai, and Melbourne. Interview subjects included politicians, members of urban sharing organizations, experts, other researchers, NGO staff, and employees at incumbent companies. Within the framework of this dissertation, I focus on shared mobility. My interviews followed a structured format as I sought information about the landscape of shared mobility in different countries and the role that it plays in these urban contexts. This knowledge helped me to frame the papers included here.

3.2.3 Empirical data

Papers II and III were based on empirical data from a shared mobility company, consisting of three years of records on car sharing, including information about the duration of rentals, distances driven, costs, types of vehicles, and more. I used this data to understand how users engage in car sharing and the cost of the service for leases and income from the service for sharers. I used this data as one input in the assessments.

3.2.4 Publicly available data

I use publicly available quantitative and qualitative data in Papers II, III, and IV, this data included implemented policies in the locations I studied: for example, Amsterdam's Clean Air Policy in Paper II and transportation policies to be implemented in the Netherlands, Sweden, and the United States in Paper IV. This quantitative data served as a basis for estimating the travel demand in Papers II, III, and IV and for characterizing each country's passenger fleet. For example, I used the Dutch Travel Survey from the Central Agency of Statistics (CBS) in the case of the Netherlands or Amsterdam. For the United States, I used the National Household Travel Survey from the United States Department of Transportation, and for Sweden my data source was the 2030 Environmental Barometer from the Environmental Barometer.

I obtained emissions levels from two sources. I used Ecoinvent in Paper II to find emissions levels, which I then used to assess GHG emissions via SimaPro. In Papers III and IV, I used the input and output tables available in EXIOBASE v3.8.2 for the year 2019.

3.3 Methods of data analysis

In this dissertation I use both quantitative and qualitative methods of data analysis, although I primarily use quantitative methods.

3.3.1 Coding of data extracted from the literature

I used the Gioia methodology to analyze my data in Paper I. This methodology consists of three steps for extracting and grouping data into the categories that will later frame the analysis. First-order concepts, second-order themes, and aggregate dimensions, which together provide the base for the analysis. In defining the first-order concepts, the researcher is informed by the data collected, and it is thus an inductive step. The second-order themes are defined based on the first-order, and these are then analyzed to establish aggregate dimensions in the third and last step of the method. This methodology comes from the field of organizational studies. However, its flexibility has led to its application in other fields of research (Gioia et al., 2013).

3.3.2 Life-Cycle Assessment

LCA is an environmental assessment method that quantifies the real and potential environmental impacts that a product or service causes during its lifecycle (Organisation., 2006). One of the key features of LCA is that it can include impacts from the extraction of raw materials and the production, use and end-of-life of a product or a service, covering impacts across the whole life of the product or service. In addition, this method is able to quantify a variety of environmental issues, allowing the identification of possible trade-off among impacts—situations when a decrease in one environmental impact category is accompanied by an increase in another (Hauschild et al., 2018).

LCA started out—as did many sustainability assessment methods in the 1960s—being used mainly in the United States and Nordic countries. The first LCAs were focused on material and energy accounting that resembled material flow accounting (Hauschild et al., 2018). These material and energy inventories were then used to calculate environmental impact potential in several impact categories, such as climate change, acidification, and human toxicity. ISO 14040, published in 1997, seeks to establish a framework for LCAs. This standard was followed by ISO 14041 and 14042, which add more detail to the framework (Hauschild et al., 2018). Currently, LCA has evolved to include social aspects (social LCA) and economic aspects (lifecycle costing).

LCA can be attributional or consequential. Attributional LCA isolates the product or service from the rest of the economy and the technosphere; the model therefore contains only direct impacts from the product or service. Attributional LCA seeks to find the impacts of producing one product or providing a service (Hauschild et al., 2018). Consequential LCA considers the entire economic system and seeks to find the direct and indirect impacts of consuming one product by considering interactions between the product or service and all other products and services in the system (Earles & Halog, 2011; Hauschild et al., 2018).

We can see the differences between consequential and attributional LCA in how they define system boundaries: the processes that are to be included in the quantification of impacts. Attributional LCA usually does not include processes related to complementary products, while in consequential LCA such processes are included.

Nowadays, LCA is used to support both corporate and governmental decision-making, such as the design or redesign of products or the identification of critical materials or supply chains (Hauschild et al., 2018).

Given that LCA design reflects objectives, it is a flexible method that allows the measurement of impacts at different levels and with different system boundaries. LCA can be applied at several levels: per product, per capita, or for a specific city, country, or region. System boundaries can likewise be defined either more narrowly, including just the production or use phase, or more broadly to include the whole supply chain. Other components of LCA are similarly flexible, such as the functional unit and environmental impact categories included.

I use LCA in Paper II to quantify WTW emissions impacts from transportation in Amsterdam considering the use of car sharing. I chose this method due to its flexibility in levels of analysis and its detailed nature, which allowed me to build an inventory of mobility using a bottom-up approach. This paper explores impacts at the personal and city level by quantifying travel demand for three travel profiles—car owners, car-free residents, and car sharing users—considering the travel distances and modal splits for each profile. The assessment of the environmental impacts for each profile represents the personal level. I then scaled up this quantification to the city level, classifying the traveling population into car owners, car-free residents, and car sharing users. This LCA included variables from the urban context, the technology used in the private, public transit, and shared fleet, and travel behavior. These analyses were done using SimaPro.

3.3.3 Multi-Regional Input and Output

MRIO is based on the input and output analysis (IOA) and input and output tables (IOTs) that Wassily Leontief proposed in the 1930s. IOA is a macroeconomic method that looks at interdependency among sectors within a region or across several regions (MRIO). The IOTs represent economic flows between sectors (or products) from one or more regions recorded in one year. IOTs also contain information about final demand, including government, households, and investment, as well as information on taxes, employment, and emissions per sector (or product) in every region. The IOTs are based on the Use and Supply tables collected at the national level, which are then transformed into IOTs following a standardized process (Miller & Blair, 2009).

Considering the interdependence of sectors and countries, IOA is used to quantify economic, environmental, and social impacts from changes in consumption, economic structure, and new technologies. This approach has been used to study carbon, water, and ecological footprints (Lenzen et al., 2012; Peters et al., 2011; Weber & Matthews, 2008). In terms of social impacts, this method has been used to study child labor, hazardous work, and slavery footprints (Shilling et al., 2021; Simas et al., 2014). In terms of economic aspects, IOA has been used to model impacts on employment (Cooper et al., 2016).

IOA allows researchers to model direct, indirect, and induced impacts (Miller & Blair, 2009). I will use the example of a household to explain the difference between these types of impacts. For a household, direct emissions include tailpipe emission from traveling by car, cooking over a wood fire, or heating the home using a pellet stove or oil furnace. Indirect impacts come from the production and transportation of services and products that the household uses, such as the emissions caused during fuel production or food harvesting. Lastly, induced emissions are direct and indirect emissions that are produced thanks to the spending of additional household income. For example, if a household member gets a salary raise, this extra income might be used to increase the consumption of imported fruits (Cheng et al., 2020).

IOA also allows researchers to differentiate between two main perspectives: consumer and producer. The producer perspective uses an approach to allocate responsibilities for impacts to the country where the impact originated, even if the final product or service is consumed abroad. In contrast, a consumer perspective allocates embodied impacts to the country where goods and services are consumed. The consumer perspective is also referred to as the footprint approach.

While the producer perspective allows implementation of measures to decrease impacts locally, such as policies that target the most-polluting sectors, it does not account for embodied emissions in international trade (Imura et al., 2005; Wyckoff & Roop, 1994). The consumer perspective considers impacts not only caused by products produced and consumed locally but also imported ones. The two perspectives are complementary and allow us to understand impacts in a more holistic way.

In this dissertation I used MRIO because it can simultaneously model impacts from changes in consumption, (such as the adoption of new transportation modes), rebound effects, the implementation of new transportation services, and gives the possibility of modelling different countries.

I use MRIO in Papers III and IV to assess impacts from a consumption perspective directly linked to spending, which is represented in final demand. In Paper III, the analysis focuses on the Netherlands, where I assess changes in final demand after residents started using car sharing. I conducted this analysis using IOTs divided by sector. To perform this analysis, I modified the size of the IOTs by augmenting them. This augmentation of the IOTs followed a process that is used when there is a need to disaggregate sectors or products that are grouped in the tables. For this paper, the IOTs were augmented to account for public and shared transportation.

In Paper IV, MRIO was used to model impacts in the Netherlands, Sweden, and the United States, using IOTs disaggregated at a product level. For this paper, I calculated final demands considering the travel behavior of residents of each country and then modified these final demands according to the scenarios developed (see details in section 4.3.4). In both papers, I used the EXIOBASE 3.8.2 database, which contains the IOTs divided in 49 regions and 163 sectors or 200 products.

3.3.4 Scenario analysis

A scenario describes one possible future based on assumptions about how that future might look (Alcamo & Henrichs, 2008). Scenarios represent a complex system, including supply and demand parameters and demographic dynamics (Nakicenovic et al., 2000). Scenario analysis entails the development of scenarios, where possible futures are explored and impacts quantified (Alcamo & Henrichs, 2008). Environmental scenario analysis focuses on developing scenarios that are tailored to the evaluation of environment impacts. One of the purposes of developing scenarios is to understand the factors that drive change in environmental impacts and the uncertainty associated with these changes (Nakicenovic et al., 2000). Developing scenarios helps researchers arrive at a better understanding of a possible future and its environmental consequences. This makes it possible to test the potential consequences of policies, technological developments, or consumption changes.

Scenario analysis requires developing a baseline that represents the current situation or the most likely situation that might unfold. This baseline is used as a point of comparison for the rest of the scenarios. Scenarios reflect change over time or alternative possible futures, describing different pathways to how the future might look or unfold (Alcamo & Henrichs, 2008). Scenario analysis can be performed at different levels, including individual, city, region, or country.

I use scenario analysis in Papers II, III, and IV to construct potential new travel behaviors, consumption patterns, and changes in the context. I built the scenarios based on assumptions drawn from publicly available information and literature review. In Paper II, the scenarios model the adoption of a policy—namely Clean Air from Amsterdam—and changes in travel behavior due to car sharing. These scenarios address the personal level, modeling changes in travel profiles as shown in Figure 4. The baseline consists of the car owner and car-free profiles. In the scenarios, these two profiles shift to using electric vehicles (reflecting the application of the Clear Air Policy), either through B2C or P2P car sharing. Each of these changes implies modification in the modal split and distance traveled, as well as the type of car that is used to travel. These changes in travel behavior were based on the findings of Nijland and van Meerkerk (2017). At the city level, the scenarios represent a portion of the population shifting from being car owners or car-free residents to electric car owners and B2C or P2P car sharing users.

