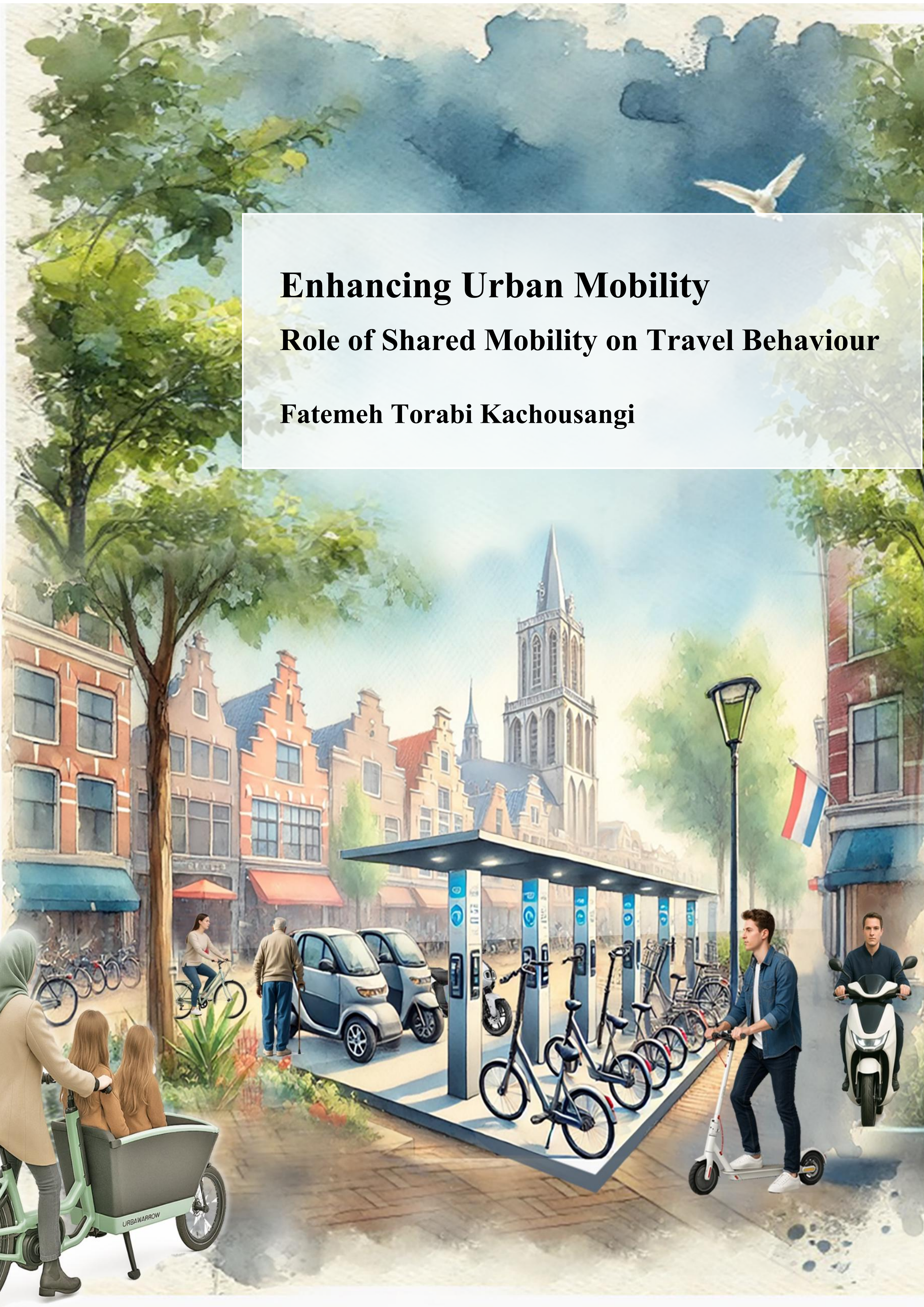
Enhancing Urban Mobility

Role of Shared Mobility on Travel Behaviour

Fatemeh Torabi Kachousangi



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Fatemeh Torabi Kachousangi

Delft University of Technology

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Dissertation

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Fatemeh TORABI KACHOUSANGI

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To my parents

To Majid

To my lovely daughters, Bahar and Yara

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Delft, January 2026

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Chapter 1: Introduction

1.1 Research motivation

"By 2040, travel for people in the Netherlands will be fast, sustainable, safe, comfortable, reliable, and affordable. To travel to work, school, and leisure destinations, they will use their own transport, public transport, or a combination. […] Public transport is an essential component of the whole transport system which focuses on passengers and their door-to-door journeys"

(Ministry of Infrastructure and Water Management et al., 2019, p7)

This ambition is compelling, yet densely populated regions face mounting constraints: urbanization and growing car dependence continue to intensify traffic congestion, air pollution, and reduced urban liveability (UN-Habitat, 2020; van Arem et al., 2022; Geržinič et al., 2024). Realising the Dutch 2040 vision therefore requires more than technological progress; it requires changes in travel behaviour that make sustainable options the default choice.

Recent trends underline the challenge. Car ownership increased from 0.8 per household (1990) to 1.1 (2022) in the Netherlands (KiM, 2022), and parking assets remain idle for most of the day (over 90% unused) (KiM, 2018). While part of this increase can be attributed to income growth and accessibility expectations, demographic shifts, particularly the rise in one-person households, also contribute to higher car ownership rates per household. In 2019, private cars accounted for 49% of all trips (CBS, 2020), and the past decade set record global emissions, reinforcing the urgency of a behavioural pivot in transport (IPCC-Climate Change, 2022). The continued dominance of the private car can be explained by its perceived affordability on a per-trip basis and the high degree of comfort, flexibility, and it offers relative to other transport modes (van Arem et al., 2022).

Against this backdrop, emerging modes—shared, electric, and automated—together with mobility hubs offer a route to door-to-door connectivity that can rival the car in cost, comfort, reliability, and flexibility. Mobility hubs integrate services, improve interchange quality, and can reduce operational inefficiencies such as rebalancing; however, infrastructure alone is insufficient. Success depends on user acceptance and behavioural adaptation, meaning design must centre on perceived viability and not merely technical availability (Klanke, 2022).

Yet critical knowledge gaps persist. Much existing work emphasises conventional shared services (e.g., bike-sharing) and younger, digitally fluent populations, with less evidence for other segments, contexts, and the mechanisms of choice (Bösehans et al., 2021; Tran & Draeger, 2021). This risks policies that are effective for early adopters but less inclusive for car-dependent or ageing residents. Understanding how and why individuals choose specific modes—and what contextual, psychological, and cost factors enable a shift to shared and public options—is central to achieving durable modal change.

This thesis adopts a behavioural perspective to examine how emerging modes and mobility hubs could shape urban travel. Through case studies and Stated Choice experiments it investigates: (i) modal shifts involving shared and electric vehicles; (ii) passengers' preferences for shared first/last-mile transport; (iii) the influence of car-free inner-city areas on mode choice and avoidance; and (iv) adoption among older adults in midsized cities. In doing so, it seeks to identify the determinants of choice, assess the inclusivity and scalability of shared options, and inform the design of mobility systems that reduce emissions, enhance accessibility, and advance equity.

1.2 Research gaps

Despite extensive research on the environmental and operational benefits of shared mobility, significant gaps remain in understanding how these emerging alternatives influence individual travel behaviour and mode choice in different urban contexts. There is limited insight into the behavioural responses of diverse user groups to emerging mobility services, particularly regarding their use across first/last mile and main mile segments within different urban settings. The focus is placed on how users interact with these services at two types of mobility hubs: major public transport nodes (e.g., train stations) and car-free inner-city areas. The following outlines four specific research gaps that the thesis seeks to address.

Research gap 1: insufficient system -level evidence linking emerging modes, mobility hubs, and life-cycle CO_2 reductions

Although in recent years, we have seen significant research on shared, electric, and micro-mobility as sustainable alternatives to private car ownership, the literature remains fragmented and methodologically inconsistent. Most studies address individual modes or technologies in isolation—examining shared mobility (Kuss & Nicholas, 2022), micro-mobility (Svennevik et al., 2021; Bösehans & Bell, 2021), or vehicle electrification (González et al., 2019)—without integrating them into a unified, system-level understanding of their collective role in CO_2 mitigation.

Existing research also tends to focus predominantly on direct or operational emissions, often neglecting indirect and life-cycle processes related to vehicle production, maintenance, energy supply, and rebalancing operations (Luo et al., 2019; Bonilla-Alicea et al., 2020; de Bortoli & Christoforou, 2020). Despite growing recognition of mobility hubs as nodes for multimodal integration and shared service consolidation (Berndsen & Basta, 2021; Aydin et al., 2022), empirical evidence on their environmental and systemic contributions remains scarce (Rongen et al., 2022; Bernardes Real et al., 2021).

A lack of integrated frameworks connecting behavioural mechanisms, operational efficiencies, and life-cycle CO_2 outcomes limits the ability to assess the collective decarbonisation potential of emerging mobility systems. Further research is needed to integrate these dimensions and provide a system-level understanding of how mobility hubs can contribute to sustainable urban transport transitions.

Research gap 2: limited behavioural evidence on passenger preferences for emerging first/last-mile modes in multimodal systems

While multimodal public transport systems are recognized as key enablers of sustainable urban mobility, their performance is often constrained by inefficient and unattractive first/last-mile connections (Baek et al., 2021). Integrating emerging shared and automated modes—such as shared bikes, e-steps, e-scooters, and autonomous vehicles—within multimodal hubs has the potential to enhance accessibility and continuity of public transport trips. However, success depends primarily on traveller behaviour and user acceptance, not solely on the provision of infrastructure.

Existing behavioural research (Ohnemus & Perl, 2016; Yap et al., 2016; Shaheen & Chan, 2016; Kamargianni et al., 2016; Scheltes & Correia, 2017; Shaheen & Cohen, 2020) remain fragmented, often focusing on single modes or isolated contexts. Few studies have systematically compared emerging shared and automated alternatives within first/last mile settings or quantified how situational and perceptual factors influence choice behaviour. Critical determinants such as weather conditions, luggage handling, and trip purpose remain underexplored (Van Kuijk et al., 2021; Abe, 2021), despite their relevance to real-world adoption.

Furthermore, most behavioural models simplify complex decision structures by either assuming homogenous preferences across the population or failing to account for the systematic substitution patterns (nested relationships) between emerging transport modes. This limitation results in insufficient empirical evidence on how contextual and psychological factors shape multimodal mode choice.

Research gap 3: insufficient knowledge of adoption and avoidance behaviour in shared mobility within car-free inner-city transitions

Urban mobility strongly influences the liveability and sustainability of dense city centres, where car dependency exacerbates congestion, air pollution, and pedestrian safety issues (UN-Habitat, 2020; van Arem et al., 2022; Geržinič et al., 2024). In response, many European cities are pursuing car-free and low-traffic urban policies to reclaim public space and reduce emissions (Nieuwenhuijsen, 2020; Geurs & Münzel, 2022; van Arem et al., 2022; Aumann et al., 2023), often supported by the introduction of shared mobility services (van Marsbergen et al., 2022; van Arem et al., 2022; Zhou et al., 2023) such as shared (e-)bikes, scooters, and cars. Despite the acknowledged potential of these strategies, residents' behavioural responses during transitions toward car-free environments remain poorly understood.

Existing studies have mainly examined the substitution potential of shared modes for private cars (Jeekel, 2013; Pojani et al., 2018; Selzer & Lanzendorf, 2022), often overlooking social, demographic, and psychological heterogeneity in adaption decisions. Moreover, conventional mode choice models typically assume participation, focusing only on which mode users choose, while neglecting whether individuals choose to participate at all. This omission—often referred to as avoidance or non-use behaviour—represents a critical knowledge gap (Delclòs-Alió et al., 2023).

Avoidance behaviour reflects the decision not to engage with shared modes even when access and policy conditions are favourable. Neglecting this dimension excludes a segment of the population resistant to mobility transitions—particularly older and higher-income residents—and limits understanding of social equity in transport transitions. Incorporating avoidance and non-adoption behaviour is essential to understanding mobility transitions and supporting inclusive, behaviourally informed policy design.

Research gap 4: limited insight into behavioural heterogeneity and adoption barriers among older adults in shared mobility systems in small and medium-sized cities

While shared mobility has emerged as a cornerstone of sustainable urban transport, research has predominantly centred on younger, digitally literate, and metropolitan populations, overlooking older adults (50+)—a group representing a growing share of urban travel demand. Evidence indicates low participation rates among older users (Dill & McNeil, 2021; Kim et al., 2021; Van Kuijk et al., 2022), yet the behavioural mechanisms underlying this exclusion remain poorly understood.

Most existing studies treat older adults as a homogeneous group, rarely disentangling how digital literacy, physical capability, and attitudinal dispositions interact to shape adoption decisions. Additionally, the literature is biased toward large metropolitan areas, while small- and medium-sized cities—where car dependency is high and public transport alternatives limited—pose distinct challenges and opportunities for shared mobility transitions (Nieuwenhuijsen & Khreis, 2016; Baehler, 2019).

Another major limitation is the absence of segmentation-based analytical approaches capable of capturing behavioural diversity within the older population. Evidence from Haustein & Siren (2015) and others indicates substantial variation in mobility attitudes, preferences, and capabilities among older adults, yet most modelling frameworks overlook this heterogeneity. Consequently, the current knowledge base for designing inclusive, age-sensitive, and equitable shared mobility systems in smaller urban contexts remains inadequate.