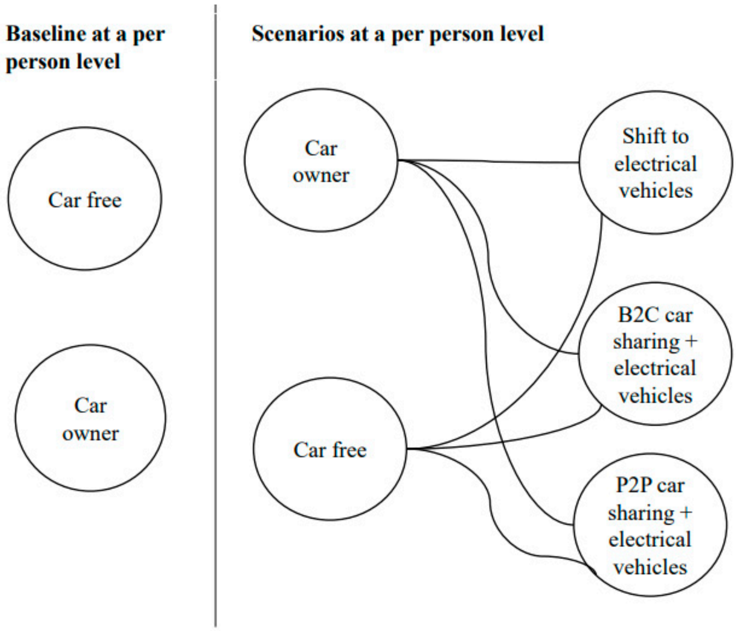

Figure 4 - Scenarios at the per person level in Paper II

For Paper III, scenarios were developed at the per-person level and focused on changes in travel profiles. The profiles modelled in the baseline of this paper include car owner, car free and car buyer. The scenarios include a profile of car owners that shared their car in P2P car sharing and a shift in the baseline profiles to B2C and P2P car sharing (Figure 5). Changes in travel behavior were based on Nijland and van Meerkerk (2017). Since this assessment was performed with MRIO all travel profiles were represented in yearly transportation and non-transportation expenditure. Transportation expenditure was based on the profiles while non-transportation expenditure was based on average expenditure patterns reported in EXIOBASE. For the calculation of rebound effects in two situations were considered. The first one when people gets additional income because they shared their car in P2P car sharing and the second one when people has a new disposable income due to changes in travel behavior. Income elasticities were used to model spending scenarios of new or additional income. Income elasticities were taken from Bjelle et al. (2021).

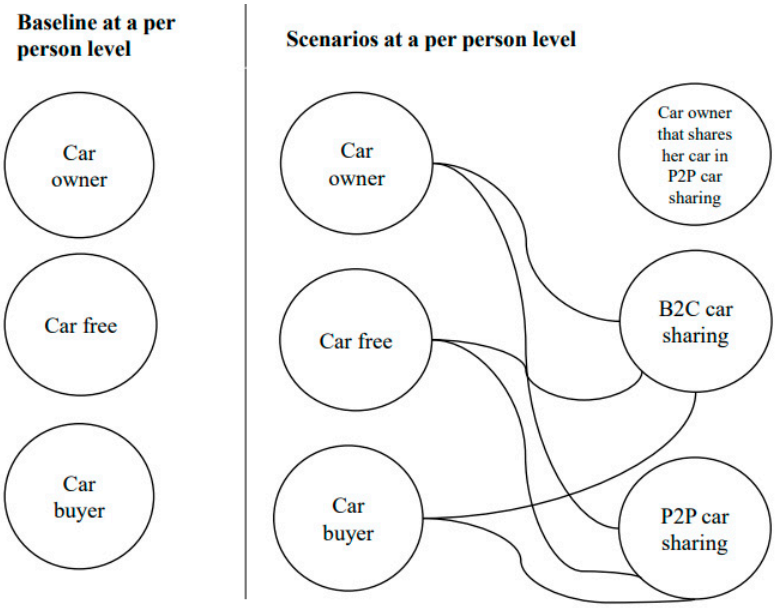

Figure 5 - Scenarios at a per person level paper III

For Paper IV, scenarios were built at the country level, focusing on the urban population (Figure 6). Drivers of change in the scenarios were digitalization, well-being, shared mobility, and fleet electrification. Environmental impacts at the baseline were calculated with respect to impacts from travel behavior and the state of the passenger fleet in 2019. To further understand what drives impacts at the baseline, contextual indicators were collected that reflected the passenger transportation situation in the Netherlands, Sweden, and the United States These indicators were grouped in well-being, attractiveness of public transportation, digitalization, and electrification readiness (Table 5). A first scenario—transportation as usual (TAU)—represents the pathways for each of the countries where current passenger transportation trends continue (increasing travel distance, car ownership, and car use). The digitalization scenario includes changes in travel behavior that were framed using the avoid-shift-improve (ASI) framework in a manner similar to Brand et al. (2021). These changes in travel behavior were based on findings from previous research (Center for Sustainable Systems, 2022; Giesel & Nobis, 2016; Nijland & van Meerkerk, 2017)

The last scenario, digitalization and social transformation, included more drastic changes in travel behavior enabled by a social transformation. The performance of scenarios in this paper was assessed in terms of GHG emissions, air pollution and energy used, where target thresholds were established for each of these indicators. For GHG emissions, the target threshold was established considering transport emissions per capita to stay under 1.5 °C which is 0.75 t CO_2eq for the three countries (Akenji et al., 2021; van Vuuren et al., 2018). For the other environmental impacts, relative target thresholds were established with respect to emission in the baseline for each country: for energy use a reduction of 60% while for particulate matter a reduction of 30%.

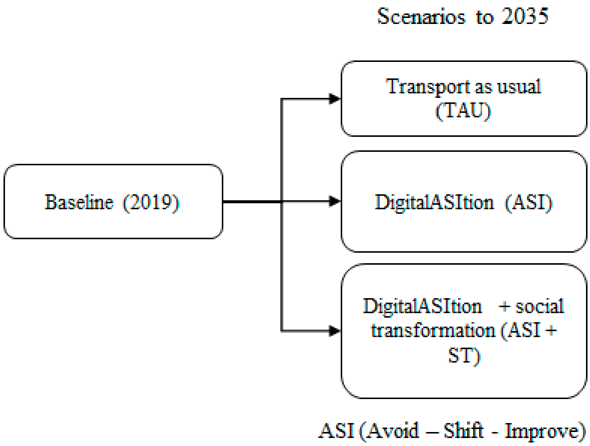

Figure 6 - Country-level scenarios (Paper IV)

Table 5 - Context indicators with description and their goals (Paper IV)

	Indicator	Description	Goal
Well-being	Levels of congestion	Percentage of prolonged time in traffic	Below 15%
	Road safety for active transportation	Number of pedestrian and cyclist fatalities	Zero
	Modal share of active transportation	Share of distance traveled by active transportation	≥ 11.3%
Attractiveness of public transportation	Satisfaction with public transportation	Percentage of the population satisfied with public transportation	≥ 82.6%[1]
	Affordability of public transportation for average-income households	Percentage of household budget used spent for a one-month public transportation fare pass in average-income households	Below 10%
	Affordability of public transportation for low-income households	Percentage of household budget used spent for a one-month public transportation fare pass in low-income households	Below 10%
	Accessibility of public transportation for people in wheelchairs	Percentage of transportation modes accessible for people in wheelchairs	100%
Digitalization	Internet access	Percentage of the population that has Internet access	100%
Readiness of electrification of private fleet	Electric vehicles in the private fleets	Percentage of electric vehicles in the private fleet	≥ 20%[2]
	Energy from renewables	Percentage of energy that comes from renewables	≥ 98%[2]
	Availability of public charging stations	Number of electric vehicles per public charging station	2.4[2]

[1] Based on the threshold specified in Sustainable Development Report (2022)

[2] Norway was used as a reference to establish the thresholds.

3.3.5 Sensitivity Analysis

Sensitivity analysis is used to identify which inputs or parameters have the greatest influence on the results of a model, and it can also be used to identify variables that need to be more accurate (Possingham et al., 2013). There are several methods to conduct sensitivity analysis, with different purposes. In this dissertation I use the one-at-a-time-method. With this method, one input or parameter is changed at a time to explore how that change affects the results (Saltelli & Annoni, 2011). Since the aim of using sensitivity analysis was to identify the factors with the greatest effect on how shared mobility changes the environmental impacts of passenger transportation, this method was considered appropriate. Papers II and III use one-at-a-time sensitivity analyses, applying relative changes to only one model parameter or input at a time and keeping all other variables constant. This was then repeated for selected input variables. The inputs changed were travel behavior, technology used, and consumption.

3.4 Validity and reliability

Validity refers to how accurate the results and conclusions of a research study are, and when pertinent to the topic, how generalizable they are (Liu, 2017). To confirm the validity of the results of this dissertation, I consulted the academic literature that quantifies environmental impacts from passenger transportation and shared mobility. I found that the academic literature on footprints was also relevant to this process. I then benchmarked the results of this review against my own results. In addition, peer review was also helpful to check the validity of my results here.

Reliability refers to the consistency of research results (Liu, 2017). In this dissertation, reliability depended to some extent on the inputs that were used to calculate impacts. I compared my results with those from other assessments conducted using other databases to determine whether the inputs I used were reliable. The results from the assessments showed to be close to others results demonstrating their validity and reliability.

4 Results

In this chapter I first elaborate on the environmental and economic impacts of shared mobility. This section is divided by level of analysis, looking at the analysis at the per-person level first, followed by the analysis at the city level. I then look at rebound effects and per-person economic impacts. In the second section of this chapter, I present results concerning the factors that affect shared mobility's potential to decrease environmental impacts from transportation.

4.1 Environmental and economic impacts of shared mobility

4.1.1 Per-person environmental impacts from passenger transportation due to shared mobility

The systematic literature review found that the environmental impacts of passenger transportation due to shared mobility at a per person level can change (Figure 7). B2C and P2P car sharing can dampen or exacerbate climate impacts, while B2C car sharing might potentially decrease fuel consumption. Ridesharing decreased both climate impacts and resource depletion. Micromobility sharing modes performed poorly in almost all the impact categories except for ecosystem damage in the case of e-mopeds. This because in the reviewed assessments, use of shared modes was compared to the use of privately owned bikes, e-scooters, and e-mopeds. Privately owned bikes, e-scooters and e-mopeds do not need to be rebalanced, nor do they need additional tracking equipment or docking stations, and thus their impacts are lower compared to shared micromobility.

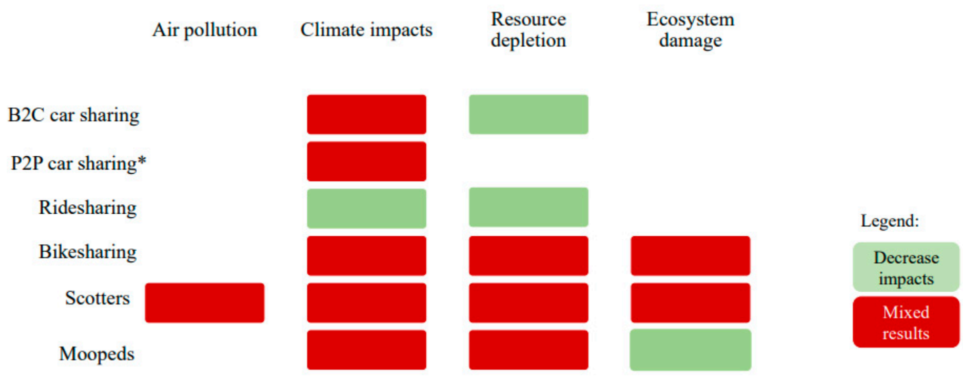

Figure 7: Summary of environmental impacts of shared mobility modes in assessments at the per-person level[3] (Paper I)

Car-sharing users in the Netherlands who gave up their car or did not purchase one might reduce their transportation emissions (Figure 8-A and Figure 9-A). When the system boundaries are limited to WTW, there was a decrease of 924.8 and 941.5 kg CO_2eq annually for B2C and P2P car sharing in combination with the Clean Air Policy, respectively. This decrease is higher than the decrease found from the implementation of the Clean Air Policy (savings of 247.8 kg CO_2eq) (Figure 8-A). When the system boundaries were expanded to include impacts caused during the entire use phase (including, for example, maintenance and insurance) the savings potential for a car owner that gave up their car and joined a car sharing system were 993.5 and 1033.6 kg CO_2eq for B2C and P2P car sharing, respectively (Figure 9-A). For car buyers that abandoned car purchase and joined car sharing, including both production and extended use phases, the potential savings were 8473.1 and 8513.2 kg CO_2eq for B2C and P2P car sharing (Figure 9-A). Car owners who shared their car increased their emissions due to the additional maintenance and insurance needed for shared vehicles (Figure 9-A)

[3] Personal-level assessments were the ones that reported results per passenger kilometer, per trip, per year of passenger transportation, or per household.

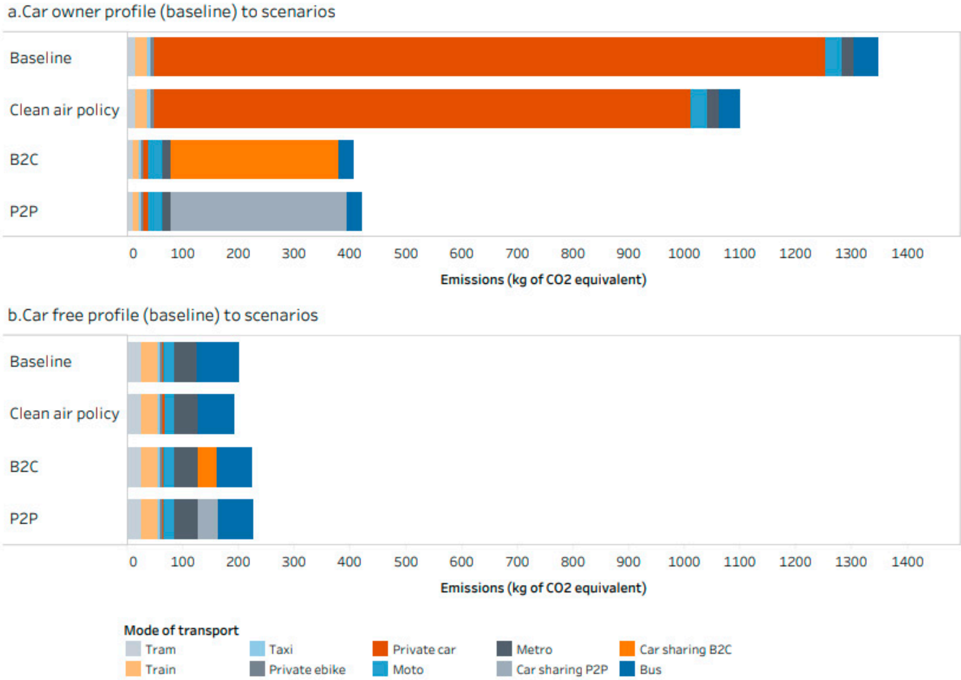

Figure 8 - Annual GHG emissions from the travel habits of car owners (a) and car-free individuals (b), differentiating between modal share. Results are at a per-person level for Amsterdam (Paper II).

In the Netherlands, there was an increase in emissions from car-free individuals who gained access to a car through car sharing (Figure 8-B and Figure 9-B). When the system boundaries are limited to WTW, we see an increase in emissions of 23.4 and 25.2 kg CO_2eq for B2C and P2P car sharing (Figure 8-B). When the system boundaries are expanded to include other impacts during the entire use phase of the transportation mode (including maintenance and insurance), there was an increase of 5.8 and 10.86 kg CO_2eq, respectively, for B2C and P2P car sharing, due to changes in travel behavior (Figure 9-B).

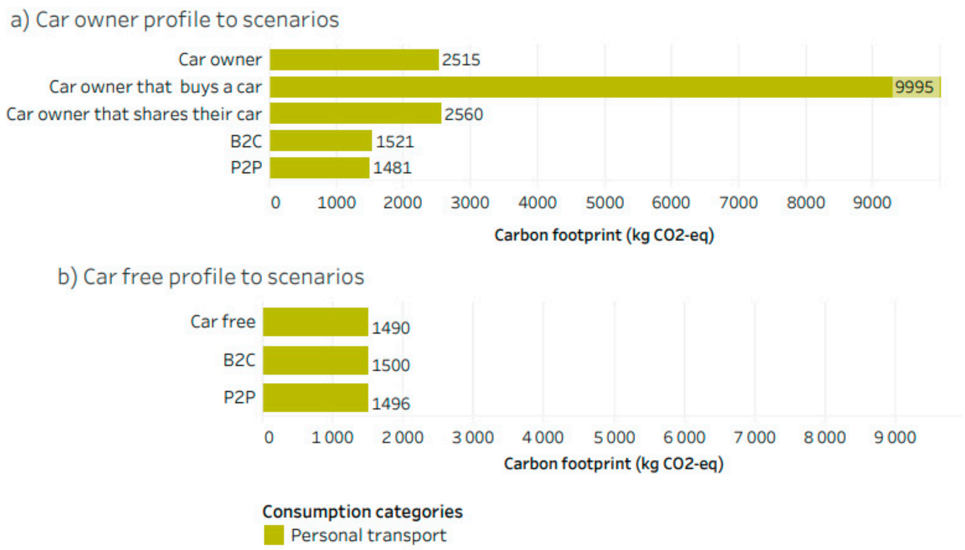

Figure 9 - Annual carbon footprint of car owners (a) and car-free individuals (b). Results are at the per-person level for the Netherlands. (Paper III)

GHG, energy, and $PM_{2.5}$ footprints decrease to meet the target thresholds at different paces in each of the three countries, and therefore the strength of actions needed to achieve this varies in different contexts (Figure 10). The strength of actions refers to how drastic the changes in travel behavior or shared fleet technology need to be in order to achieve the thresholds: for example, how fast and drastic the modal shift towards active and public transportation needs to be. The United States needs a radical transformation in the way people travel, as well as the technology used in the passenger fleet, if it is to meet environmental impact thresholds. This transformation includes, for example, a drastic 35% reduction in distance traveled and a 52% increase in the share of travel using public and active transportation. In the case of Sweden and the Netherlands, moderate actions suffice to reach the threshold: a 15% reduction in the annual travel distance and the full electrification of the fleet.

Potential environmental savings are greater if car sharing, low- or zero-emitting cars, and other lifestyle changes are combined, something that was found to be true in all three countries analyzed. In section 4.2 I discuss the degree to which these factors affect the potential reduction in environmental impacts from passenger transportation.

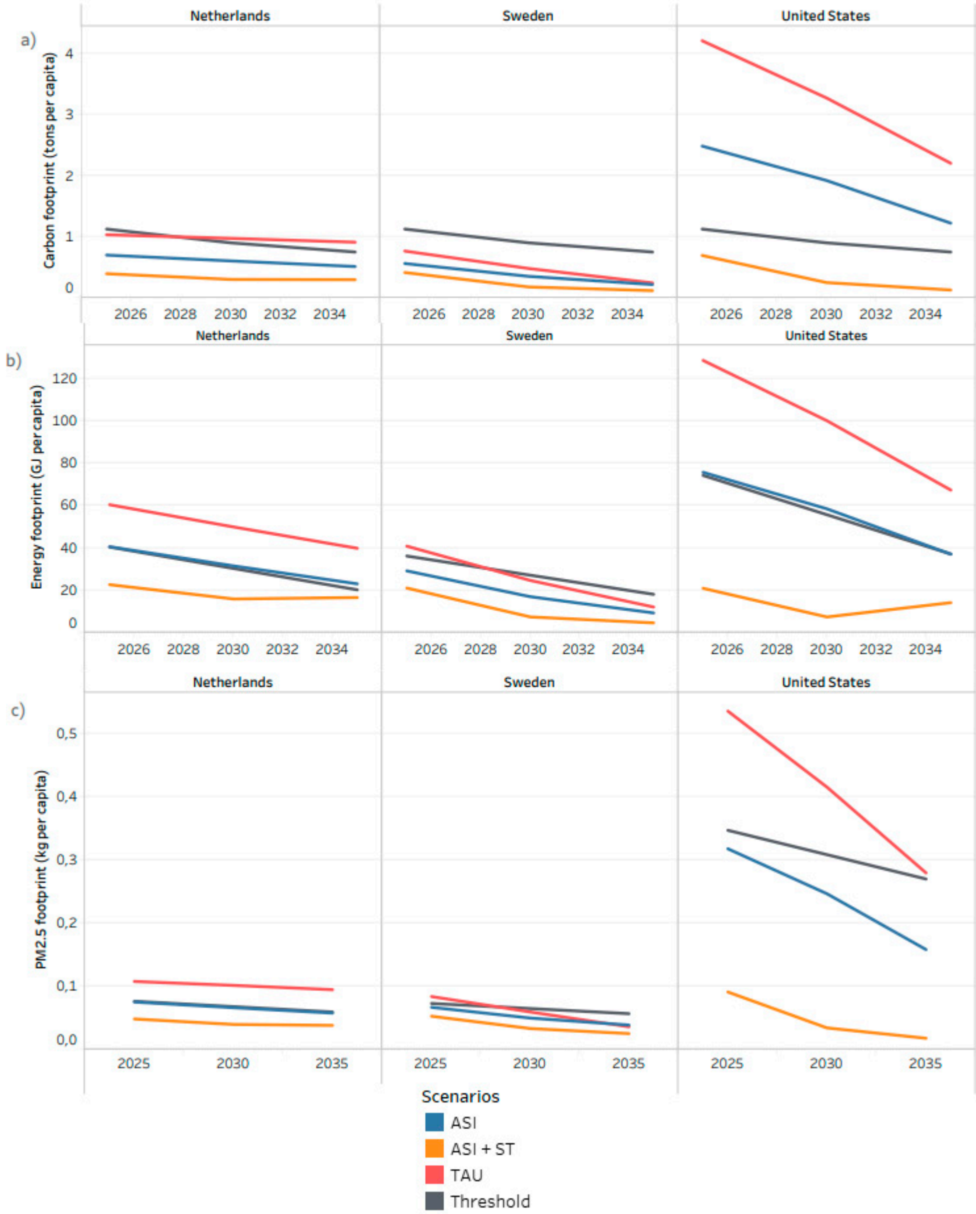

Figure 10 - Environmental impacts from passenger transportation in different scenarios (per capita emissions) (Paper IV).

4.1.2 City-level environmental impacts of passenger transportation due to shared mobility

At a city level, the systematic literature review showed that B2C car sharing can exacerbate climate and air pollution impacts but potentially lessen resource and ozone depletion, as well as land use (Figure 11). P2P car sharing showed the potential to both decrease and increase climate impacts, as did bikesharing with respect to air pollution (Figure 11).