1.3 Research objectives and questions

Building on the identified research gaps and overarching motivation to promote sustainable urban mobility, this thesis aims to analyse the behavioural impact of emerging transport modes and mobility hubs across different spatial and demographic contexts. Specifically, it models how individual, contextual, and infrastructural factors influence travel behaviour, preferences, and adaption patterns among divers user's groups.

The overarching objective is to determine how shared (micro-) mobility options, when integrated through well-designed mobility hubs, can encourage shifts away from private car use and contribute to low-carbon, accessible, and equitable urban transport systems.

To achieve this goal, the research adopts a behavioural and user-centred approach, employing stated choice experiments, structured surveys, and advanced discrete choice modelling techniques (Nested Logit, Mixed Logit, and Latent Class Models). Although empirical data are collected in Dutch cities, the insights and methods are transferable to other developed urban contexts pursuing similar mobility transitions.

The research addresses the following main research question:

Main RQ: How does shared mobility influence travel behaviour and modal choice across different urban contexts?

The thesis addresses four specific research questions, grouped by analytical focus:

Environmenta perspective

RQ1: Which roles do shared mobility and mobility hubs play in reducing CO_2 emissions by facilitating modal shifts in urban transportation systems? (Chapter 2)

Behavioural and user-centred perspective

RQ2: Which factors influence passenger's preferences and acceptance of shared access/egress modes at multimodal railway stations? (Chapter 3)

RQ3: Which determinants shape mode choices and avoidance behaviour among residents in car-free inner-city areas considering shared modes as their primary travel options? (Chapter 4)

RQ4: Which behavioural and socio-economic factors affect the adoption of shared mobility among adults aged 50 and above in small and mid-sized cities? (Chapter 5)

1.4 Research approach and methods

In this thesis, we use empirical and mixed-method research design that combines systematic literature synthesis, survey-based data collection, and advanced behavioural modelling. The approach is defined by a systematic and iterative structure that first stablishes the conceptual foundation through literature synthesis, and then moves to empirical investigation, ensuring both theoretical depth and empirical robustness.

As illustrated in Figure 1, the research progresses from a system-level conceptual synthesis (addressing *RQ1*) to a set of focused behavioural modelling studies (addressing *RQ2–RQ4*). This structure enables a coherent connection between conceptual understanding, empirical investigation, and behavioural analysis across different urban contexts.

1.4.1 Methodological framework

The study is grounded in a travel behavioural modelling paradigm, aiming to understand how shared mobility options influence modal choices across different urban contexts. It combines Life Cycle Assessment (LCA) (on emissions and mobility hubs) with individual-level behavioural data (on preferences, avoidance, and adoption). This dual focus allows the research to capture both the macro perspective of sustainable mobility transitions and the micro perspective of individual travel behaviour.

A mixed-method approach was deliberately adopted, reflecting a conceptually cumulative and analytically integrated research design:

Conceptual foundation

The systematic literature review (Chapter 2) establishes a conceptual and theoretical baseline by integrating fragmented evidence on shared, electric, and micro-mobility within a unified life-cycle framework. This synthesis clarifies how behavioural modal shifts, infrastructure integration, and operational characteristics jointly influence CO_2 emissions.

This conceptual foundation informed the scope and design of the empirical studies by identifying key behavioural mechanisms, relevant mode attributes, and critical research gaps—such as travellers' preferences for access and egress modes at multimodal hubs, participation versus avoidance behaviour in car-free urban contexts, and user heterogeneity in shared mobility adoptionwhich are subsequently examined through the stated choice experiments.

Empirical investigation

The empirical studies (Chapter3,4, and 5) use surveys and stated choice experiments to provide quantitative evidence of user preferences and decision-making mechanisms across different urban contexts and population groups. Each study addresses a distinct behavioural dimension of shared mobility adoption, while remaining grounded in a common behavioural framework.

This empirical phase ensures that theoretical relationship identified in the conceptual foundation are examined through observed and hypothetical choice bahaviour, enabling robust estimation of behavioural parameters related to cost, time, accessibility, context, and socio-demographic characteristics.

Methodological triangulation

By combining systematic literature review, multiple empirical datasets, and advanced discrete choice modelling techniques (Nested Logit, Mixed Logit, and Latent Class Models), the study achieves methodological triangulation. Nested Logit captures substitution patterns between related travel alternatives, Mixed Logit accounts for unobserved preference heterogeneity, and Latent Class Models identify distinct behavioural segments within the population. This approach enhances the credibility of findings by allowing behavioural mechanisms to be examined consistently across different data sources, analytical methods, and spatial contexts.

1.4.2 Sequential research design

The research is structured in two complementary phases, each aligned with the research questions. This sequential design first develops a conceptual understanding of the environmental and systemic roles of emerging mobility modes and mobility hubs, subsequently examining their behavioural implications through empirical analysis.

Phase I – conceptual synthesis (RQ1 / Chapter 2)

A systematic review of 71 studies assesses the role of emerging modes and mobility hubs in promoting modal shift and reducing CO_2 emissions. A systematic literature review was selected because existing research on shared mobility, micro-mobility, and electrification is fragmented across different domains. The review enables the integration of dispersed evidence and supports the development of a life-cycle conceptual framework linking technological change with behavioural mechanisms. This framework directly responds to the identified gap in integrated evidence connecting emerging modes, mobility hubs, and life-cycle CO_2 reductions.

Phase II – behavioural modelling (RQ2–RQ4 / Chapters 3–5)

This phase empirically investigates individual travel behaviour through three stated preference studies conducted in Dutch cities, each addressing one of the remaining research gaps. Stated preference methods were selected because many emerging mobility services—such as automated vehicles and integrated mobility hubs—are not yet widely available in real-world settings. SP experiments therefore allow the analysis of travellers' responses to hypothetical but policy-relevant mobility scenarios.

First/last-mile access at railway stations (Chapter 3)

> This study examines passenger preferences for emerging shared and automated access/egress modes at small and medium-sized multimodal hubs. Using a Stated Preference (SP) approach and a Nested Logit model, it quantifies how cost, time, availability, and contextual conditions shape first/last-mile mode choice. The Nested Logit model was selected to account for correlations between related alternatives within the access/egress choice set, providing a more realistic representation of substitution patterns between emerging modes. The analysis provides a robust behavioural foundation for designing user-centred, inclusive, and adaptive multimodal transport systems.

Mode choice and avoidance in car-free city centres (Chapter 4)

> This study analyses adoption and non-adoption behaviour within shared mobility options in the context of Delft's inner-city transformation under the Mobility Plan 2040. Using a stated choice experiment with an "optout" alternative and a Mixed Logit model that captures both observed and unobserved preference heterogeneity, it quantifies how travel cost, walking distance, trip purpose, and socio-demographic characteristics influence adoption and avoidance decisions. The Mixed Logit specification was chosen because it allows preference parameters to vary across individuals, enabling a more flexible representation of behavioural diversity in car-free policy contexts.

Shared mobility adoption among older adults (Chapter 5)

> This study investigates behavioural heterogeneity and adoption barriers among adults aged 50 and above in 45 small and medium-sized Dutch cities. Employing a Latent Class Model (LCM) on stated preference data, it distinct identifies behavioural segments and key determinants of shared mobility adoption related to digital literacy, physical capability, and attitudes. The LCM approach was selected to capture underlying behavioural segments within the population and to reveal differences in adoption patterns that may be masked in aggregate models. The results inform age-sensitive transport planning and contribute to the design of socially inclusive, sustainable mobility systems.

This sequential design allows for cumulative learning: each empirical study progressively deepens understanding of behavioural mechanisms relevant to sustainable mobility transitions.

1.4.3 Integration and analytical logic

The methodological architecture of the thesis (Figure 1.1) reflects a sequential and complementary relationship between theory and empirics, in which each research component informs and supports the others. However, the empirical studies are designed to examine specific behavioural aspects rather than to directly validate the entire conceptual framework.

- The systematic literature review (Chapter2) provides a broad system-level framing and identifies a range of conceptual and empirical gaps. From this synthesis, a subset of behaviourally relevant mechanisms is selected to guide the empirical investigations.

- The empirical studies (Chapters 3- 5) are intentionally more focused and address specific research questions derived from these selected gaps. Using stated choice experiments and behavioural data from diverse urban contexts, the studies empirically examine key dimensions—such as cost, time, and walking distance sensitivity, potential substitution options, heterogeneity, and participation versus avoidance behaviour.

- The behavioural modelling phase quantifies choice parameters, that describe how individuals respond to shared mobility attributes and contextual conditions. These insights support interpretation of how individual-level choices may contribute to broader system-level outcomes, such as modal shift potential and policy effectiveness, without directly estimating aggregate emission impacts. Together, these components form a coherent and conceptually consistent analytical structure that connects behavioural evidence with sustainable transport planning objectives. The robustness of the research is supported by rigorous behavioural modelling, the use of diverse case study settings, and a shared behavioural-sustainability perspective that supports the thesis's theoretical and policy contributions.

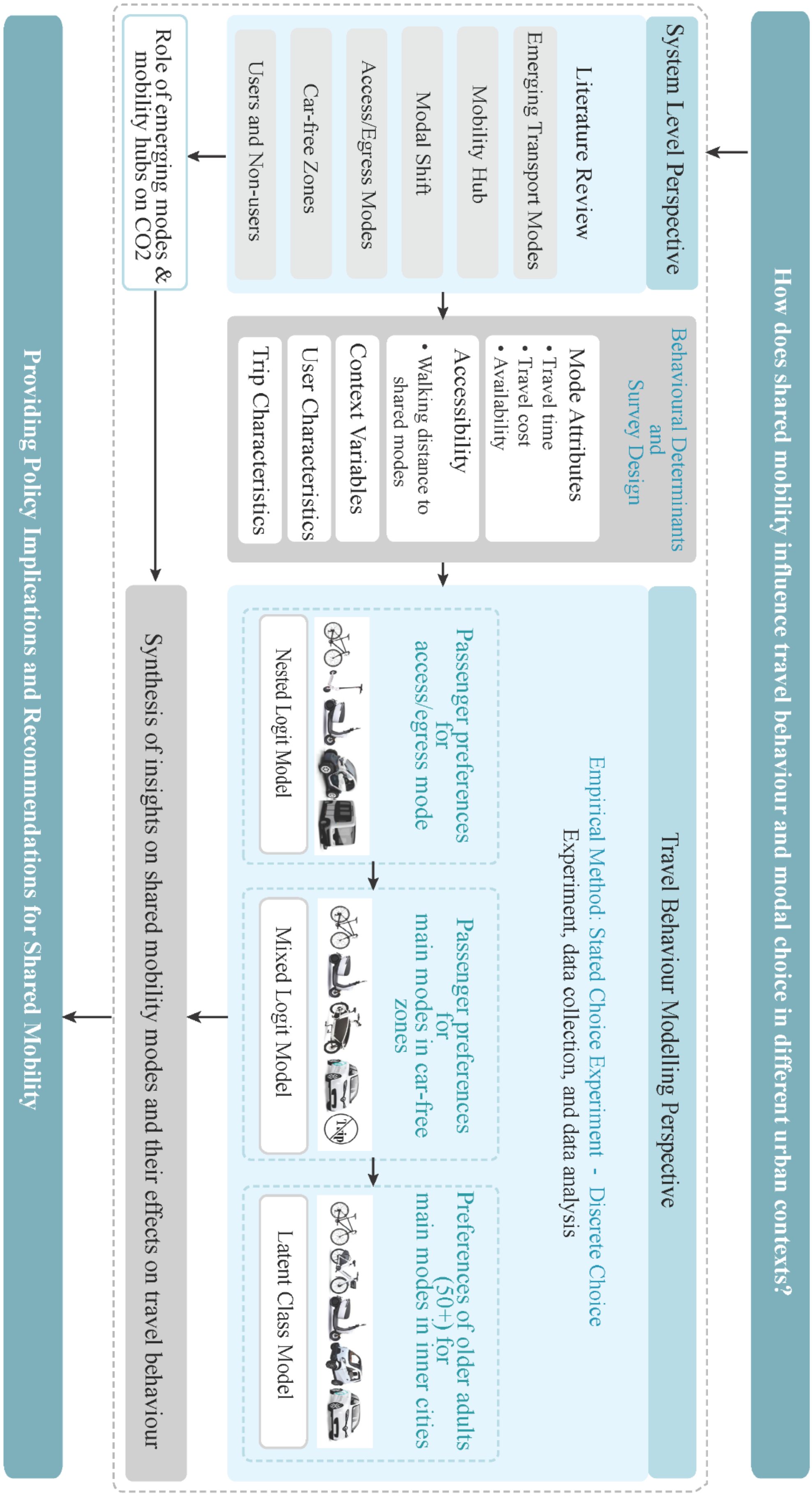

Figure 1.1: Research approach

1.5 Thesis contributions

This thesis offers scientific and societal contributions by enhancing understanding of how emerging transport modes and mobility hubs influence urban travel behaviour. The findings are structured around the core research questions and contribute to academic knowledge while providing evidence relevant for transport policy and planning.

1.5.1 Scientific contributions

This multi-method approach adopted in this thesis provides a robust basis for addressing the central research question. Scientifically, the thesis contributes by:

- demonstrating how mixed-method triangulation can be used to examine complex mobility behaviours across different contexts;
- applying behaviourally grounded discrete choice models to analyse adoption, resistance, and heterogeneity in shared mobility use; and
- offering a coherent analytical approach that can be applied in comparable urban settings.