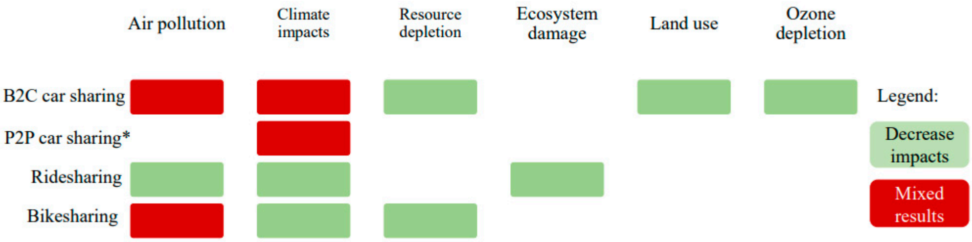

Figure 11 - Summary of environmental impacts from shared mobility modes based on city-level assessments (Paper I)[4]

Car sharing and the implementation of the Clean Air Policy can potentially decrease GHG emissions from passenger transportation by 105.7 and 106.5 million kg CO_2eq for B2C and P2P car sharing, respectively. While with just the implementation of the Clean Air Policy potential emissions savings are limited to 63 million kg CO_2eq in the Netherlands. The highest savings come from a shift from private car use to a combination of public transportation and car sharing use. It is worth noting that this result depends on how many car owners and car-free individuals adopt car sharing. For example, if there is a large-scale adoption of car sharing by car-free individuals while no car owners give up their cars, emissions would increase in the short term (Paper II).

At the city level, the decrease in GHG emissions is possible due to car owners who shift to car sharing whom present considerably larger decrease in GHG emissions than the increase in emissions from car-free individuals who start car sharing (Paper II).

[4] City-level assessments were ones that reported impacts at a neighborhood or city level.

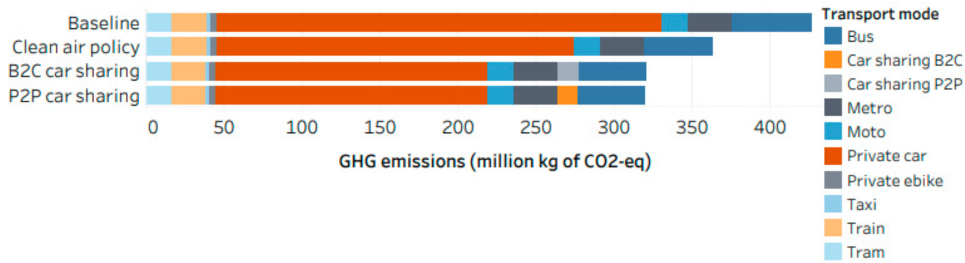

Figure 12 - Total transportation emissions in each of the scenarios (Paper II)

4.1.3 Per-person rebound effects of car sharing

Changes in spending after people adopt car sharing were shown to have consequences on the environmental impacts of consumption both in transportation and other consumption categories (i.e., accommodation or food) (Paper III). Consumption in transportation-related services and products changed depending on how people changed their travel behavior after adopting car sharing. People that got rid of their car or avoided purchasing one when they started using car sharing reduced their spending on transportation and therefore the GHG emissions of transportation decreased (Figure 9-a).

As explained previously, additional income from sharing one's private car in a P2P car sharing system, or changes in disposable income due to changes in one's transportation behavior, have the potential to change spending patterns. Changes in spending were modeled considering income elasticities. Car owners or potential car buyers that started using car sharing increased their GHG emissions from non-transportation consumption, causing rebound effects (Paper III). In the analyzed case, sectors with high income elasticities are also those with high emissions factors, and thus the rebound effects of reallocated spending were high, ranging from 71.2 to 84.5%. These rebound effects reduced the potential GHG savings from car sharing (Table 6). Car owners who shared their car in a P2P car sharing scheme increased their total annual emissions by 5.7%.

Table 6 - GHG emissions rebound effects (including both direct and indirect rebound effects) (Paper III)

	Reduction of potential GHG savings due to rebound effects
Car owner to B2C car sharing	82.4%
Car owner to P2P car sharing	84.5%
Car buyer to B2C car sharing	71.2%
Car buyer to P2P car sharing	72.4%

4.1.4 Per-person economic impacts from passenger transportation due to shared mobility

Because of changes in the consumption of transportation and non-transportation categories when people engage in car sharing, sectors will most likely also experience changes in their economic output (Paper III). When Dutch car owners get rid of their car, transportation is the sector whose economic output is most reduced at a national level, while mining and extraction of materials also experience a reduction at the international level (Figure 13). When a Dutch person avoids the purchase of a car, the economic output of all economic sectors is reduced at both the national and international levels (Figure 14). This reduction takes place because in this case, the individual saves the money that they might have spent on a new car. Lastly, when a car-free Dutch person engages in car sharing, the economic output of the transportation sector increases at a national level, but most other economic sectors reduce their output (Figure 14). This because people with this profile reallocate their budget, spending more on transportation but less on other consumption categories (Paper III).

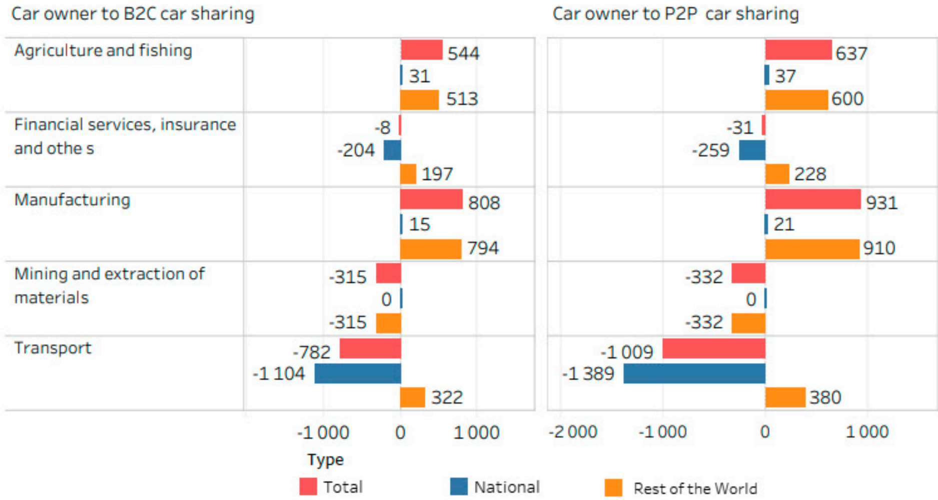

Figure 13 - Changes in the total output of sectors due to changes in overall consumption when a car owner starts car sharing. Total refers to total changes in total output (x), national refers to changes in sector output in the Netherlands, and Rest of the World refers to changes in total sector output in all other countries except the Netherlands). The graph shows the sectors that experience the biggest changes (Paper III).

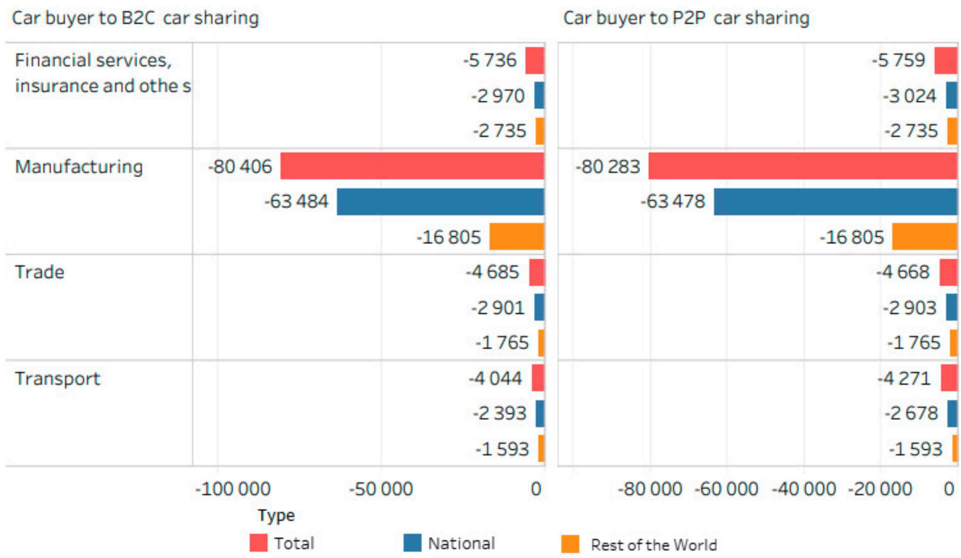

Figure 14 - Changes in total sector output due to changes in overall consumption when a car buyer starts car sharing. Total refers to total changes in total output (x), national refers to changes in sector output in the Netherlands, and Rest of the World refers to changes in total sector output in all other countries except the Netherlands). The graph shows the sectors that experience the biggest changes(Paper III).

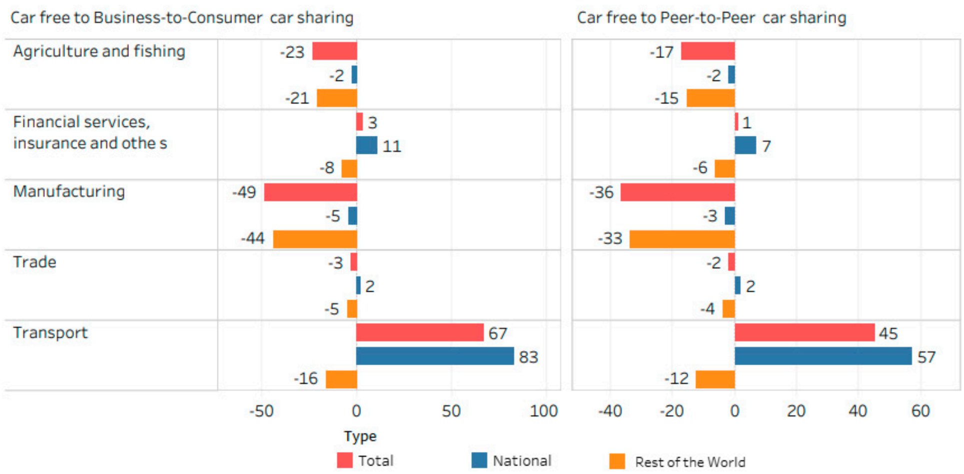

Figure 15 - Changes in total sector output due to changes in overall consumption when a car-free individual starts car sharing. Total refers to total changes in total output (x), national refers to changes in sector output in the Netherlands, and Rest of the World refers to changes in total sector output in all other countries except the Netherlands). The graph shows the sectors that experience the biggest changes(Paper III).

4.2 Factors that affect the potential of shared mobility to reduce environmental impacts from passenger transportation

All the articles included in this dissertation analyze the factors that affect shared mobility's potential to reduce environmental impacts from passenger transportation. The first insights on this topic came from Paper I, in which I identified such factors in the reviewed articles, leading me to group these factors in to four categories: *travel behavior*, *design and operation of transportation modes, consumption*, and *context* (Table 7). Papers II, III and IV test specific factors within these categories to see how they affect environmental impacts from passenger transportation (Table 7). In Papers II and III I used sensitivity analysis to do so, while in Paper IV I did so by qualitatively comparing different countries. In this section I address each of these categories. Table 7 contains the factors that were identified in Paper I and the factors that were explored in Papers II, III and IV.

Table 7 – List of factors that influence the environmental impacts of passenger transportation due to shared mobility. Factors in Paper I were collected through a literature review. Factors in Papers II and III were tested using a sensitivity analysis. Factors in Paper IV were explored by comparing different countries.

	Factor	Category	Environmental impact
Paper I[5]	Changes in modal share due to shared mobility, travel distance per vehicle, passengers per vehicle, and car ownership rate	Travel behavior	Climate impacts, air pollution, material depletion, ozone depletion, land use, and ecosystem damage
	Rebalancing strategy, age of shared vehicles, number of shared vehicles in the system (and utilization rate), shared vehicles technology, parking strategy (dockless or docked/ stationary or free-floating), material used in manufacturing shared vehicles, end-of-life	Design and operation of transportation modes	
	Purchase of new car	Consumption	
	Electricity mix used to charge vehicles	Context	
Paper II	Changes in modal share, vehicle kilometers travel, car occupancy and car ownership.	Travel behavior	GHG emissions
	Ownership in car sharing: B2C and P2P car sharing and fuel consumption of vehicles	Design and operation of transportation modes	
Paper III	Changes in modal share, distance traveled per vehicle, and car ownership rate.	Travel behavior	GHG emissions
	Car sharing ownership model: B2C or P2P.	Design and operation of transportation modes	
	Income and spending on fuel, B2C car sharing fees, and vehicle purchase	Consumption	
	Prices and emission intensities	Context	
Paper IV	Changes in modal shares, distance traveled per vehicle, and car ownership rate.	Travel behavior	GHG emissions, energy use, and PM$_{2.5}$ footprints
	Changes in transportation consumption	Consumption	
	Prices, emission intensities, attractiveness of public transportation, and electrification readiness.	Context	

4.2.1 Travel behavior factors

The climate impacts from passenger transportation change when people engaged in car sharing and ridesharing due changes in the modal split, total distance traveled, vehicle occupancy, and car ownership rates (Papers I, II, III, and IV). In most of the articles included in the literature review, the availability of car sharing led to a decrease in solo driving and vehicle ownership and prompted a shift to active and public transportation (Amatuni et al., 2020; Firnkorn & Müller, 2011; Martin & Shaheen, 2016; Nijland & van Meerkerk, 2017; Raugei et al., 2021). Studies rarely considered potential heterogeneous effects from car sharing on people's travel behavior, although there is evidence that points in this direction (Nijland & van

[5] Includes B2C car sharing, P2P car sharing, ridesharing and micromobility sharing.

Meerkerk, 2017; Severis et al., 2019). When assessments considered an increase in travel distance or a shift from public and active transportation to solo driving after engaging in car sharing, climate impacts increased (Nijland & van Meerkerk, 2017; Severis et al., 2019). In the case of ridesharing, the increase in vehicle occupancy led to a reduction in climate impacts (Lausselet et al., 2021; Sun & Ertz, 2021).

In terms of other environmental impacts, car sharing and ridesharing prompted a modal shift from private driving to active, public, and shared transportation, together with a decrease in car ownership, resulting in a decrease in material depletion, land use, and ecosystem damage (Lausselet et al., 2021; Ma et al., 2018; Te & Lianghua, 2020; Yu et al., 2017) (Paper I). These drops in impacts were the result of fewer cars and less fuel needed to supply travel demand.

In Paper II, annual travel distance, car driving, and car occupancy were the factors with the biggest effect on GHG emissions from passenger transportation. This paper sought to quantify changes in emissions from transportation. A decrease in annual travel distance reduced GHG emissions by 25%, while a decrease in distance traveled by car reduced GHG emissions by 20%. An increase in vehicle occupancy was found to reduce GHG emissions by 21% (Paper II). Paper III explored changes in GHG emissions from overall consumption (including both transportation and non-transportation consumption). For car owners, an increase in annual travel distance and travel by car boosted GHG emissions by 1.2% and 1.5%, respectively. However, for car sharing users, an annual increase in travel distance leads to a decrease in emissions of 3.16% (Paper III). This shows that changes in individuals' travel behavior affect GHG emissions differently depending on which travel mode the individuals use.

Paper IV analyzed average travel behavior in the Netherlands, Sweden, and the United States in 2019, followed by an assessment of GHG emissions, air pollution, and energy use. The United States generates the highest environmental impacts in all categories, and out of this sample it is the country with higher annual travel distance, car ownership rate, and private car use. Sweden and the Netherlands had much lower environmental impacts, given that travel using active or public transportation accounts for a considerable share of the modal split (Paper IV).

For micromobility sharing, changes in travel behavior were key in determining whether sharing modes implementation led to environmental gains or losses (Paper I). Some reviewed articles considered scenarios where micromobility sharing replaced car driving; in this case, they found savings in climate impacts and resource depletion (Luo et al., 2019; Tao & Zhou, 2021). The assumption that micromobility sharing can replace car driving is somewhat questionable, given that trips by bike are normally shorter than trips by car. When micromobility sharing was compared to the use of private bikes or e-scooters (the most frequent situation reported in the reviewed articles), researchers found an increase in climate impacts and material depletion (Bonilla-Alicea et al., 2020; de Bortoli & Christoforou, 2020; Kazmaier et al., 2020; Luo et al., 2019; Schelte et al., 2021).

4.2.2 Design and operation factors

Environmental impacts from passenger transportation can change depending on the design and operation of shared mobility modes. In the case of car sharing and ridesharing, environmental impacts were affected by the type and number of shared cars (Baptista et al., 2014; Schelte et al., 2021; Zhang et al., 2021). Car sharing systems that have an oversupply of cars and experience low utilization rates are likely to have higher climate and material depletion impacts (Chen & Kockelman, 2016; Ding et al., 2019; Sun & Ertz, 2021). Using electric or hybrid cars for car sharing or ridesharing fleets results in lower climate impacts and fuel depletion compared to ICV fleets (Ding et al., 2019; Raugei et al., 2021; Sun & Ertz, 2021). The type of vehicle in the shared fleet and their fuel economy was also a relevant driver of air pollution, ecosystem damage, and ozone depletion (Migliore et al., 2020).

Differences between the ownership model—B2C versus P2P car sharing—was found to have limited influence on GHG emissions from transportation (Figure 8, Figure 9 and Figure 12). Other aspects, such as fuel consumption of cars in the fleet or the pricing of sharing services, likewise had limited influence on the level of decrease in GHG emissions (Paper II). Paper IV found that the technology of cars in the shared fleet was a relevant factor in decreasing emissions; however the extent to which this factor influenced the potential decrease was not explored.

Design and operation factors that were relevant in micromobility systems were rebalancing, parking and maintenance strategies, as well as the number of shared vehicles. Systems that used the dockless parking strategy or offered a greater number of shared vehicles exacerbated the material depletion and climate impacts caused during the production of shared bikes, scooters and mopeds (Bonilla-Alicea et al., 2020; Kazmaier et al., 2020; Moreau et al., 2020). Material depletion was also higher when the shared system required the fabrication of docks or additional equipment such as locating devices (Sun & Ertz, 2021). Rebalancing and maintenance strategies caused environmental impacts during the use phase. Climate impacts and fuel depletion increased when the fleet distribution was rebalanced using high-emitting vehicles. In this case, the distance driven to pick up fleet vehicles had a significant role in increasing or decreasing these impacts (de Bortoli, 2021; Hollingsworth et al., 2019; Luo et al., 2019). The potential for micromobility sharing to increase environmental impacts can be mitigated by rebalancing fleet distribution using electric vehicles charged from a low-carbon energy mix (de Bortoli, 2021).

4.2.3 Consumption factors

In my review article, I found one study that looked at changes in consumption due to shared mobility with a focus on changing new vehicle purchasing rates, finding that decreased car ownership led to climate impact savings (Ma et al., 2018). In Papers III and IV I explore changes in consumption in greater depth. I found that changes in transportation consumption due to car sharing have the potential to decrease GHG emissions, air pollution, and energy use when there is a shift from private car driving to public, active, and shared transportation, as well as when there is a decrease in travel distances (Papers III and IV). However, when people decrease their consumption of public and active transportation and shifted to driving shared cars, there was an increase in GHG emissions from passenger transportation (Paper III). Changes in consumption in transportation were directly linked to changes in travel behavior.

Changes in non-transportation consumption due to car sharing also influence GHG emissions (Paper III). The extent to which emissions increased or decreased depended on where people reallocated their spending after starting to use car sharing; this variable is context dependent, given that different countries and income groups have different income elasticities. The sensitivity analysis found that changes in GHG emissions were highly sensitive to increases in income generally and to income from car sharing, as well as to increased spending on new vehicles (Paper III).

4.2.4 Contextual factors

In Paper IV I collected contextual indicators at the baseline timepoint to understand how the context influences the environmental impacts of passenger transportation. At the baseline, the United States was the country with the highest GHG emissions, air pollution, and energy use from transportation, while the Netherlands and Sweden had relatively similar impacts. The contextual indictors showed that of the three countries, the United States has the lowest share of active transportation use, the lowest level of satisfaction with public transportation, the lowest level of readiness for passenger fleet electrification, and the highest rate car ownership. This contributes to the United States being the country with the highest annual travel distance and the greatest travel distance by car. These contextual indicators and their consequences are reflected in the high environmental impacts that United States generates compared to Sweden and the Netherlands. A correlation or causation analysis would enable further understanding of how the contextual indicators shape impacts from passenger transportation when shared mobility is incorporated into the transportation landscape.

In Paper I, the energy mix used to charge shared vehicles was identified as a relevant factor in shaping the climate impacts of passenger transportation when shared mobility is used when electric or hybrid vehicles are used (Paper I). Paper III found that changes in fuel prices had a limited effect in the GHG emissions. Other contextual factors, including build environment, cultural beliefs and social norms, have the potential of influencing the transport landscape in cities and also shape how shared mobility fits in these systems. The influence of these factors will be discussed in the next chapter.

5 Discussion

This section includes a discussion about the environmental impacts of shared mobility and the factors identified in this dissertation as relevant in shaping them. This is followed by a reflection about scaling up shared mobility and recent development in the industry. A reflection about sustainable consumption and production practices is also presented and I finish this section with a reflection about my research approach.

5.1 Sustainability impacts of shared mobility in cities

Shared mobility modes have considerable potential to change the environmental impacts of passenger transportation. The results of this dissertation show that car sharing can potentially increase or decrease annual GHG emissions from passenger transportation. Increases in emissions ranged between 23 and 25 kg CO_2eq, and decreases ranged between 924.8 and 8513.2 kg CO_2eq (Papers II and III). These findings are in line with other research, which has also found that car sharing can have both positive and negative effects on emissions at the per-person level (Martin & Shaheen, 2011; Nijland & van Meerkerk, 2017). Since GHG emissions can vary both positively and negatively, we can presume that when other impacts such as air pollution, material depletion or energy use are assessed at the per-person level, they will exhibit the same behavior. Thus, it is critical that we understand the factors that shape these outcomes so we can build shared mobility systems that deliver on their environmental promises.

Shared mobility systems that are incorporated into the urban transportation landscape must have a clear purpose. Does the city need additional transportation options to cover the first and last miles? Does the city need mobility options that allow residents to transport bulky furniture or reach remote areas? With a clear purpose in mind, shared mobility systems can be designed, implemented, and evaluated in a more informed manner. Micromobility sharing has been linked to environmental gains because it promises to cover the first and last mile for residents who switch from car use to a combination of public and active transportation (Shaheen & Chan, 2016). However, research is finding that rather than replacing car trips, these modes are replacing trips made by private bike or scooter and wind up increasing environmental impacts from passenger transportation (de Bortoli, 2021; Ding et al., 2021).