Exploring the role of emerging modes and mobility hubs on modal shift and CO_2 emissions (RQ1, Chapter 2)

This study provides the systematic synthesis of the literature linking shared, electric, and micro-mobility with the concept of mobility hubs in the context of CO_2 reduction. It contributes to sustainable transport research by organizing fragmented studies within a life-cycle analytical framework that highlights how modal shift, operational characteristics, and infrastructure integration related to emission outcomes.

Methodologically, this study consolidates existing research through a transparent review protocol, enabling comparison across empirical and conceptual studies. By organising the evidence within a life-cycle analytical framework, the study identifies how modal shifts, operational characteristics, and infrastructure integration influence CO_2 emissions. The analysis highlights the potential role of mobility hubs not only as integration points but also as elements that may support emission reduction by improving operational efficiency and reducing rebalancing needs.

Overall, this study contributes to a structured overview that supports more informed assessment of how coordinated deployment of emerging modes, when supported by mobility hubs, can contribute to urban transport decarbonisation.

Empirically modelling passengers' preferences for emerging access/egress modes (RQ2, Chapter 3)

This study contributes to behavioral transport research by empirically analysing passenger's preferences for shared and automated first/last-mile modes at multimodal hubs. Using stated preference data collected at Delft Campus railway station, it examines how travel attributes (cost, time, and availability), contextual conditions (weather and luggage) and socio-demographic factors influence access and egress choices.

Methodologically, the research applies nested logit modelling to analyse substitution patterns and correlated preferences between shared micro-mobility modes and automated vehicle alternatives. The inclusion of context-dependent effects provides a more nuanced representation of traveller decision-making under very varying conditions.

The findings offer empirical insights into the relative importance of cost, situational sensitivity, and mode stability, contributing evidence relevant to the design of first/last-mile services at small and medium-sized multimodal hubs.

Advancing the understanding of transportation choices and modelling of behaviour avoidance in car-free zones (RQ3, Chapter 4)

This study contributes to transport behaviour research by explicitly incorporating avoidance behaviour into a Mixed Logit modelling framework, enabling analysis of both participation and mode choice in car-free urban contexts. Using data from Delft's inner city, currently transitioning under the Mobility Plan 2040, the study examines how cost, access distance, trip purpose, and socio-demographics characteristics influence preferences for shared mobility options.

By including a "opt-out" alternative, the analysis provides insight into non-adoption and behavioural resistance, highlighting that a substantial share of residents may opt out even under supportive policy conditions

Methodologically, the study demonstrates how Mixed Logit models can be used to account for unobserved heterogeneity and relax restrictive assumptions, contributing to more behaviourally realistic representations of choice in car-free policy contexts.

Behavioural segmentation of shared mobility adoption among older adults (RQ4, Chapter 5)

This study contributes empirical evidence on shared mobility adoption among adults aged 50 and above in small and medium-sized cities, a population group that remains underrepresented in literature. Using Latent Class Modelling (LCM) model, the analysis identifies distinct behavioural segments characterised by differences in digital literacy, physical capability, attitudes, and cost sensitivity.

Methodologically, the study illustrates how latent segmentation can be applied to stated preference data to capture behavioural heterogeneity within ageing populations. Substantively, the findings highlight that older adults' engagement with shared mobility is shaped by both individual capabilities and structural barriers within the mobility system.

These results contribute to ongoing discussions on mobility transitions and social inclusion by providing empirically grounded insights into age-related diversity in travel behaviour.

1.5.2 Societal contributions

Toward enhancing urban liveability and environmental sustainability

The research provides evidence on how emerging transport modes and mobility hubs can support more sustainable and liveable urban environments. The findings suggest that integrating shared, electric, and micro-mobility systems through mobility hubs has the potential to reduce CO_2 emissions while delivering co-benefits such as reduced congestion, improved air quality, and more efficient use of public space. By positioning shared mobility as a core component of broader low-carbon mobility strategies, the study supports policy approaches that jointly address environmental performance, spatial efficiency, and quality of urban life.

Promoting user-centred and equitable multimodal connectivity

The analysis of first/last-mile behaviour highlights the importance of behavioural and contextual factors, such as cost, physical effort, weather, and luggage, in shaping user acceptance of emerging modes. The findings suggest that the effectiveness of first/last mile integration depends not only on technological deployment, but also on behavioural inclusivity and social responsiveness. Shared and automated services therefore benefit from designs that accommodate varying levels of digital literacy, affordability, and physical capability.

The results provide empirical insights that can inform the user-centred design of mobility hubs and access/egress services, helping transport planners better align infrastructure and service provision with traveller behaviour.

Understanding behavioural inclusion in car-free urban transitions

The study examines the societal challenges associated with implementing car-free and low-traffic zones, offering evidence on behavioural resistance and social acceptance in the context of Delft's Mobility Plan 2040. The findings indicate that, even under supportive infrastructural and policy conditions, a substantial share of residents may still choose not to adopt shared mobility due to cost sensitivity, accessibility limitations, and attitudinal resistance.

These results suggest that urban decarbonization policies cannot rely solely on infrastructure provision or financial incentives. Instead, successful transitions are likely to require attention to behavioural inclusion and citizen engagement. The study illustrates how social heterogeneity, particularly across age, income, and lifestyle can affect willingness to adapt, identifying non-participation or avoidance behaviour as a critical yet often overlooked barrier in transport policy. By identifying factors associated with avoidance behaviour, the research provides insights that can support more inclusive implementation of car-free and low-traffic policies.

Understanding equitable and age-sensitive mobility systems

The analysis of mobility behaviour among older adults' (50+) shows that this population is heterogeneous and that adoption of shared mobility depends on digital access, physical capability, trust, and affordability. These insights highlight the importance of age-sensitive design and policy measures to ensure that mobility transitions do not exacerbate social exclusion.

The findings suggest that digital exclusion, accessibility barriers, and trust deficits in technology can exacerbate social inequalities if unaddressed. They offer evidence-based recommendations to inform inclusive service and policy design, including adaptive vehicle ergonomics, affordable pricing structures, non-digital access interfaces, and targeted community outreach to foster confidence and awareness.

Together, these insights contribute to ongoing efforts to support age-friendly mobility transitions that align with broader societal objectives of accessibility, independence, and social participation among ageing populations.

Informing evidence-based urban and transport policy

Across all four studies, the thesis provides empirical evidence that can inform evidence-based transport policymaking. The behavioural and contextual insights derived from systematic review, stated preference experiments, and behavioural segmentation offer municipalities and regional authorities' analytical inputs to guide the design of socially inclusive, environmentally sustainable, and technologically adaptive transport strategies.

By linking behavioural evidence with policy-relevant challenges, the thesis supports data-informed planning approaches that integrate environmental objectives with social equity and accessibility considerations. Overall, the research contributes to a human-centred perspective on sustainable urban mobility, in which policy effectiveness can be assessed not only through emission reductions or modal shifts, but also through the extent to which mobility systems enable participation, fairness, and quality of urban life.

1.6 Thesis outline

This dissertation is structured into six chapters that progress logically from conceptual foundations to empirical analysis and synthesis of findings. The overall structure is presented in Figure 1.2.

Chapter 1 introduces research motivation, gaps, objectives, and methodological approach.

Chapter 2 presents a systematic synthesis of literature on emerging transport modes and mobility hubs, establishing a conceptual framework that links modal shift, life-cycle emissions, and behavioural mechanisms.
(Addresses RQ1)

Chapter 3 examines travellers' preferences for emerging shared and automated modes in first- and last-mile contexts using stated preference data and discrete choice modelling.
(Addresses RQ2)

Chapter 4 explores user preferences and avoidance behaviour in car-free urban areas, analysing factors that encourage or deter shared mode use.
(Addresses RQ3)

Chapter 5 investigates shared mobility adoption among adults aged 50 and above, identifying behavioural heterogeneity through latent class modelling.
(Addresses RQ4)

Chapter 6 synthesizes findings across all studies to answer the main research question, highlights scientific and policy contributions, and outline directions for future research.

Together, these chapters form an integrated investigation of how shared mobility options and hubs can foster low-carbon, inclusive urban transport by shaping individual travel behaviour across diverse urban contexts.

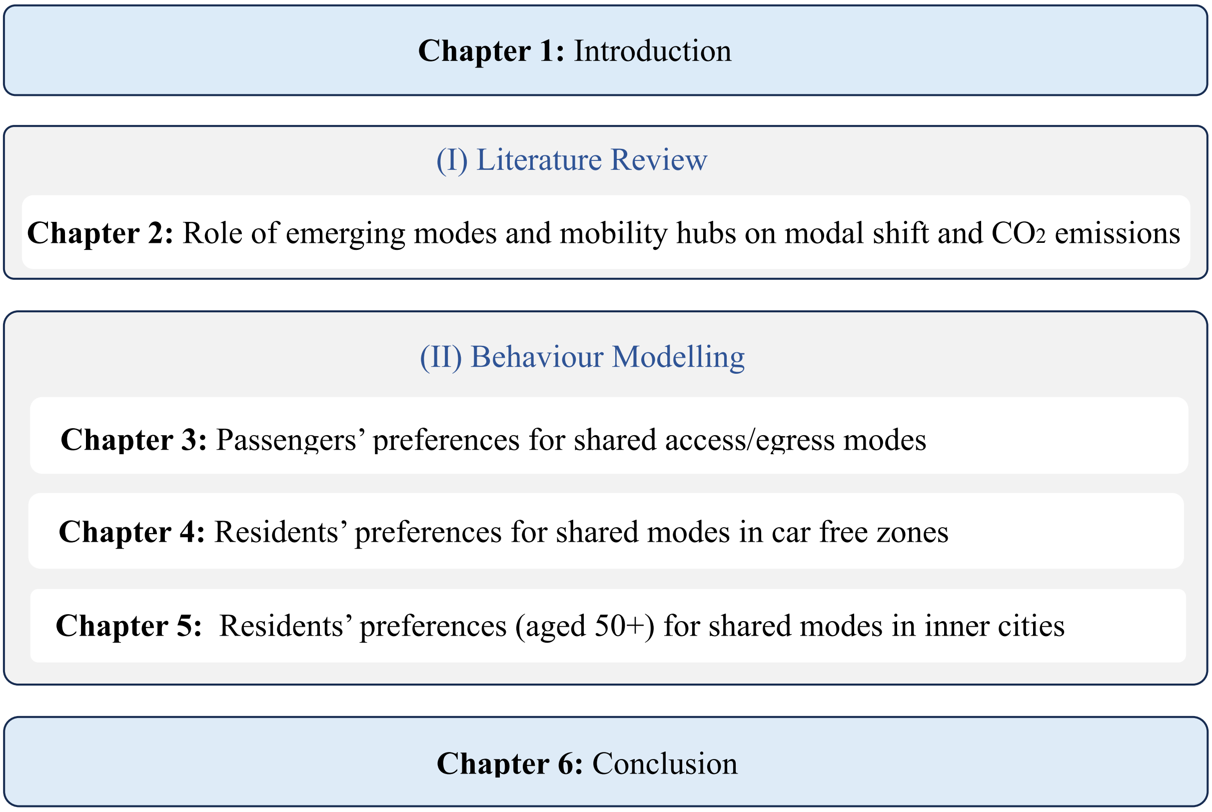

Figure 1.2: Overview of the thesis outline

Chapter 2:

Role of Emerging Transport Modes and Mobility Hubs on Modal Shift and CO_2 Emissions

Chapter 2:

Emerging transport modes and mobility hubs: a review of their impacts on CO_2 emissions

As cities pursue the goal of reducing CO_2 emissions and transition towards sustainable urban mobility, emerging transport modes—such as micromobility, shared mobility, and electric mobility—offer promising opportunities. When integrated effectively with mobility hubs, these modes can facilitate modal shifts away from private cars, thereby lowering emissions and improving urban liveability. However, while many of these options reduce direct (in-vehicle) emissions, their overall climate benefit depends strongly on life-cycle factors (e.g., production, maintenance, lifespan) and operational impacts (e.g., rebalancing logistics), as well as how well they are embedded in infrastructure and supported by policy.

This chapter (paper) examines how emerging transport modes can support urban decarbonisation, with a particular focus on modal substitution effects and on the role of mobility hubs as enabling infrastructure that can mitigate operational and life-cycle inefficiencies.

The paper is structured as follows: Section 2.1 (Introduction) frames the decarbonisation challenge and motivates the need to evaluate emerging modes and mobility hubs. Section 2.2 (Methodology) outlines the analytical approach, including the LCA-based analytical framework and the distinction between direct and indirect emissions used throughout the review. Section 2.3 synthesizes evidence on modal shift towards emerging modes, focusing on shifts from private cars to shared and electric alternatives. Section 2.4 (Mobility hubs concept, definition and characteristics) then reviews what mobility hubs are and how they can support (and conditionally improve) the CO_2 performance of emerging modes. Finally, Section 2.5 (Discussion and conclusions) discusses trade-offs and rebound risks and concludes with implications for policy and research.

This chapter is based on the journal publication:

Torabi Kachousangi, F., *Emerging transport modes and mobility hubs: A review of their impacts on CO_2 emissions*. Frontiers in Sustainable Cities, 8, 1685930. https://doi.org/10.3389/frsc.2026.1685930

Kreutzberger, E., van Binsbergen, A., Reitemeyer, F., Drabicki, A., **Torabi Kachousangi. F.** van Oort, N., (2025). *Climate-friendly mobility in cities - Demonstration of carbon reduction in the long term in four European cities*. In: Progress in Planning. 202, 40 p., 101021.

2.1 Introduction

The rising demand for mobility has driven a substantial increase in emissions (Intergovernmental Panel on Climate Change (IPCC), 2022), with the transportation sector being a major contributor (ITF, 2024). Private cars dominate urban mobility, producing high CO_2 emissions (Tian et al., 2022; González et al., 2019), air pollution (Adams and Requia, 2017; Degraeuwe et al., 2017), congestion (Struyf et al., 2022; Fan and Harper, 2022), and urban fragmentation (Delclos-Alio et al., 2023). In the EU, transport CO_2 emissions increased from 32 to 45% of total CO_2 emissions between 1990 and 2015, with road transport contributing 92% of these emissions (González et al., 2019). Cars alone accounted for half of road transport emissions, highlighting their significant role in rising CO_2 levels (González et al., 2019). This highlights the urgent need for practical strategies to decarbonize urban transport.

Over the past 15 years, mobility has undergone profound transformation, including the rise of shared mobility services, vehicle electrification, stricter environmental policies, advancements in automation, and disruptions caused by economic and health crises (de Bortoli, 2021). Evaluating these changes requires monitoring transport demand, modal shifts, and their impacts on energy and emissions. Van Wee et al. (2005) provided an early but still highly relevant framework for sustainable urban mobility, identifying six key determinants: (1) reducing transport volume in terms of number of trips or tonnes, (2) decreasing travel distances, (3) improving occupancy rates, (4) employing fuel-efficient and cleaner technologies, (5) changing driving habits to lower speed and a smoother driving style, and (6) shifting to sustainable modes like walking, cycling, and public transport. Notably, their framework predates the emergence of shared mobility, it does not explicity address these modes, which has since become a central element in sustainable transport strategies. Shared vehicles address several of these determinants by reducing trip volumes and distances, while shared electric vehicles additionally contribute through cleaner technologies. Together, they represent a new type of modal shift—away from private car use toward shared alternatives—thus advancing low-carbon mobility (Kuss and Nicholas, 2022; Svennevik et al., 2021; Bösehans et al., 2021).

Despite their promise, shared mobility systems are not without limitations. While they reduce direct in-vehicle emissions, indirect impacts such as shorter vehicle life cycles, rebalancing operations, and maintenance can offset these gains. Therefore, a life cycle perspective is necessary to fully assess the impact. In addition, significant uncertainties remain regarding emerging forms of shared and micro-mobility. Shared e-mobility systems are still at an early stage of development in most regions, and academic research on micromobility is likewise only beginning to take shape (Liao and Correia, 2022). The literature on shared e-scooters remains limited (Badia and Jenelius, 2021), and although shared micromobility services are expanding rapidly, there is still little evidence about their effects on travel behavior (Reck et al., 2022). As these modes are nascent, their technical performance is evolving quickly (ITF, 2024), which contributes to unstable findings. More broadly, the effectiveness and environmental impacts of such novel mobility types have not yet been comprehensively evaluated in either research or policymaking (D'Almeida et al., 2021).

In response, mobility hubs have emerged as an important strategy to centralize shared services, reduce rebalancing needs and vandalism, and encourage sustainable travel behaviors (Aydin et al., 2022). They are increasingly promoted in local and national policies (Department for Business, Energy and Strategy, 2022; Arnold et al., 2023), with investments in Europe, North America, and Asia (Nottingham City Council, 2020; Berndsen and Basta, 2021; Aono, 2019).

However, their long-term environmental effectiveness remains insufficiently studied, and consensus on their definition and optimal design is still lacking (Rongen et al., 2022; Bernardes Real et al., 2021).

This review aims to synthesize existing knowledge on emerging modes including micro-mobility (bicycles and scooters), shared mobility, electric mobility, and their combinations into a comprehensive framework for evaluating their impact on modal shift and CO_2 reduction. It also explores the role of mobility hubs in reducing life cycle emissions, without engaging in hub typology debates. The analysis covers three key modes: conventional and electric carsharing, bike-sharing, and scooter-sharing, chosen for their diverse environmental benefits and relevance to contemporary urban planning.

Previous studies have largely examined these elements individually. For instance, research has focused on the emission reduction potential of shared mobility (Kuss and Nicholas, 2022), of micro-mobility (Svennevik et al., 2021; Bösehans et al., 2021), or of the electrification of vehicles in reducing tailpipe emissions (González et al., 2019). Mobility hubs have similarly been studied across several functional dimensions, specifically regarding their role in service integration and accessibility (Berndsen and Basta, 2021), and more recently for improving operational efficiency in shared mobility (Aydin et al., 2022). Together, these studies indicate that the literature remains fragmented, with three notable gaps: first, a lack of a comprehensive synthesis linking micro-, shared, and electric mobility to decarbonization targets; second, limited attention to the environmental role of mobility hubs, particularly in regarding Life Cycle Assessment of emissions; and third, finding which suggest that shared mobility is currently relegated to a niche rather than a mainstream transport mode. These gaps also reflect limitations in the extant research, which frequently adapts narrow spatial scopes or short-term evaluations while overlooking systemic synergies and longitudinal behavioral dynamics.

This paper addresses these gaps through three contributions. First, it systematically synthesizes evidence on emerging transport modes with explicit reference to their CO_2 reduction potential. Second, it advances understanding of mobility hubs by positioning them not only as integration tools but also as strategies to reduce life cycle emissions. Third, it situates shared mobility within the broader trajectory from niche adoption to mainstream urban transport, highlighting the planning and policy conditions necessary for achieving meaningful climate benefits. Together, these contributions provide new insights for policymakers, planners, and researchers seeking integrated approaches to sustainable, low-carbon mobility.

The paper first outlines emissions determinants and environmental effects. It presents the methodology for assessing emerging modes and mobility hubs, followed by an analysis of shared and electric vehicles, the concept of mobility hubs, and factors influencing their effectiveness in reducing CO_2 emissions. The paper concludes with findings, implications for policy and practice, and recommendations for future research.

2.2 Methodology

This section outlines the analytical framework for investigating the determinants of transport emissions and the environmental sequences of the transition toward emerging mobility systems. We introduce the Life-Cycle Assessment Model as an analytical framework and a dynamic Mitigation Model, as a novel theoretical perspective to explore the roles of modal shift and mobility hubs in reducing CO_2 emissions.

2.2.1 Life cycle assessment (LCA)–based analytical framework

This study adopts a Life Cycle Assessment (LCA)–based analytical framework to synthesize how emerging transport modes influence both direct and indirect CO_2 emissions. Rather than proposing a new model, the framework integrates established emission determinants, modal shift dynamics, and life-cycle processes into a coherent conceptual structure suitable for comparative literature review.

Traditional LCA studies of transport emissions often assess vehicle technologies or transport modes in isolation, focusing on specific life-cycle stages such as vehicle production or use-phase emissions. However, the literature increasingly shows that the environmental outcomes of emerging mobility modes depend on interactions between modal shift, operational logistics, and life-cycle characteristics. In particular, technological efficiency gains may be offset by rebound effects, increased transport demand, or shortened vehicle lifespans. Figure 2.1 visualizes these interactions by linking classical transport emission determinants (van Wee et al., 2005) to modal shift outcomes and their corresponding direct and indirect emission pathways.

2.2.2 Direct and indirect emissions

In line with sustainability policies and research, we distinguish between direct and indirect emissions.

For mobility systems, direct emissions are further subdivided into vehicle use (tailpipe emissions from vehicle use, or “tank-to-wheel”) and direct operational requirements. This latter category includes the emissions generated by rebalancing operations—the repositioning of shared fleets by vehicle service, which are a direct consequence of providing a flexible mobility service.

Indirect emissions, by contrast, arise from upstream fuel or electricity production (“well-to-tank”) and broader life-cycle stages. In the European Covenant of Mayors for Climate and Energy (2019), these align with Scope 1 emissions (direct emissions occurring within the city boundary, including rebalancing) and Scope 2 emissions (indirect emissions from imported energy), respectively. As emphasized by Prussi et al. (2020), accounting for electricity generation and fuel production is essential to capture the full environmental footprint of transport systems.

Direct emissions have technical, logistical, and operational dimensions. They also encompass secondary operations required to support primary activities, such as the rebalancing of shared vehicles.

Technical factors influencing environmental impact include vehicle weight, shape, engine type, fuel type, and loading capacity (van Wee et al., 2005). Heavier vehicles consume more energy for acceleration, while electric engines are more efficient and emit fewer pollutants than internal combustion engines (ICE). Efficiency and emissions in ICE vehicles depend on fuel type (diesel vs. petrol), engine design, and exhaust after-treatment systems (van Wee et al., 2005).

Logistical factors relate to vehicle occupancy rates and load factors, reflecting how effectively a vehicle’s capacity is used (van Wee et al., 2005). Additionally, infrastructure density, population distribution, and functional mix influence travel distances and energy consumption.

Operational factors are tied to vehicle usage and infrastructure characteristics, such as average speed, driving dynamics, and fluctuations between cruising and braking, all impacting energy consumption and emissions (van Wee et al., 2005). Anticipatory driving can significantly reduce fuel use and emissions, whereas aggressive driving increase emissions by 30–40% compared to defensive driving (Szumska and Jurecki, 2020). Despite shared mobility's sustainable image, it still has environmental impacts from operations like bike rebalancing and manufacturing (Luo et al., 2019).

Rebalancing or repositioning of shared vehicles is required in station-less business concepts. This is especially the case for shared scooters and bikes from high capacity to under-stocked locations. Such repositioning can substantially increase energy demand and– in the case of repositioning by fossil-fuel vehicles- also CO_2 emissions (Bonilla-Alicea et al., 2020). In London, 2.2 km of car travel was needed per 1 km of bike travel (Schuijbroek et al., 2017). Such rebalancing is typically carried out with trucks or vans, generating additional emissions (Pal and Zhang, 2017); in fact, it accounted for about 766,000 km of extra vehicle travel annually, offsetting much of the car trip reduction benefit (Fishman et al., 2014). Station-less systems have higher emissions, with rebalancing contributing to 36% of station-based and up to 73% of station-less system emissions (Luo et al., 2019).

Rebalancing significantly affects the use of CO_2 emissions. The frequency of rebalancing correlates with the fleet size and impacts maintenance-related emissions (Luo et al., 2019) and depends on the type of sharing involved, like station-based back-to-one or other service concepts. While reducing fleet size can increase emissions due to bike oversupply and frequent rebalancing, optimizing rebalancing strategies can mitigate these emissions (Luo et al., 2019). In station-based back-to-one shared services hardly any rebalancing is required, contrary to free-floating concepts.

Indirect factors include energy consumption and emissions related to other lifecycle processes of vehicles and infrastructure, such as production, construction, maintenance, and end-of-life processes like recycling. These stages play a significant role in determining the environmental footprint of transport systems (Van Wee et al., 2005). For instance, resource extraction, raw material processing, and manufacturing contribute heavily to emissions (Prussi et al., 2020). Maintenance processes, including component replacements and material use, further add to lifecycle impacts (Luo et al., 2019). Emissions from maintenance are crucial for evaluating the life cycle impact of shared vehicles particularly for shared micro-mobility. Recognizing these factors is crucial for accurately comparing modes of transport and understanding their environmental effects (Van Wee et al., 2005; de Bortoli and Christoforou, 2020).

A study by Chen et al. (2020) found that during production and maintenance, each bike is transported 1.67 km in China. Assuming 25% of bikes are dispatched daily, this results in 0.087 kg CO_2 emissions. However, the majority of carbon emissions from shared bikes originate from production, particularly from material production and processing, rather than from transportation or daily operations. The total emissions for a shared bike are estimated at 34.56 kg CO_2, with production accounting for 91%, operation and maintenance 4%, and disposal 5%. Raw material emissions contribute 84% of production energy consumption, emphasizing the importance of managing energy usage during production to improve environmental sustainability (Chen et al., 2020).

Vandalism, through deliberate damage to transport modes, shortens their lifespan and necessitates frequent replacements, significantly impacting carbon emissions in mode-sharing systems (Luo et al., 2019). Repairing or replacing vandalized bikes consumes additional resources and energy, undermining carbon reduction efforts (Luo et al., 2019). Both bicycles and sharing infrastructure are designed for a ten-year lifespan, but effective maintenance can extend this to 15 years (Luo et al., 2019).