In this dissertation I also assessed other dimensions of sustainability, such as economic ones. At a national or regional level, shared mobility can lead to a contraction in the economic output of specific sectors. This was the case when car owners gave up car ownership because they had access to car sharing and consequentially decreased their fuel, insurance, and maintenance consumption. How these changes in consumption impact national sectors varies depending on the country's economic structure. Hypothetically speaking, if car sharing were to be upscaled and came to replace car ownership in combination with active and public transportation, the car manufacturing industry would reduce its output. In countries that source most of their cars from national producers, this would entail a reduction in sales for this industry, which might then reduce employment in that sector. However, this does not need to represent an absolute loss of jobs and capital; what it means is that governments need to design and implement transition plans in cooperation with incumbent sectors affected by car sharing. Such a transition is similar to the transition to renewable energies, were the new sector's growth and job creation means that the eventual contraction of the non-renewable sector need not result in an absolute loss of jobs in the overall economy (Bali Swain et al., 2022; IRENA & ILO, 2022).

In this dissertation I do not directly assess social impacts; however, we can extrapolate social benefits from decreasing car ownership/use and increasing use of active, public, and shared transportation. Shifting to public and active transportation can increase individual's physical activity: walking to the bus stop or cycling, for example. This shift besides decreases emissions, can offer social benefits such as a healthier population thanks to better air quality and more use of active transportation (Mizdrak et al., 2019; Xu et al., 2013). Moreover, the availability of car sharing and other shared mobility modes can also be a cornerstone in making the transportation system more resilient. We can see an example of this when, during the COVID-19 pandemic, China's shared bike systems enable people to travel safely at a time when public transportation presented a risk of transmission (Hu & Creutzig, 2022).

An urban transportation system that maximizes the use of active, public, and shared transportation must ensure equitable access to transportation for all residents and minimize transportation poverty. Given the current situation—where some areas lack public, shared, and paratransit transportation options—some people still need to own cars. Examples include those who need to travel by private car due to health issues or who live in areas where there is no public transportation. The urban transportation system needs to be flexible enough to cover the transportation needs of everyone.

5.2 Factors that influence the environmental impacts of shared mobility

A decrease in car ownership and a switch to active and public transportation are known to contribute to a decrease in the environmental impacts of passenger transportation. Nonetheless, many people continue to own and use cars and prefer this option over using active and public transportation alternatives. Travel behavior is shaped by travel preferences, which in turn are connected to values, availability of transportation information, and personal capacity to use different transportation modes (Flamm & Kaufmann, 2006). Rising car ownership and use rates suggests that there is a strong value in car ownership that acts as a barrier in the shift away from car dependency as a society. The perceived value of car ownership and use is linked to its flexibility, security (compared to other transportation modes), and comfort (Moody et al., 2021; Verma, 2015). In monetary terms, car owners value car ownership much more than its actual annual cost, while public transportation options are given less value than cars. Thus, public transportation alone is not an alternative to car ownership (Moody et al., 2021).

There is a tension between sustainability and profit in the design and implementation of shared mobility modes (Santos, 2018). It's well known that shared mobility modes are not sustainable by default and must be designed and operated in specific ways to realize their potential to decrease the environmental impacts of passenger transportation (Curtis & Mont, 2020). We have numerous examples of shared mobility systems that are being operated in unsustainable ways: for example, systems that have larger vehicle fleets than necessary or that retire vehicles before they actually reach the end of their service life—operational choices that influence the environmental impacts of shared mobility. How government officials and sharing organizations address this tension between the sought-after decrease in environmental impacts from passenger transportation and organizational profit in the future is one key to ensuring that shared mobility schemes actually do result in decreased environmental impacts.

Car sharing has the potential to change how people consume by generating additional income or by freeing up part of the household budget formerly spent on transportation. How households allocated this additional income or savings were found to cause rebound effects. In this research, these effects ranged between 71.2% and 84.5%; other researchers have found rebound effects of a similar magnitude, ranging from 78.5% to 92.6% (Briceno et al., 2005; Chen & Kockelman, 2016). Although these rebound effects show that most of the savings from transportation emissions are lost by changes in consumption, potential rebound effects should not discourage the design and implementation of sustainable solutions such as car sharing. The implementation of car sharing has shown to have the potential to decrease car owners' GHG emissions, and thus car sharing is fulfilling its purpose of decreasing impacts from transportation.

As mentioned above, when people start to use car sharing they can increase their disposable income by abandoning car ownership or sharing their car through P2P schemes. This can be financially beneficial for many households and individuals. This increase in income led households to simultaneously increase their consumption and GHG emissions in other categories (Paper III), a trade-off identified here that has also been identified in the implementation of other sustainable solutions (Murray, 2013).

Additional income generated by P2P car sharing has different environmental impacts depending on the household's previous income level. Previous research has found a strong correlation between income levels and environmental impacts from consumption (Baiocchi et al., 2010; Ivanova & Wood, 2020).

Policymakers, researchers, and consumers should be aware of rebound effects and possible trade-offs, and incentivizing polices should target emission-intensive products and sectors to curb impacts from consumption. Implementing individual-level sustainable solutions in transportation, energy consumption, and so on, is not as effective as implementing systemic solutions that consider the whole system, including consumption (Creutzig et al., 2022).

Contextual parameters, such as residential density or the accessibility of public transportation networks, have been found to influence car ownership and how people choose to travel (Ding et al., 2017; Ding et al., 2018). In addition to shaping travel behavior, such contextual parameters determine how a city is built, specifically the locations where people work and live, the road network, whether the city is compact or sprawling, and the amount of urban greenspace. Determining these parameters in a city is a complex process and can lead to lock-in effects from major infrastructure projects such as highway or cycling network construction. In the next section, I discuss the complexity of this process and how different actors influence it.

5.3 Reflections about scaling up environmentally sound shared mobility systems

This dissertation has demonstrated that shared mobility has the potential to decrease environmental impacts from passenger transportation in cities. Moreover, shared mobility can complement public transportation, and together they can offer an alternative to car ownership. However, car sharing and other modes of shared mobility have not been upscaled in cities in ways and to the dimensions at which they could significant positive environmental change, for several reasons. These reasons include the value of car ownership for car owners and the lock-in effects of a car-dependent society, such as road infrastructure, cultural norms and beliefs, and lobbying from various industries (Mattioli et al., 2020; Moody et al., 2021).

The lock-in effects of a car-dependent society are supported and incentivize by actors such as the automotive and transportation infrastructure industries, as well as by cultural norms that support car ownership (Mattioli et al., 2020). The automotive industry is central to the economy of many countries, generating employment, innovation, and ultimately economic growth. The viability of this industry depends on growth in car ownership or the rotation of the existing stock of cars. Powerful industry lobbying can mean that innovations that might jeopardize the industry's growth and stability are de-prioritized in the political agenda, even if they represent improvements for the environment (Orsato & Wells, 2007; Wells & Orsato, 2005). The transportation infrastructure industry—for example road construction and construction materials manufacturing—is another sector that supports a car-dependent society. For some countries, this industry is representative domestically, and its growth depends on government spending.

Car-centric cultures are another barrier to upscaling car sharing; such cultures frame cars as social status symbols and a society with high car ownership and car infrastructure as a symbol of progress and modernity (Gartman, 2004). Rising household incomes have been found to correlate strongly with car ownership, and thus countries or regions where incomes are on the rise are experiencing steep increases in car ownership (Dargay, 2001; Nolan, 2010). This car-centric culture constitutes another barrier to upscaling car sharing, given that many people are not willing to give up their car, even if they live in an urban area with a well-connected public transportation network (Moody et al., 2021).

Forming a family and changing jobs or residence have been identified as points in life when people evaluate their travel behavior and vehicle ownership status, possibly deciding to buy a first or additional car (Beige & Axhausen, 2012; Oakil et al., 2016b). Understanding how car ownership rates and travel habits change during the human lifecycle can enable the development of transportation systems that include shared and public mobility modes that cater to all life stages and the specific needs of the entire range of the population. A deeper understanding of these factors may also challenge cultural beliefs and norms that dictate when people expect to buy their first car (Beige & Axhausen, 2012).

Actors lobbying for a system that supports and enables a car-dependent society—and citizens that embrace this—creates a push for a built urban environment that prioritizes cars over pedestrians, public transportation, and cyclists. Cities are planned and built in ways that affords most of the landscape to cars. Infrastructure is thus one element of the built environment that can generate long-term locked-in effects that are hard to change or work around.

How to overcome these barriers is, again, a complex and context-dependent issue. Cities can face two situations: one where the car ownership rate is already high (more than 500 cars per 1,000 inhabitants) or another where car ownership is at a low or medium level (fewer than 300 cars per 1,000 inhabitants). Cities with low car ownership rates should focus on developing flexible and robust public transportation systems, using shared mobility as a complement to cater for diverse needs. Cities with high levels of car ownership require a systemic change to ensure a shift away from car ownership. The specifics of how to accomplish this is not within the scope of this dissertation; however, my findings here do point to certain drivers that can enable this shift.

These drivers of sustainability shifts include increasing well-being, urbanization, novel services, and digitalization (Barrett et al., 2022; Creutzig et al., 2022; Grubler et al., 2018). In the specific context of passenger transportation, in order to decrease car ownership rates and increase the use of public, active, and shared transportation, well-being can serve as a drive that encourages people to choose transportation modes with lower environmental impacts (such as less-emitting transportation modes that preserve good local air quality), as well as active transportation modes. Urbanization can drive the development of more robust public transportation networks and make collective transportation more feasible in higher-density areas. Novel services can encourage people to look to car access rather than car ownership, priming a shift to shared mobility that contributes to increasing quality of life in cities. And digitalization supports the information services that make it possible for individuals to have access to timely scheduling information, smart ticketing apps, and integrated transportation planning services (Grubler et al., 2018).

The upscaling of shared mobility and the shift away from a car-dependent society requires changes on both the supply and demand sides; these changes are enabled by the above-mentioned drivers. To accomplish this, a societal, technological, and institutional transformation needs to take place, modifying the system through which passenger transportation is provided and used (Creutzig et al., 2022).

It is important to note that car ownership and use remains necessary and valuable in specific situations, such as for individuals with special mobility needs or who live in or travel to low-populated ares. Thus, car ownership is also needed as part of the transportation solution but will not always be the central component of urban personal transportation for healthy city inhabitants.

5.4 Recent development in shared mobility organizations

Shared mobility organizations continue to appear in cities, in different and evolving formats. As a result, some emerging issues that were not included in my assessments here nevertheless merit discussion. One of the points discussed above is the tension between profitability for shared mobility organizations and environmental impacts (Santos, 2018). This tension becomes evident in the way some shared mobility organizations are operated, such as B2C car sharing organizations that have a high car rotation and only operate shared cars for two to three years at most. This raises two issues: what happens to retired cars, and how does this affect the environmental performance of shared mobility? If these shared cars are then sold on the used market, it might enable and encourage higher rates of private car-ownership due to the availability of cheap used cars. This high rotation of cars might also increase production-related environmental impacts such as material depletion and GHG emissions during manufacturing. Although we do not have much research on these two issues, they are important to achieving a holistic understanding of the environmental impacts of car sharing.