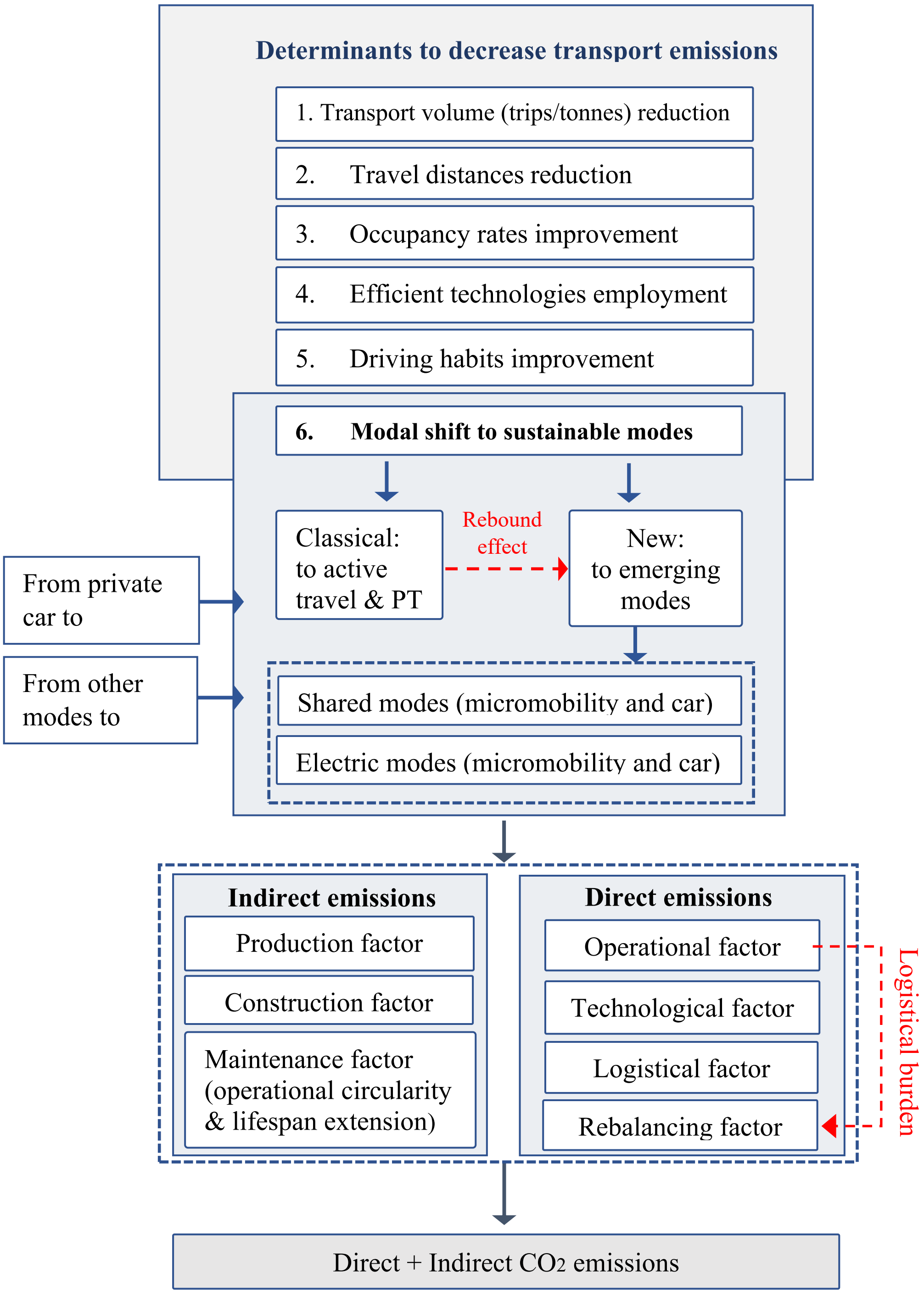

Figure 2.1: Life-cycle pathways linking transport emission determinants, modal shift, and direct and indirect CO_2 emissions.

The environmental performance of shared micro-mobility is heavily influenced by the underlying operational business model, typically categorized into station-based (docked) and free-floating (station-less) systems. While Free-floating (station-less) systems offer greater user flexibility, they are more vulnerable to vandalism and physical degradation compared to their station-based modes (O'Kane, 2018). This increased critical concerns regarding vehicle longevity and the necessity for accelerated replacement cycles.

This scenario often compels operators to expand fleet sizes to compensate for high demand, wear and tear, or rebalancing inefficiencies. Crucially, these factors do not increase the emissions of the bicycles themselves but rather escalate the Direct Operational Emissions stemming from the motorized service vehicles used for redistribution, alongside the broader life-cycle environmental impacts of manufacturing (Luo et al., 2019). Similar challenges are emerging for free-floating car-sharing models; however, there is currently a paucity of literature specifically quantifying the impact of reduced vehicle lifespans on the net carbon balance of station-less shared automobile systems.

To minimize rebalancing needs, reduce vandalism, and extend the lifespan of shared modes while lowering life cycle emissions, the literature highlights the role of mobility hubs as an effective mitigation strategy. By centralizing shared services, improving security, and optimizing operations, hubs can reduce indirect emissions and enhance the environmental performance of emerging mobility systems. Complementary measures, such as improved fleet management and more durable vehicle design, further support these outcomes.

2.2.3 Conceptual framework

This study applies an LCA–based analytical framework to examine how emerging mobility modes activate determinants 1, 2, 4, and 6 of the sustainable transport frameworks proposed by van Wee et al. (2005). Rather than treating these determinants as independent variables, the review adopts modal shift as its central analytical lens, reflecting evidence that shifts to emerging modes simultaneously affect occupancy, energy intensity, and life-cycle CO_2 emissions. This approach enables the identification of cascading effects that are often overlooked in determinant-by-determinant analyses.

Although emerging mobility modes and mobility hubs are increasingly discussed in the literature, empirical evidence on their combined net CO_2 impacts remains limited. To address this gap, the review synthesizes findings across studies to identify conditions under which emerging modes contribute to net decarbonization, as well as circumstances that generate rebound effects, such as substitution away from active travel or increased logistical emissions.

The Dynamic Mitigation framework (Figure 2.2) integrates these insights by linking the decarbonization potential of emerging modes to their realized environmental performance. While shared and electric mobility can reduce emissions through car substitution and first/last-mile integration, three recurring systemic risks are identified: negative modal substitution; substitution patterns between transport modes, life-cycle emissions related to production, maintenance, and vehicle lifespans, and operational and logistical emissions (including rebalancing). Mobility hubs are conceptualized as targeted interventions that mitigate these risks by consolidating operations, extending asset lifespans, and reducing indirect emissions, thereby supporting net urban decarbonization.

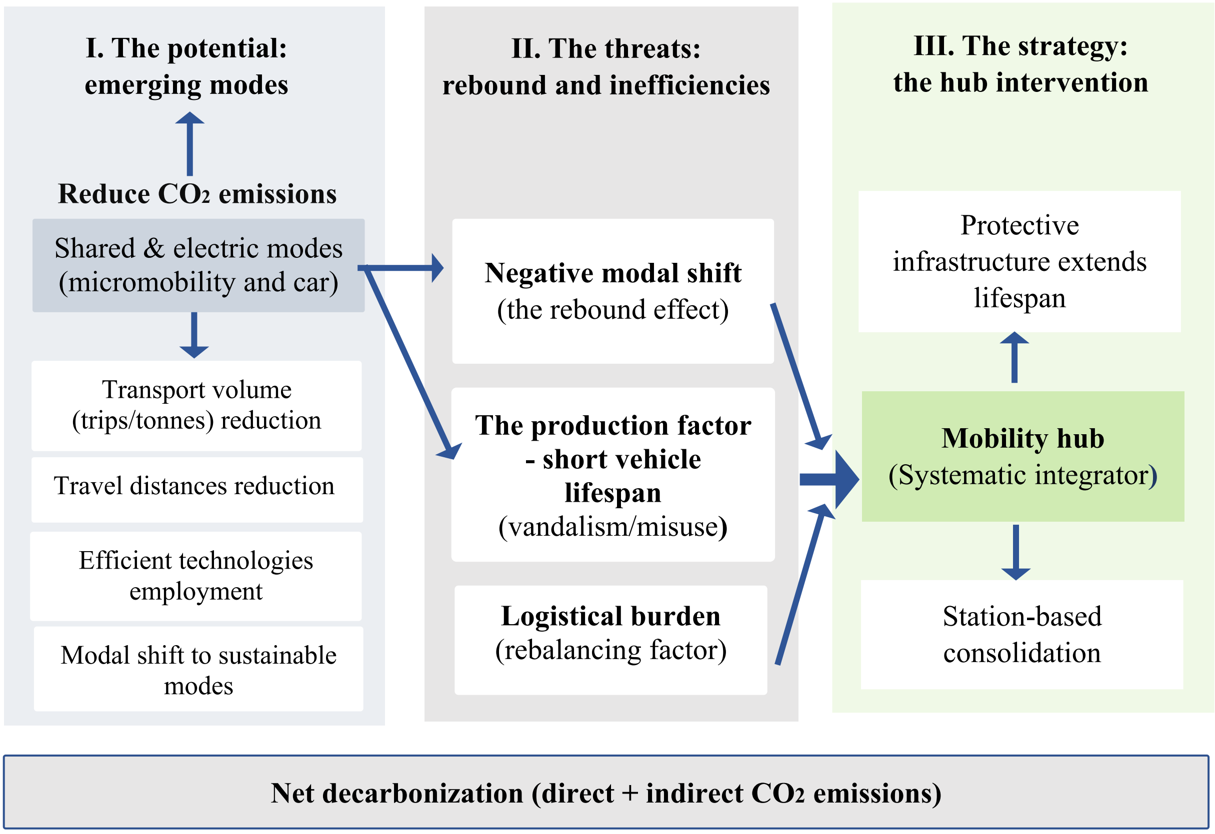

Figure 2.2: the Dynamic Mitigation Model: mobility hubs as systemic integrators.

2.2.4 Selection and quality assessment

To ensure a comprehensive and systematic review, scientific papers and reports were collected using Google Scholar and Scopus, focusing on studies based on field experiments, surveys, GPS data, simulation models, and scenario analyses. Keyword searches covered micro-mobility, shared mobility, electric mobility, modal shift, CO_2 emissions, and mobility hubs (Table 2.1).

To ensure the scientific rigor of the review, the identified studies were evaluated based on their methodological contribution to CO_2 quantification. We conducted a multi-stage screening process: first reviewing titles, abstracts, introductions, conclusions, followed by thorough examination of full texts to assess suitability for data extraction. Reference lists were screened using backward snowballing to identify additional literature.

While the primary objective was to establish the link between modal shifts to shared and electric modes and the role of mobility hubs in mitigating emissions, we applied a formal quality assessment filter:

Phase 1 (modal shift): We first prioritized studies quantifying the shift from private cars or other vehicles to shared/electric modes. These were evaluated based on the transparency of their emission factors and the empirical basis of their data (e.g., utilizing GPS trackers or validated simulation models).

Table 2.1: Sets of keywords for systematic literature review.

Theme	Content involved in keywords
Shared mobility	Emerging modes, innovative modes, shared micro-mobility; shared scooters, scooter-sharing, shared bike, bike-sharing, shared car, carsharing, sustainable modes, sustainable transport modes.
Electric mobility	Emerging modes, electric micro-mobility; e-scooters (sharing), e-bike (sharing), and e-car (sharing), sustainable modes, sustainable transport modes.
Modal shift to emerging modes	Shift from private car to shared modes, electric modes, shift from PT to, short distance, access egress modes, first/last mile, owned car, car ownership, conventional car, travel time, travel distance, travel cost
CO_2 emission	CO_2 emissions from vehicle use, from the production of fuels and electricity and of other lifecycle activities (production, maintenance and recycling of vehicles and infrastructure). Life cycle, life cycle emission, used emission, in vehicle use, direct emissions, indirect emissions.
Mobility hubs	Transport services, mobility hub, multimodal hub, e-mobility hub, station, access egress modes, first/last mile, seamless mobility.

Phase 2 (mobility hubs): We subsequently examined mobility hubs as intermodal nodes designed to consolidate and optimize shared mobility services. Given the paucity of empirical literature explicitly quantifying the direct CO_2 impact of hubs, our analysis focuses on their capacity to mitigate operational inefficiencies identified in Phase 1—such as rebalancing-related externalities and premature vehicle depreciation. Furthermore, we explore how hubs may counteract potential rebound effects, such as induced demand resulting from freed-up road capacity as private vehicle usage declines.

We focused on studies published between 2016 and 2024 to capture the most recent technological advancements, with three exceptions (2011–2015) included for their foundational data. Ultimately, 118 studies were excluded due to redundancy or lack of quantitative CO_2 metrics, leaving a total of $N = 71$ publications for data extraction: 34 sources on the modal shift and 37 sources on mobility hubs (Figure 2.3). While the review primarily targets English-language literature, a high- relevance German research was included. The analysis focuses on European contexts, particularly Germany and Netherlands, while integrating comparative data from the US, UK, and China to assess generalizability.

To manage the methodological and contextual heterogeneity of the sources, we adopted a qualitative synthesis of consensus trends based on modal shift and mobility impact descriptions rather than comparing exact numerical values. This approach accounts for methodological and contextual heterogeneity, recognizing that findings from diverse locales (e.g., London vs. Beijing) are shaped by different factors, for instance varying transport habits. By organizing these studies in the Appendix by location and impact description, we provide a transparent basis for comparing findings across diverse landscapes while identifying the current lack of standardized CO_2 reporting as a significant research gap.

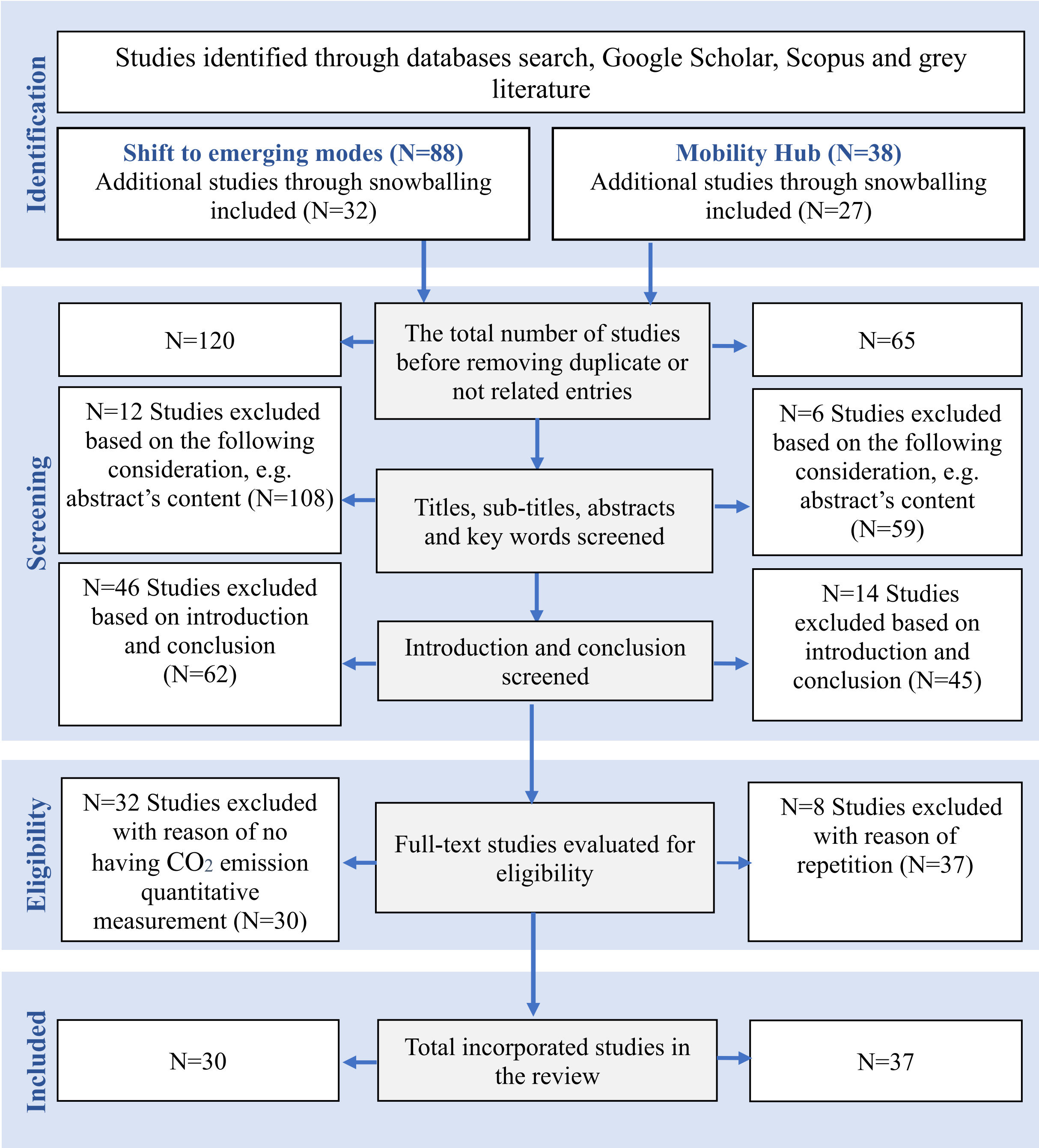

Figure 2.3. Flowchart of search and selection of literature for both areas; modal shift and mobility hubs in this study.

Studies were selected based on three criteria: (i) examining shifts from car and/or other modes to shared mobility, (ii) focusing on (shared) electric modes, and optionally (iii) quantifying the impact on CO_2 emissions. While we primarily address lifecycle CO_2 emissions (often referred to in literature as CO_2e), sources limited to use-phase emissions were included, with noted limitations to ensure a transparent assessment of the current state of the field. For simplicity, the term CO_2 is used throughout. Although comprehensive, the review acknowledges that the dynamic nature of this field makes complete coverage difficult.

The following sections present key findings, categorized by the LCA determinants, with a detailed overview provided in Table 2.2.

Table 2.2: Overview of the modal shift literature review in this study.

References	Country	Changes in mobility (mainly modal shift)
Modal shift to Shared mobility		
Modal shift to Shared Micro-Mobility (bike and scooter)		
Abduljabbar et al. (2021)	General	Potential of micromobility to cut emissions and travel timesaving.
Liao & Correia (2022)	General	Private car to shared e-micromobility for short trips Decrease car ownership and car use Greater adoption when integrated with public transport hubs
INRIX (2019)	General	Private car to shared micromobility
Ma et al. (2020)	Delft	Shared bike increases use of train and decreases that of tram and bus
D'Almeida et al. (2021)	Edinburgh	Shift from different modes to shared bicycles
Pfertner (2017)	Würzburg, Germany	Shift from private bike, PT, walking and non-travellers to shared bike Decrease ownership of private car Reduce CKT
Montes et al. (2023)	Rotterdam, The Netherlands	Shared micro-mobility as an egress for metro trips Complements PT, barriers include poor drop zones and high costs
Stam et al. (2021)	The Netherlands	Bicycles dominate home-end trips Shared micro-mobility complements PT Younger travelers favor shared modes
Van Marsbergen et al. (2022)	The Netherlands	Bikesharing programs replace sustainable modes, limited integration with transit, need for better planning and pricing
Modal shift to Shared Conventional Car		
Jung & Koo (2018)	Urban areas, South Korea	Private car to shared car
Nijland et al. (2015)	The Netherlands, In general	Shift from private car, PT, cycling to shared car Untravelled to shared car Decrease private car ownership Decrease Travelled distance

Schreier et al. (2018)	Bremen, Germany	Private car to shared car Reduce CKT
Pfertner (2017)	Würzburg, Germany	Shift from private bike, PT, walking and non-travellers to shared car Decrease ownership of private car
Martin & Shaheen (2016)	Calgary and Vancouver, Canada & Seattle, Washington, D.C., & San Diego, USA	Shift from private car, PT, cycling, and walking to shared car Decrease car ownership Reduce CMT
Rabbitt & Ghosh (2013)	Dublin, Ireland	Private car to shared car
Firnkorn & Müller (2011)	Ulm, Germany	Private car to (free-floating) carsharing Reduction of private car ownership
Giesel & Nobis (2016)	Berlin & Munich, Germany	Reduction in private car ownership by (free-floating) carsharing Increase car shedding rate Reduced planned car purchases
Van der Linden et al. (2025)	The Netherlands	Private car to carsharing Decrease car ownership Reduce CO_2
Modal shift to Electric Modes		
Modal shift to Electric Bike		
McQueen et al. (2020)	Portland, USA	Private car to e-bike
Kruijf et al. (2018)	North Brabant, Netherlands	Shift from private car, conventional bike, and “other’ to e-bike
Cairns et al. (2017)	Brighton, UK	Shift from private bike, PT, and walking to shared e-bike
Hiselius & Svensson (2017)	Sweden, Urban areas & rural areas	Shift from private car, PT, and cycling to e-bike
Kämper et al. (2016)	München, Frankfurt/ Main, Braunschweig/ Hannover, & Bremen/Oldenburg	Shift from motorized transport, petrol car, conventional bike to e-bike Less CTM
Astegiano et al. (2019)	Germany	PT to e-bike (base scenario) Private car to e-bike (policy scenario)

Modal shift to Shared Electric Micro-Mobility (e.g. bike, scooter and cargo bike)		
Bourne et al. (2020)	Europe, North America, Australia, & New Zealand	From any mode to private or shared e-bike
Weschke et al. (2022)	Germany	Shift from private cars, walking, cycling, PT, and other shared modes to shared e-scooter
Reck et al. (2022)	Zurich, Switzerland	From almost all modes to shared e-scooter From almost all modes to shared e-bike
de Bortoli (2021)	Paris, France	Shift from private bike to shared bike E-Scooter to shared e-scooter E-moped to shared e-moped
Bonilla-Alicea et al. (2020)	General	Shared smart bike Smart dock bike
Campbell et al. (2016)	Beijing, China	From almost all modes to shared bicycle From almost all modes to share e-bicycle
Hollingsworth et al. (2019)	Raleigh, USA	Shift from private car, PT, cycling, and walking to shared e-scooter Decrease passenger miles travelled
Smith & Schwieterman (2018)	Chicago, USA	Private car to shared e-scooter
Krauss et al. (2022)	Berlin, Düsseldorf, Paris, Stockholm, Melbourne & Seattle	From all modes to e-bike (including private/shared cars and bicycles, public transport, taxis/ride-hailing, walking, and other micro-mobility). From all modes to e-scooter (similar broad mode shift).
Towards the Shared Electric Car		
Baptista et al. (2014)	Lisbon, Portugal	Private car to e-carsharing Decrease car ownership, parking demand, & transport cost A complement to public transport
Martin & Shaheen (2016)	San Diego, USA	Shift from private car, PT, cycling, and walking to shared e-car Decrease car ownership Reduce CMT
Liao & Correia (2022)	General	Shift from private car and PT to shared e-car
Jung & Koo (2018)	Urban areas, South Korea	Private car to e-shared car Decrease car ownership Reduce CO_2

2.3 Mobility and CO_2 emission changes considering emerging modes

2.3.1 Types of emerging modes

Emerging modes refer to innovative and flexible mobility solutions that complement or substitute traditional private car use and conventional public transport. They are typically technology-based and prioritize sustainability, efficiency and accessibility. While this study primarily evaluates emerging transport modes (e.g., micro-mobility, shared, and electric mobility), it also examines mobility hubs as the critical multimodal infrastructure required to integrate and optimize these services.

Micro-mobility includes lightweight vehicles (under 500 kg) designed for relatively short distances (less than 15 km), powered by humans or electricity, and available for private ownership or sharing (Liao and Correia, 2022). Examples include bicycles, scooters, skate-boards, segways, and hoverboards (Dia, 2019). These vehicles offer a cost-effective unimodal alternative to private cars for short trips (Smith and Schwieterman, 2018; Liao and Correia, 2022; Woods, 2019) or serve as first-mile and last-mile solutions for public transport (Liao and Correia, 2022). Micro-mobility improves access to public transport nodes, increasing the overall attractiveness of public transportation (Gu et al., 2019; Abduljabbar et al., 2021).

These modes can reach areas poorly served by public transport or difficult for cars and active travel (Schwinger et al., 2022), potentially reducing car dependency and traffic congestion (Dia, 2019; Masoud et al., 2019). Smaller vehicles are more energy-efficient, using less energy than larger vehicles (Tillemann and Feasley, 2018). The popularity of micro-mobility is rising, offering a sustainable, flexible, cost-effective transportation option in some countries (Shaheen et al., 2020). In places like Netherlands, with a strong cycling culture, competition from existing modes is more pronounced. This study primarily focuses on shared and electric two-wheel vehicles within the micro-mobility framework.

Shared mobility provides short-term access to transport modes like (electric) cars and micro-mobility vehicles, such as scooters and bikes, based on demand (Shaheen et al., 2015). It aims to serve as an alternative to private cars for short trips and first/last mile connections to public transport. Shared cars serve both short and longer multi-modal journeys (Shaheen et al., 2015). The goals of shared mobility include reducing private car ownership and usage, minimizing space for parking and movement, transitioning to post-fossil vehicles, and supporting public transport. Integrating these options with public transport enhances urban liveability and reduces congestion (Rongen et al., 2022). Key factors for improving carsharing include price, availability, access, and vehicle type, supporting the transition to post-fossil fuel vehicles.

Electric vehicles (EVs) are crucial for sustainable transportation due to their high energy efficiency (Usmani and Rösler, 2015). This category includes electric cars, e-bikes, and e-scooters, all of which provide climate-friendly options, especially for short trips in congested areas. EVs contribute to reduced pollution and noise in urban environments. However, lifecycle emissions can vary among electric modes based on battery type, materials, and production processes.

Mobility hubs are multimodal interchanges where discrete transport modes are co-located and digitally integrated. As intermodal nexuses, they synchronize shared mobility services with mass transit and active transport networks, serving as the foundational prerequisite for a cohesive multimodal ecosystem (Geurs et al., 2022; Miramontes et al., 2017).

Conceptually, this study frames hubs as “spatial anchors” that mitigate transfer penalties—the temporal and psychological friction associated with switching modes. By providing seamless connectivity and reducing “availability anxiety,” hubs increase the propensity for modal shift from private vehicles to integrated transit chains (Aydin et al., 2022; Berndsen and Basta, 2021).

Beyond behavioral influence, hubs act as operational catalysts that enhance the commercial and environmental performance of emerging modes. By centralizing charging infrastructure and streamlining rebalancing logistics, hubs stabilize the stochastic usage patterns inherent in shared mobility (Aydin et al., 2022). Under this paradigm, the hub functions as a regulatory and digital gateway, transitioning fragmented “last mile” tools into a synchronized, reliable extension of the mass transit backbone.

As illustrated in Figure 2.4, these emerging modes exhibit significant functional overlap and complementarity. This section evaluates their distinct characteristics and their collective impact on urban transport sustainability, specifically focusing on the modal shift from private vehicle ownership to integrated, shared alternatives. By physically and digitally anchoring these services, mobility hubs enable the following integrated travel configurations;

Figure 2.4: Potential innovative mobility options which can be offered in mobility hubs (created by author).

First/Last-Mile Synchronization: Shared (electric) micro-mobility acts as a high-frequency feeder to high-capacity transit trunks, effectively bridging the spatial gap between low-density residential areas and primary transport nodes.

Intermodal Substitution: Strategic placement of shared electric vehicles within hubs provides a competitive alternative to private car use for medium-to-long-range orbital or tangential trips—routes typically underserved by conventional fixed-route transit.