Concerns with over-dimensioned shared bike and scooter fleets have also been raised. There is evidence that supports the claim that environmental impacts from shared micromobility services increase when there is low ridership of fleet vehicles (Hollingsworth et al., 2019; Moreau et al., 2020; Sun & Ertz, 2021). This, coupled with the fact that some shared micromobility services have been withdrawn only a short time after deployment, leads to questions about the environmental impacts of shared micromobility. Some cases suggest that these withdrawn vehicles are not repurposed into other systems but are instead abandoned.

Another recent trend is car manufacturers entering the car sharing space as owners, such as Volvo's car sharing service Volvo On Demand. As mentioned in section 6.3., car manufacturing is one of the industries that enables and supports a car-dependent society. It is yet to be seen how this emphasis might change if car manufacturers start offering mobility-as-a-service in addition to offering products. Nonetheless, given that the car manufacturing industry is dependent on economies of scales due to installed production capacity, a switch to service offerings might not deliver the expected profits and could lead to the design and implementation of car sharing services that are unsustainable and help perpetuate car dependency (Mattioli et al., 2020).

5.5 Reflections about sustainable consumption and production

The results of this thesis suggest that although certain products, services, and business models are designed and implemented with the objective of contributing to sustainable consumption and production, this outcome is not always achieved. For instance, studies of renting formal dresses demonstrate that compared to a business model based on ownership, the environmental impacts of this PSS business model depend on how people change their consumption habits or travel to pick up the rented clothes (Johnson & Plepys, 2021; Zamani et al., 2017). Research exploring the environmental impacts of buying used assets, shifts in lifestyles, and sharing space or food have also found that these practices may increase negative environmental impacts (Cheng et al., 2020; Makov & Font Vivanco, 2018; Meshulam et al.). Environmental impacts may have increased in the previously mentioned cases due to spending of the money saved when used items were bought or due to spending the additional income from sharing, as well as from additional consumption motivated by the availability of cheaper products and services.

Clearly, the environmental outcomes of sustainable consumption and production practices are affected by the existence and interplay of multiple factors. Like the factors identified in this thesis as shaping the environmental impacts of shared mobility, *behavioral changes* (including *consumption*), *context* and *business model design and implementation* have been pointed to as factors shaping the environmental outcomes of sustainable consumption and production practices (Creutzig et al., 2022).

The behavioral changes people make when they become engaged in sustainable consumption and production practices can be categorized using the ASI framework (Creutzig et al., 2022). "Avoid" behaviors are those which lead to a decrease in the amount of assets or services consumed (flying less or living carless); "shift" behaviors are changes in routines (e.g., taking public transport instead of driving a car); and "improve" behaviors are modifications to actual routines (e.g., using an electric car instead of an ICV). In the case of second-hand buying, for instance, the objective would be to avoid the manufacture of new goods, and thus people would improve their behavior by buying used rather than new items. In the context of used smartphones, however, it was found that these were bought in 18% of cases as secondary or spare smartphones. Thus, the replacement rate of used to new smartphones was not 1:1 (Makov & Font Vivanco, 2018). Used books were found to replace the purchase of new books by 16%, while the remaining 86% of used books sold would not have been bought by the purchaser as new (Ghose et al., 2006).

Changes in consumption was another factor identified in this thesis as affecting the environmental impacts of shared mobility. These changes are related with behavior change. Rebound effects resulting from changes in consumption have been found in other sustainable consumption and production practices, and have been identified as a cause of decrease in environmental savings from these practices. Makov and Font Vivanco (2018), for example, found GHG rebound effects of 27% to 46% in the case of reused smartphones, due to a combination of spending saved money and buying used smartphones for spare or secondary use. Meshulam et al. (2022) found that GHG rebound effects of sharing food range between 59% to 94%. These findings suggest a need to develop mechanisms to effectively prevent the rebound effects associated with these practices; otherwise, potential environmental savings will not be achieved (Cheng et al., 2020; Makov & Font Vivanco, 2018; Meshulam et al.).

Motivation and the capacity to change are prerequisites for behavioral change (Moser & Ekstrom, 2010). The motivation to change can come from outside factors such as legal, social and economic requirements, but can also be intrinsic, as when a person makes changes due to values, beliefs, and concern for the common good. The capacity to change refers to the context as an enabler or barrier to change, and is related to the systems of provision that are in place. When behavioral change occur collectively, new socio-cultural dynamics are established (Barr & Prillwitz, 2014).

The design and implementation of sustainable consumption and production systems is key to transforming the system of provision and enabling consumers to access alternatives outside of traditional business models. Business models based on sustainable consumption and production can, for example, create value from waste, maximize material and energy efficiency, deliver functionality instead of ownership, and/or encourage sufficiency (Bocken et al., 2014). Shared mobility delivers on the promise of functionality instead of ownership and has the potential to deliver on the material and energy efficiency and encourage sufficiency. As demonstrated in this dissertation, however, the latter two targets are not always achieved. Although business models are framed as enablers of sustainable consumption and production, evidence is needed to be able to guarantee this.

Context—including the built environment, institutions, infrastructure, technology, and social, economic, and political structures—is crucial to shaping the environmental outcomes of sustainable consumption and production practices (Creutzig et al., 2022; Moser & Ekstrom, 2010). As discussed in Section 5.3 in the case of shared mobility, there are locked-in effects that can be hard to change, such as infrastructure or political structures (Mattioli et al., 2020). These locked-in effects differ from context to context, which suggests that each context needs to be analyzed and understood to develop mechanisms to diminish factors that negatively affect the environmental impacts of shared mobility and support factors that enable positive environmental impacts.

The parallels between the drivers of environmental impacts of shared mobility identified in this thesis and the drivers of sustainable consumption and production practices raise questions: How can we guarantee that these practices have the desired environmental outcome? Or who is responsible for guaranteeing these outcomes? As mentioned before, the interactions between these factors are complex and vary from context to context. Thus, sustainable consumption and production practices must be assessed and highly sensitive factors identified. This information could be passed along to urban sharing organizations, governments, and consumers, helping them understand which factors must be controlled and monitored to increase the likelihood of success. Cooperation between actors that shape the sustainable consumption and production landscape is necessary to increase the chances of success, allowing a transparent flow of information and the alignment of sustainability goals between actors. Beyond assessing individual practices, systemic changes need to occur: car-free urban lifestyles must become viable; new social and cultural norms need to be established, such as norms that do not celebrate car ownership; new political structures that support these initiatives must be put in place; and new technologies need to be developed and adopted (Creutzig et al., 2022). Future research is needed to explore how such systemic changes can be achieved.

5.6 Reflections on the research approach

5.6.1 Methods used to assess the impacts of car sharing

Assessing environmental impacts from car sharing using a consumption perspective brought valuable knowledge to our understanding of how spending can change due to car sharing, and consequently how environmental impacts from personal transportation might vary. The consumption perspective allowed a contextualization of shared mobility in specific countries, considering their economic structure and transportation landscape. In this way, the assessments presented in Papers III and IV are different from existing assessments of shared mobility. The assessment method I use in this dissertation allowed the evaluation of environmental impacts at different levels, including per-person and citywide, as well as assessments with different system boundaries.

The results of these assessments varied depending on whether the analysis looked at per-person or citywide impacts. Analysis at the per-person level showed that car sharing can both increase and decrease environmental impacts from personal transportation, while impacts at the city level showed a decrease. Being able to assess impacts at different levels can lead to valuable insights that will help us develop better shared mobility solutions and transportation policies.

The assessments included in this dissertation use different system boundaries, Paper I was limited to WTW system boundaries, while Papers III and IV included the production and extensive use phase (including, for example, maintenance and insurance) in addition to fuel impacts. The assessments of potential savings in Papers II and III were very similar when comparing car owners who adopt car sharing and car-free individuals who adopt car sharing, a sign that most of the savings occur during the passenger transportation use phase. This finding also indicates that the car sharing sector (in the input and output tables) did not have a high input of new cars, which might misrepresent how B2C car sharing companies operate, as I discussed in section 5.4. This assumption was made based on the best proxy available and the lack of empirical data from car sharing organizations. This is evidence of the complexity of conducting assessments with broader system boundaries, as such analyses can be data intensive.

Paper III and IV use a mix of bottom-up and top-down approaches, combining a detailed description of transportation spending (bottom-up) and MRIO data (top-down). This modeling choice allowed me to show how travel behavior and fleet characteristics influence spending and how this, in turn, influences environmental impacts. Exploring this link between travel behavior, spending, and environmental impacts is a novel approach that provided benefits, such as allowing me to model different travel behaviors or fleet characteristics and to explore how these differences would influence environmental impacts from passenger transportation in different contexts. It also allowed me to explore how changes in travel behavior produce different results depending on the national context.

One inherent part of such assessments are the assumptions made, which have an impact on the uncertainty of the results presented here. The assumptions I made reflect data gaps or the need to simplify the real-world situation for modeling purposes. Examples of the assumptions I make here include the construction of average travel behavior and average transportation spending. My assumptions regarding travel behavior were based on data from the statistical offices of each of the case countries and thus represents the average resident. It would be interesting to model changes in travel behavior due to car sharing considering the neighborhood where people live or their income quintile. This would allow for more granularity in the analysis and would lead to a more fined-tuned understanding of how the built environment and income shape travel behavior. This would also allow the development of transportation policies that are more granular. Another main assumption was the approximation to the most similar sector using the Input and Output data, a practice proposed by Joshi (1999). Although this assumption has been used in other studies, it would be valuable to use empirical data to perform an assessment.

Using the same model in different contexts allowed for a deeper understanding of how shared mobility can influence environmental impacts from personal transportation. This was part of the analysis in Paper IV, where I analyze different transportation landscapes in countries that have a variety of policy perspectives in order to arrive at a more systemic understanding of how car sharing and other shared mobility modes might fit into specific contexts. This allowed me to engage in a deeper discussion about the technological, socio-technical, and institutional changes that need to take place to push passenger transportation towards active, public, and shared mobility modes rather than private car ownership and use.

Lastly, the environmental gains from the results presented here in Papers II and III point to shared mobility and electrification as drivers of change. Paper IV, in turn, was able to link potential environmental savings to well-being, digitalization, fleet electrification, and shared mobility. Including different drivers in the assessment allows us to understand the limitations of shared mobility in driving systemic change by itself. Environmental savings from passenger transportation were found to be higher when several drivers and tools were implemented simultaneously and not just one.

5.6.2 Limitations

Using Input and Output analysis to calculate the environmental impacts of car sharing allowed me to conduct an analysis from a consumption perspective and made it possible to explore the impacts of spending, changes in the economic output of economic sectors, and rebound effects. However, Input and Output is a static model that does not includes feedback loops between the variables in the model. For example, a systemic decrease in car ownership might lead to lower demand for fuel and vehicles, which in turn could cause fuel and vehicle prices to drop. Such feedback loops between the parameters in the model are not part of Input and Output analysis. Understanding these dynamics can provide information about system dynamics and how to further decrease environmental impacts from passenger transportation through the implementation of shared mobility.

The datasets I used in this dissertation have their own limitations. For example, the travel survey of the Netherlands may include under- or over-reporting of number of trips or distances. In the case of EXIOBASE, the major limitation was related to its product and sector groupings, which makes it difficult to differentiate and disaggregate specific products and industries. In this case, public transportation was included within the "Other land transportation" segment, which also includes package holidays and recreational sports and services. This modeling decision was made due to the lack of empirical data or sector specific data. However, this dataset was the best proxy available. Another limitation, as mentioned above, are the assumptions of using averages to represent travel profiles, spending, and emissions. These averages were used to represent city or country inhabitants, and this might introduce some uncertainty into the results.