Despite these challenges, shared mobility typically reduces car use and travel distances when aligned with sustainable transport policies. The next section examines the transition from private cars to these emerging modes, highlighting steps towards a sustainable urban future.

2.3.2 Shift from private cars to shared vehicles (micro-mobilities and cars) in unimodal and or multimodal chains

Emerging modes enhance public transport accessibility and efficiency while reducing car usage and ownership (Burrieza, 2019). While some studies focus on mobility shifts, others assess impacts on CO_2 emissions. This distinction matters, as mobility shifts alone do not guarantee environmental benefits, particularly when they increase travel demand or modal shifts from active modes to motorized transport.

Emerging modes can inadvertently increase CO_2 emissions through longer or more frequent trips. For instance, in Dublin, carsharing raised car use by 60% among non-car owners, leading to higher travel costs and emissions (Rabbitt and Ghosh, 2013). Similar trends have been observed elsewhere, highlighting the potential risks associated with poorly managed shared mobility. This section explores the transition from conventional private cars to shared mobility, micro-mobility sharing and carsharing, highlighting steps towards sustainable urban transport. The reviewed literature spans global studies, but findings may not universally applicable, for example from Europe may not translate directly to China (Liao and Correia, 2022).

Micro-mobility sharing

This section reviews studies on shared micro-mobility, particularly shared bicycles and scooters. In the literature, these modes are often analyzed together, due to their similar roles in short-distance travel. However, discussions specifically on scooters remain limited.

Shared micro-mobility can operate independently or integrate with public transport. For instance, in London, it is partly combined with public buses (D'Almeida et al., 2021), while in Dublin, walking complements micro-mobility (Murphy and Usher, 2015). A Rotterdam study found shared micro-mobility, particularly shared bicycles and e-mopeds, effectively serve as egress options for metro trips (Montes et al., 2023). Integration with public transport improves the total travel experience by reducing overall travel time, especially in high-density areas where multimodal travel is common. The study also highlights that young travelers and frequent public transport users are more inclined to adopt shared micro-mobility, indicating that targeted collaborations between public transport and shared mobility providers can be beneficial. In Netherlands, bicycles dominate home-end trips, walking is preferred for short activity-end trips, and well-integrated micro-mobility complements public transport (Stam et al., 2021). However, some studies highlight competition with public transport particularly for short-distance trips. For example, Van Marsbergen et al. (2022) found that bicycle-sharing programs (BSPs) primarily support unimodal travel or travel with limited integration with urban transit. In the HTM-fiets bicycle program, only 9% of BSP trips were combined with transit. Similarly, Pfertner (2017) for Würzburg in Germany found that 46% of bike-sharing trips replace public transport rather than complement it, with the remainder replacing 27% walking, 18% private biking and only 9% introducing new mobility options. BSPs often replace other sustainable modes like public transport and walking, rather than private cars and barriers such as poorly located drop zones and high costs reduce their complementarity with transit. Nevertheless, envisaging only the use of vehicles, total mobility CO_2 emissions decline, as bicycles have zero emissions. These findings suggest that while bike-sharing can enhance public transport, it may also compete with it, particularly in cities with well-established transit networks.

Despite these challenges, bike-sharing systems contribute to multimodal transport, decreasing car use, traffic congestion, and CO_2 emissions, while also enhancing public health and urban liveability (Barbour et al., 2019; Ricci, 2015; Liao and Correia, 2022). The growth of bicycle-sharing systems is largely driven by their reduced environmental impact (Bonilla-Alicea et al., 2020), though other public-sector sustainability goals and private-sector commercial interests also play roles. Importantly, evidence shows that while bike sharing can lower CO_2 emissions compared to users' previous travel modes, its overall environmental benefits are strongly contingent on optimizing rebalancing operations and localizing bike production (D'Almeida et al., 2021). Conventional shared bikes typically cover 1–1.6 km per trip, with variations observed across different regions, including Europe, the US, and Asia (Boor, 2019; Shen et al., 2018; Campbell et al., 2016). In Washington D. C. bike sharing trips are generally under 3 miles (Bonilla-Alicea et al., 2020). Private bicycle trips tend to have longer distances. In Netherlands, private bike trips average shorter than 3–3.5 km (De Haas and Huang, 2022). Shared bikes can effectively substitute short car trips (Abduljabbar et al., 2021) and public transport trips, particularly in urban settings.

In Netherlands, the "OV fiets" scheme has significantly enhanced train usage by offering accessible last-mile options at transport hubs (Mbugua et al., 2025). According to Ma et al. (2020), the scheme led to a 17% increase in Delft, on the other hand, 60% of OV fiets users were reported to go less by bus and tram. Similarly, Mobike, a former competing shared bike system, contributed to a 14% increase in train use, while also their bus and tram usage declined substantially, namely by 40% (Ma et al., 2020). In parallel, both systems enhanced their role in reducing car use (34% or 37% respectively).

Pricing greatly influences shared micro-mobility adoption. Excessive costs for shared modes discourage their usage, while competitive pricing, especially for egress trips, can increase their attractiveness (Montes et al., 2023). Additionally, familiarity with shared micro-mobility positively influences adoption rates. Encouraging first-time usage through promotional campaigns or trials at transit hubs could foster long-term use (Montes et al., 2023). Stam et al. (2021) highlight that younger travellers prefer shared mobility and tailored first/last mile infrastructure can boost sustainable transport adoption.

De Bortoli (2021) compared the environmental impact of private and shared bikes in Paris using Life Cycle Assessment (LCA), focusing on the effects of switching between modes rather than the extent of modal shift. Private conventional bikes, with a lifespan of 20,000 km, exhibit the lowest environmental impact per passenger-kilometer traveled (pkt), emitting just 10.5 g CO_2/pkt. By comparison, private e-bikes emit 320 kg CO_2 over their lifecycle, translating to 26 g CO_2/pkt for a lifespan of 12,500 km and reducing to 16 g CO_2 /pkt when extended to 20,000 km. Shared e-bikes, while convenient, emit 24% more CO_2 than shared mechanical bikes, with 70% of their emissions stemming from manufacturing.

Bonilla-Alicea et al. (2020) assessed the environmental impacts of bike-sharing versus conventional bicycles over 10 years in a hypothetical city, without accounting for a modal shift. They found that station-less shared bikes have a higher environmental footprint compared to the station-based system. The production of bikes emits 1,460 kg CO_2 per bike (148 Pts) over its estimated lifespan, while the infrastructure for stations contributes an additional 479 kg CO_2 per bike (55 Pts). Over the lifecycle, emissions amount to 0.13 kg CO_2/km for bikes and 0.069

kg CO_2/km for station infrastructure. To match the environmental benefits of station-based systems, station-less bikes require a 71% vehicle substitution rate, whereas stations require only 38%. Both systems generate significant emissions from rebalancing, but station-less bikes need 1.8 times more ridership to offset their overall environmental impact.

INRIX (2019) reported that shared bikes and shared scooters could replace 50% of car trips in the US, 60% in Germany, and 70% in the UK for distances under 3 miles, helping reduce traffic congestion and emissions. As previously discussed, Pfertner (2017) emphasized the versatility of bike-sharing as both a complement to public transport and an alternative to car use. However, this example is an exception regarding the typical modal shift, as there is no shift from the private car, which contrasts with the patterns typically observed. A summary of all studies is provided in Appendix 2.1.

Sharing of conventional cars

According to Shaheen et al. (2019), carsharing reduces total (= private and shared) car-km and private car ownership, contributing to reductions in fuel consumption, and greenhouse gas emissions while offering alternative mobility options among car-free households. It also reduces reliance on public transport for primary trips but often enhances first and last-mile connections. The effects on bicycle usage vary based on local conditions and user preferences. Rabbitt and Ghosh (2013) found that in Ireland, carsharing positively impacts travel behaviours and helps reduce CO_2 emissions, especially in densely populated areas. Participants who sold their cars to join a carsharing system reduced their Car Kilometers Travelled (CKT) by 9%, which saved an average of 1,197 kg of CO_2 annually. Non-car owners who joined the system saved 337.2 kg of CO_2, while those who sold their cars saved about 859.8 kg. Overall, carsharing reduced Ireland's CO_2 emissions by 86 kt annually. If electric carsharing systems were adopted, the savings could increase to up to 895 kt. Active travellers and public transport users who sold their cars saved 145.7 kg and 316.6 kg of CO_2, respectively. However, non-car owners experienced a 60% increase in car dependence, with raised travel costs and CO_2 emissions.

Van der Linden et al. (2025) conducted a case study in Netherlands with 1,281 Greenwheel users. The study revealed that station-based car sharing replaces up to 11 private cars per shared vehicle. Around 41% of environmentally conscious users disposed of at least one private car after joining the service, indicating a meaningful shift in car ownership patterns. In contrast, skeptical users demonstrated smaller reductions, suggesting they retained some or all of their private cars. Before joining, many users owned more than one private car, making the observed reductions particularly relevant. Car sharing primarily substitutes private car trips (25%) and public transport trips (36%), indicating that it serves as both an alternative to car ownership and a flexible addition to existing transport options. Overall, users reported a net CO_2 reduction of 30%, highlighting the environmental benefits of car sharing in urban mobility system.

Nijland et al. (2015) analyzed carsharing's impact on annual CO_2 emissions in Netherlands in 2014. Prior to using shared cars, participants traveled 38% of kilometers by private car, 35% by train, 4% by public transport and 2% by cycling. Carsharing led to an 18% reduction in annual travel (1,600 km), which resulted in an 11% decrease in CO_2 emissions (250 kg/year; percentage by authors). However, the shift from sustainable transport modes to carsharing added 160 kg of CO_2 (7%; percentages by authors), leading to a net reduction of 90 kg/year (4%). Carsharing also lowered average car ownership from 0.85 to 0.72 cars per household, reducing CO_2 emissions by an additional 85–175 kg annually due to lifecycle effects. In total, carsharing achieved a net CO_2 reduction of 175–265 kg per respondent per year, corresponding to an 8 to 12% reduction in emissions related to car use and ownership. Nijland et al. (2015)

highlight that convenient carsharing services help promote the shift from private car ownership, encouraging users to adopt carsharing rather than purchasing new vehicles. A similar conclusion is drawn by Liao et al. (2020).

Chen and Kockelman (2016) found US carsharing users consumed 51% less energy and emitted less CO_2 from vehicle use compared to private car users. This reduction is primarily due to fewer trips overall and the shift from private to shared vehicles. Additionally, carsharing reduces the demand for parking infrastructure and fuel consumption. Similarly, Firnkorn and Müller (2011) evaluated the environmental impact of car2go in Ulm, Germany. They showed that car2go, a free-floating carsharing system, decreased the total number of cars and reduced the carbon footprint of carsharing users from 2,786 kg to between 146 and 312 kg annually, a reduction of 5 to 11%.

Jung and Koo (2018) studied the impact of carsharing on greenhouse gas emissions in Seoul. They found that while carsharing increases CO_2 emissions due to a shift from public transport to shared cars (an increase of 11,833 t CO_2 daily), it reduces emissions by shifting from private cars to shared vehicles (−5,929 t CO_2) and lowering other car lifecycle emissions (−3,093 t CO_2 daily). The result is a net daily increase of 2,809 t CO_2, or an annual rise of 1,026,000 t CO_2. Jong and Koo suggest that this represents approximately 1.2% of total road transport emissions. More reduction can be achieved if shared cars are electric ones.

Pfertner (2017) examined mobility behavior changes in Würzburg, Germany also of shared cars and bicycles. The study identified key factors contributing to CO_2 reduction, such as lower emissions per kilometer from smaller, modern vehicles and fewer overall car kilometers. A significant modal shift to carsharing was noted, with 50% of trips replacing public transport, 32% replacing private car trips, 29% replacing new mobility trips, 22% replacing private bicycles and walking, and 10% replacing rental cars. Overall, carsharing led to a net CO_2 reduction of 650 tons annually, consisting of 629 tons from reduced fossil car kilometers, 10 tons from shared cars being more efficient, and a 31-ton increase due to shifts from public transport and active travel. This net reduction represents about 1% of local transport emissions.

Giesel and Nobis (2016), in contrast, focused more on conceptual insights related to ownership behavior, showing that both station-based and free-floating carsharing in Berlin and München significantly reduce private car ownership. Among the 819 surveyed DriveNow users, 6.5% reported selling their cars, and 7.1% avoided planned purchases. Similarly, among the 227 Flinkster users surveyed, 15.3% reported selling cars, and 8.3% avoided planned purchases. In Bremen, Schreier et al. (2018) reported that each shared car replaced 16 private ones, removing about 5,000 vehicles from the streets, which also reduced parking demand. Users of shared cars also drove 50% fewer kilometers, utilizing shared cars for three-quarters of their trips.

Martin and Shaheen (2016) studied car sharing in five US and Canadian cities. They found that Car2go resulted in a 2–5% reduction in car ownership, with 7–10% of users forgoing vehicle purchases. The impact on PT varied by context, with changes in bus usage ranging from a 32% decrease to a 5% increase, reflecting shifts in how users employed carsharing for first/last-mile connections. Car2go led to a 6–16% decrease in car miles traveled (CMT) per household, translating to a 12% average reduction in GHG emissions, with each Car2go vehicle displacing 4 to 14 tons of GHG annually. Similarly, Jochem et al. (2020) found that among regular carsharing users in several European cities, between 3.6 and 16.1% reported selling a vehicle after joining the scheme, while 14.3 to 40.7% indicated that they had postponed or foregone a vehicle purchase. Consistent with these findings, Van Gerrevink (2021) reported that, in 2008, European carsharing users drove 2.5 times fewer kilometres than private car users. All the mentioned studies have been summarized in Appendix 2.2.