There are other perspectives from which impacts from shared mobility can be understood—such as traffic and transit assessments. Such assessments provide another perspective as we seek to understand the environmental impacts of passenger transportation due to car sharing from a holistic perspective (Alisoltani et al., 2021; Ke et al., 2020; Migliore et al., 2020). However, they are outside the scope of this dissertation.

The assessment methods I use in this dissertation can be replicated in different contexts; however their data-intensive nature is a barrier to further replication. The data needed—such as information about the transportation habits of residents or the characteristics of the private fleet— are not available in some counties, and these are essential elements to performing the assessments I make in my research here.

6 Conclusion

The last chapter of this dissertation contains a summary of its findings and contributions with suggestions for possible future research at the end of the chapter.

6.1 Summary of findings

The effects of car sharing on the environmental impacts of personal transportation are heterogeneous. GHG emissions from transportation decreased when people shifted from car ownership to car sharing, but there was an increase when car-free people gained access to a car through this shared mobility mode (Papers II and III). These mixed results at the personal level, something found not only in this research but other studies as well, indicate that car sharing does not deliver environmental gains in all circumstances (Nijland & van Meerkerk, 2017; Severis et al., 2019).

Although some people that use car sharing might increase their environmental impacts in the short term, having access to a shared car might be enough for them to never purchase their own car. Postponing a car purchase due to participation in car sharing is one of its known effects (Becker et al., 2018; Nijland & van Meerkerk, 2017). Thus, car sharing can potentially lead to more environmental savings.

The assessments in this dissertation have shown that car sharing entails environmental gains at a city and country level (for urban dwellers) (Papers II and IV). This finding is influenced by the assumptions used in the assessments, in which a big share of these environmental gains comes from a drop in car ownership and a shift to an electric fleet.

Given that car sharing has the potential to change how people travel, their spending on transportation may also change; furthermore, people who share their private cars via P2P car sharing schemes have the potential to earn additional income. This can cause rebound effects that significantly decrease the environmental savings from car sharing. This is not a phenomenon that is exclusive of car sharing; other sustainable solutions have been shown to cause rebound effects that can even negate their initial environmental savings (Walnum et al., 2014).

The implementation and eventual upscaling of car sharing can cause changes in economic output from various sectors (Paper III). How sectors are affected depends on the country's economic structure. Countries that produce most of the cars that are consumed domestically may experience a contraction in their car manufacturing industries if car sharing is upscaled. These countries might simultaneously experience growth in the economic output of other sectors, however, as Paper III shows.

Car sharing can deliver sustainability gains under certain circumstances, depending on several factors, as pointed out in section 5.2. *Travel behavior, design and operationalization of the shared mobility system, consumption, and context* are the main groups into which I classify these factors here.

Changes in travel behavior when people engage in car sharing were found to strongly influence variations in environmental impacts of personal transportation (Papers II and III). This was especially true when people shifted from private driving to car sharing, public and active transportation. A shift from private cycling, walking, and public transportation ridership to shared micromobility modes is a somewhat undesirable outcome of shared mobility, however (Paper I). Other research has found this to be one of the main variables leading to a negative influence on environmental impacts from passenger transportation (de Bortoli, 2021; Ding et al., 2021).

In addition to implementing car sharing, we need to build urban transportation systems that are flexible and that enable residents to abandon car ownership. This given that changes in travel behavior take place due to the availability of active, shared and public transportation systems. Multimodality is a requirement to achieve this, with this multimodality including the various shared mobility modes (Javaid et al., 2020).

The design and operationalization of shared mobility systems is another variable that influences environmental impacts from personal transportation (Papers I, II, and III). System design and operationalization influences how people use a shared mobility system, and thus it determines which transportation modes the system will replace and complement. The design and introduction of shared mobility systems in cities should not be determined by sharing organizations alone; rather, shared mobility systems should be shaped synergistically with city officials in ways that enable such systems to replace private car ownership and complement active and public transportation.

Environmental impacts can increase depending on the way in which shared mobility systems are operated. Operational needs that go beyond the transportation process using private vehicles (for example, fleet rebalancing, docking infrastructure, or more-frequent maintenance) have the potential to exacerbate the environmental impacts of personal transportation. The way these additional operational needs are handled can dampen or exacerbate negative environmental impacts (Bonilla-Alicea et al., 2020; Ding et al., 2019; Luo et al., 2020).

B2C and P2P car sharing performed similarly with regard to GHG emissions from transportation (Papers II and III). However, saying with certainty that there is no difference between the two car sharing ownership schemes is impossible. We still have a knowledge gap regarding material depletion, which could potentially cause a trade-off between these two types of car sharing.

Consumption changes due to the use of car sharing; reallocation of spending towards non-transportation consumption categories such as housing or food, as well as possible rebound effects, call into question consumption choices and not the sustainability of car sharing as a practice. If car sharing enables a car-free lifestyle, it has the potential to decrease impacts from personal transportation and thus can be an effective tool for targeting personal transportation impacts (Papers III and IV).

The context in which car sharing or other shared mobility systems are implemented ultimately shapes how people change their travel behavior and consumption patterns, as well as how these shared mobility systems are designed and operationalized. Although they were each analyzed separately, the group of factors included in this research are interlinked to each other, with context being central in shaping each of the other factors. Thus, changes in one group of factors might influence another group of factors.

The potential for environmental savings from residents' use of shared mobility is greater when several of the factors presented here are combined (Papers I, II, III and IV). The combination of positive changes in travel behavior and improvement in the technologies used in the shared fleet is a combination that enhances the potential emissions savings compared to simply implementing shared mobility systems. Previous studies have pointed to the combination of different factors that maximize potential gains from sustainable solutions (Wiedmann et al., 2020).

Possible trade-offs between environmental impact categories emerge from how people change their travel behavior, the design and operationalization of shared mobility systems, consumption, and the context. For example, a car sharing system that replaces vehicles after two years of use would probably cause more material depletion than private car ownership (private cars are used for 11 years), even if it allows many people to give up their private vehicles. More research is needed to understand possible trade-offs between environmental impact categories when shared mobility systems are implemented.

6.2 Contributions of this dissertation

This research makes several contributions to expanding our knowledge of the environmental impacts of shared mobility, which can be used in practice to develop transportation policies, plan changes in urban transportation systems, and design shared mobility systems. It does so first by systematically reviewing the academic literature about the environmental impacts of shared mobility (Paper I), and second, by assessing how car sharing affects the environmental impacts of passenger transportation (Papers II, III and IV).

At a more detailed level, this research explores the knowledge gap concerning differences in environmental impacts from B2C and P2P car sharing, findings that in terms of GHG emissions, at least, the differences in impacts between these two types of car sharing are not significant. The dissertation also explores rebound effects from car sharing, finding that this phenomenon has the potential to substantially lessen the positive impacts of car sharing. However, this finding is not specific to car sharing, as other sustainable solutions also cause rebound effects. Thus, addressing rebound effects requires a more systemic approach that addresses the consumption of environmentally intensive products and services.

This research also contributes to policy making specifically by exploring possible pathways to decrease environmental impacts of passenger transport. These pathways included the combination of shared mobility, well-being, digitalization, and the electrification of the passenger fleet were used as central element to shift away from car ownership (Paper IV). This contributed to understanding the actions that need to take place in these contexts to decrease impacts from passenger transportation. It also contributed by clarifying how dramatic changes need to be in these contexts. Moreover, this research exemplified how the combination of several drivers can enable more drastic savings than just relying on one driver.

Another novel aspect of this research is its methodological contribution by applying MRIO to a specific case and in a specific way, where Input and Output was bridged with a detailed analysis of transportation spending. These modeling exercises are not only novel but also provide a new perspective for understanding the impacts of shared mobility. Impacts were quantified using a consumer perspective that accounted for all inputs for personal transportation (Papers III and IV). Using MRIO as a method means that impacts from insurance and parking were also included, along with impacts produced throughout the entire supply chain. Previous research has not adopted this perspective, and thus the focus of this research had mostly been on impacts from car and fuel production and tailpipe emissions. These assessments analyze impacts at different levels, finding differences at both the individual and city/country levels (Papers II, III and IV). These modelling exercises provided new insights into data gaps and required methodological adaptations for modelling the case of shared mobility. Employing MRIO for scenario analyses provided a deeper insight into direct and indirect environmental and economic impacts of car sharing including the perspective on the effects of international trade.

This dissertation expands the methodology for assessing environmental impacts by mixing top-down and bottom-up approaches to them. Assessing impacts using a mixed method leads to a quantification that considers a wider range of factors that influence outcomes. For example, in Papers III and IV, several system layers needed to be understood and captured in the model. Bottom-up methods were used to build the travel and spending profiles. The environmental and economic evaluation was subsequently conducted using top-down approaches such as MRIO.

6.3 Future research

The systematic literature review identified several research gaps regarding both shared mobility modes and environmental impacts that are yet to be studied (Figure 7 and Figure 11). One of the most pressing questions is the difference between B2C and P2P car sharing regarding impacts on material depletion. This dissertation found that such differences in GHG emissions were not that significant. Still, there might be a significant difference regarding material depletion, considering how B2C car sharing schemes are currently managed (as discussed in section 6.4). Other impacts that are yet to be researched include land use for almost all shared mobility modes, and ecosystem damage. Quantifying environmental impacts can provide more knowledge about possible trade-offs between impact categories.

Future research about the factors that influence environmental impacts from passenger transportation due to car sharing can go in several directions. One option is to deepen our knowledge about how different aspects of business models influence how people use sharing services. For example, researchers could explore how different payment schemes encourage people to use shared services. Another possible option is to explore how the characteristics of a certain context influence how people engage in shared mobility. This topic is closely related to research that explores how the built environment influences modal splits or car ownership rates.

One general challenge in assessing the sustainability impacts of shared mobility is getting access to the necessary data about the logistics, operation, economics, and users of shared mobility organizations. If future researchers get access to this data, it will reduce the number of assumptions that must be made about how these organizations work, reducing the uncertainty linked to results. Future researchers who are able to access such data might populate the IOT to decrease uncertainty arising from the assumptions made in this dissertation.

Future research could also expand on and include other forms of the sharing economy, such as accommodations and goods, as part of sustainable consumption and production. Sharing in other sectors can also be understood from a consumption perspective, expanding our understanding of the potential that sharing in other sectors has and the factors that influence these outcomes.

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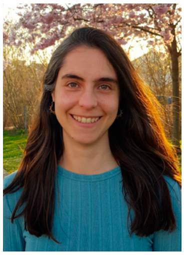

PASSENGER TRANSPORTATION IS one of the sectors where greenhouse gas emissions continue to grow due to an increase distance travel and a shift to more emission intensive transportation modes (from public and active transportation to private car or motorcycle riding). Alternative transportation modes that allow a shift away from emission intensive transportation modes and enable the use of active and public transportation are needed. One of these alternatives is shared mobility. However, it is still unclear what is the potential of shared mobility in decreasing the environmental impacts of passenger transportation? And moreover, which are the factors that influence this potential? This thesis aims to understand the potential that shared mobility has in decreasing the environmental impacts of shared mobility and the factors that influence this potential.

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