Shared cars emit less CO_2 than private cars over their lifecycle. While shared micro-mobility (e.g., scooters) has low use emissions, depending on the return model, repositioning and mishandling may increase total emissions. Shifting from public transport and cycling to carsharing can increase travel distances, despite lower private car emissions (Jung and Koo, 2018). Overall, private vehicles rank lowest in CO_2 performance, while shared vehicles vary based on the analysis focus.

2.3.3 Shift from private cars to (shared) electric vehicles (micro-mobility vehicles and cars) in unimodal and or multimodal chains

Shared electric mobility has similar mobility effects as shared fossil-fuel mobility but offers greater sustainability due to technological differences. It is discussed separately here to avoid confusion with studies that jointly analyze shared and electric vehicles. Shared electric mobility can contribute to reduced traffic congestion by offering alternatives to private car use—particularly single-occupancy trips, while also promoting environmental sustainability and enhancing accessibility (Liao and Correia, 2022). The following sections explore the CO_2 impacts of shifting from private cars to shared electric micro-mobility and vehicles.

Electric bicycle (sharing)

Electric bicycles (e-bikes) can significantly reduce CO_2 emissions from transportation (McQueen et al., 2020, referring to Portland). There is a willingness to cycle longer distances with e-bikes than with conventional in the US (McQueen et al., 2020) and Netherlands (Sun et al., 2020). They enable longer distances with less physical effort compared to conventional bikes, making them more effective at replacing private car trips (Bourne et al., 2020, many countries; Cairns et al., 2017, Brighton, UK; Kruijf et al., 2018, Netherlands). E-bikes potentially lead to less traffic congestion, lower energy consumption, and improved air quality (McQueen et al., 2020; Sun et al., 2020). E-bike sharing systems can enhance these benefits by increasing accessibility and mobility options, further promoting sustainable urban transport.

Studies show that a large percentage of short commutes in Sydney (67%) and Melbourne (76%) rely on private vehicles. In the US, half of all car trips are under 5 km, while in Europe, over half are less than 8 km. Shared e-bikes and e-scooters are emerging as low-carbon alternatives for these short trips (Woods, 2019), particularly those around 2 km, due to their greater convenience and ease of access compared to carsharing (Liao and Correia, 2022). At the trip level, e-bikes have been shown to outperform taxis and public transport for shorter distances in Zürich (Guidon et al., 2019), while e-scooters demonstrate similar advantages over public transport in San Diego (Arnell et al., 2020). However, while electric micro-mobility options are viable for short distances, they are less effective for longer trips (Smith and Schwieterman, 2018).

Reflecting on these findings, the potential for shared e-bikes and e-scooters as alternatives to private cars may vary by region. In Europe, where public transport systems are generally well-developed, the impact of shared micromobility may be more limited. In contrast, in the US and Australia, where public transport is often less accessible and travel distances are longer, shared e-bikes and e-scooters could play a crucial role in replacing short car trips. The tendency of Americans to use cars even for very short trips, sometimes within walking distance, highlights the considerable potential for shared micromobility to reduce car dependency in such contexts. It should be noted, however, that private electric bicycles may also offer substantial potential, as suggested by Hiselius and Svensson (2017), who found that private e-bikes could significantly reduce car use in Sweden.

E-bikes, e-scooters, and other micro-mobility options enhance accessibility to hard-to-reach areas (MacArthur et al., 2017; Smith and Schwieterman, 2018) and are more efficient due to their higher speeds. Astegiano et al. (2019) examined the shift from cars and public transport to traditional bikes and e-bikes for trips under 50 km from 2015 to 2050. They found that road pricing significantly reduced car use and CO_2 emissions, while a base scenario, which projected trends without additional policy interventions, led to greater declines in public transport use as natural growth favored e-bike adoption. The impact varied by country, with Netherlands showing less change due to its strong cycling culture, suggesting toll policies could drive more significant shifts (Astegiano et al., 2019). However, it is important to note that this study focused only on Scope 1 (tank-to-wheel) emissions, which may underestimate the total lifecycle emissions impact of mode shifts.

Kämper et al. (2016) studied the CO_2 impacts of e-bike use and ownership in 5 cities in Germany, and Hiselius and Svensson (2017) for urban and rural areas in Sweden. They found that e-bikes significantly reduce reliance on cars, sometimes competing with public transport. In Germany, 41% of e-bike trips replaced car trips and 38% replaced conventional bike trips (Kämper et al., 2016). In Sweden, where 80% of urban car trips are under 3–4 km (Naturvårdsverket, 2019), e-bikes effectively substituted car use in urban and rural areas (Hiselius and Svensson, 2017). In Germany, car was the most replaced mode for any travel motive. In Sweden, e-bike commuters mainly used cars before, while for e-bike leisure this was the conventional bike.

Kämper et al. (2016) found that e-bikes reduce CO_2 emissions by at least 25% per passenger kilometer (pkm) compared to other motorized transport, with a 90% reduction when switching from petrol cars, saving nearly 150 g CO_2 per pkm. However, switching from conventional bikes to e-bikes increases emissions by 7.4 g CO_2 per pkm. The shift from less sustainable modes to the e-bike was analyzed to save 2,400 kg of CO_2 weekly, while the shift from conventional bikes and walking to the e-bike would add 50 kg. Overall, e-bikes significantly lower emissions, especially for frequent car trips, potentially replacing up to 80 million pkm of car travel for trips under 15 kilometers in Germany.

Hiselius and Svensson (2017) examined the impact of private e-bikes on CO_2 emissions in rural and urban Sweden. E-bike users reduced car use by 55 km per week in urban areas and 62 km in rural areas. This resulted in weekly CO_2 reductions of 7.7 kg (urban) and 8.6 kg (rural), averaging 8.2 kg. This corresponds to a 14–20% reduction in annual emissions, depending on the frequency of e-bike use throughout the year. However, the study considers only direct (tank-to-wheel) emissions and does not account for lifecycle emissions, which may lead to an underestimation of the full environmental impact.

Regarding average trip distances, e-bike sharing has a median trip length of 2 km, e-scooters of 1.8 km per trip (Liao and Correia, 2022), while conventional shared bikes have average trip lengths of 1–1.6 km (Boor, 2019; Shen et al., 2018). In specific urban case studies, shared electric modes have been found to overlap with public transport and taxis (Guidon et al., 2019), pointing to replace short car trips (Abduljabbar et al., 2021). For instance, e-bikes often have the potential to replace car (45%) and traditional bike (32%) trips (Kämper et al., 2016). McQueen et al. (2020) studied e-bike adoption in Portland, USA, focusing on private e-bikes. They found that e-bikes mainly replace car trips (72%), followed by public transport (13%), conventional bike trips (12%), and walking (2%). Increasing e-bike market share from 0 to 15% could reduce daily car passenger miles travelled from 28.9 million to 25.5 million (12% reduction) and CO_2 emissions from 8,079 to 7,088 metric tons per day. Each e-bike would then save around 225 kg of CO_2 annually, even assuming the current carbon intensity of U.S.

electricity. However, cars would still account for 98.9% of total emissions at a 15% e-bike mode share.

Campbell et al. (2016) explored shared bike and e-bike usage in Beijing. They found that 17% of shared e-bike users had previously used private cars, compared to 8% for shared bikes. Among shared e-bike users, 30% had been public transport users before, while 20% of shared bike users came from public transport. Regarding current bike users, 11% of shared e-bike users and 17% of shared bicycle users reported switching from private bicycles. Furthermore, 27% of shared e-bike users and 49% of shared bike users previously walked as their primary mode of transport. Mean distances of shared e-bike trips are 4.5 km, and those of shared e-bike trips are 2.9 km, making them suitable for longer distances and potentially replacing up to 80 million pkm of car trips. The study noted that conventional bike-sharing is influenced by habits and environmental factors, often competing with bus use. E-bike sharing is more effective in low-density areas and appeals primarily to younger males with lower education and income levels. Travelers previously accustomed to unsheltered modes such as walking, private cycling, and private e-cycling were found to be more likely to switch to shared (e-)bicycles than those who previously relied on sheltered modes like cars, buses, or metro. While e-bikes are efficient for longer trips, they can lead to congestion and safety concerns at intersections, but they have strong potential to promote sustainable urban mobility.

Reck et al. (2022) analyzed mode choices among 540 participants in Zurich to estimate former modes of current micro-mobility users. Among current shared e-bikes users, 9% of their travel distance previously involved walking, 43% public transport, 15% car, 29% bicycle, and 5% private e-bike trips. Shared e-bikes have gross emissions of 83 g CO_2/pkm, resulting in a net increase of 25 g CO_2/pkm compared to the emissions of replaced modes (58 g CO_2/pkm). In contrast, for private e-bike users, 9% of travel distance originated from walking, 29% from public transport, 48% from car, 14% from bicycle, and 5% from another private e-bike usage. In contrast, private e-bikes achieved a net reduction of 54 g CO_2/pkm, with gross emissions of 34 g CO_2/pkm and replaced modes averaging 88 g CO_2/pkm. These results underscore the importance of Life Cycle Assessment (LCA) when evaluating micro-mobility impacts, demonstrating the greater CO_2 reduction potential of private e-bikes relative to shared services.

Krauss et al. (2022) analyzed the impact of shared electric scooters and bicycles in six cities worldwide. They found that shared e-bicycles trips in Berlin, Düsseldorf, Paris, Seattle and Melbourne formerly took place by walking (25–49% dependent on the city), public transport (13–39% of which metro 2–33%, buses 4–11%) or used taxi or ridehailing (6–14%). The study compares the CO_2 emissions per pkm. Shared bicycles emit 0 g CO_2/pkm during use, while this is 0.1–10.9 for shared electric bicycles (dependent on the city and hence to the characteristics of national electricity production). In addition, there are 23–24 g CO_2/pkm for servicing (repositioning). The total life cycle emissions are higher:46.1–47.3 g CO_2/pkm for shared bicycles and 60–70.6 g CO_2/pkm for shared e-bicycles. These LCA emissions are less than for a fossil-fuel private cars, average (of all envisaged cities) than for electric private cars, also less than for taxi/ridehailing and bus/shuttles, however larger than for metro and urban rail. Taking account of changing pkms per mode, the e-bicycle lets net emissions increase in Berlin and decrease in the other cities. The explanation for Berlin's deviation is the larger share of private bicycle use and public transport and the lower share of taxi use and ridehailing there, compared to the other cities analyzed. All the mentioned studies have been summarized in Appendix 2.3.

Electric scooter (sharing)

Multiple studies emphasize the potential of e-scooters as a transportation option. Hollingsworth et al. (2019) and PBOT (Portland Bureau of Transportation) (2019) found that shared e-scooters could replace 34% of car trips in the US, while Fitt and Curl (2019) reported up to 28% in New Zealand. Fearnley et al. (2020) found that 57% of shared e-scooter users integrate them with other modes, with notable shifts from walking (60%), public transport (23%), and cars (8%) to e-scooters in Oslo.

Reck et al. (2022) found that, on a distance basis, among current shared e-scooter users, 25% of their travel previously involved walking, 38% public transport, 15% cars, and 13% bicycle trips. Shared e-scooters exhibited gross emissions of 106 g CO_2/pkm, resulting in a net increase of 51 g CO_2/pkm compared to replaced modes (55 g CO_2/pkm). Among current private e-scooter users, 19% of travel distance originated from walking, 27% from public transport, 25% from car, and 27% from bicycle use. Private e-scooters have gross emissions of 42 g CO_2/pkm, yielding a net reduction of 16 g CO_2/pkm relative to replaced modes (58 g CO_2/pkm). As with e-bikes, the private versions of e-scooters in Zurich show lower emissions than the modes they replace, while shared versions show higher emissions.

Hollingsworth et al. (2019) analyzed the lifecycle emissions of station-less e-scooter sharing in Raleigh, US. Their survey found that 34% of e-scooter users would have driven a car, 11% would have taken a bus, 7% a bike, and 41% would have walked. Shared e-scooters emit 202 g CO_2 per passenger mile, compared to 414 g for private car use. Emissions are primarily from materials and manufacturing (50%) and repositioning (43%). With an estimated lifetime mileage of 7,300 miles, shared e-scooters have higher emissions than buses (82 g CO_2/pass-mile) and private e-bikes (40 g CO_2/pass-mile). Urban density affects emissions, with denser areas reducing repositioning distances. Increasing repositioning distance to 2.5 miles raises emissions by 27%, and shortening the scooter lifespan to 0.5 years increases CO_2 emissions to 450 g. Strategies like enhancing urban density and extending e-scooter lifespan to 2 years could reduce emissions by up to 50%, achieving a net reduction of 141 g CO_2 per passenger mile.

Smith and Schwieterman (2018) examined shared e-scooters in Chicago, finding them effective for short trips (0.5–2 miles), increasing the share of non-auto trips from 47 to 75% in the city's North area and from 55 to 66.8% in the South and West areas. However, for longer trips (over 3 miles), e-scooters were less economical and mainly used for reaching bus or train stations. The study does not address carbon emissions changes related to the mode shift.

Weschke et al. (2022) found that shared e-scooters serve as feeder modes to improve public transport accessibility in Germany. They replace walking (42%), public transport (20%), biking (11.5%), and cars (11.3%) in Germany. However, with a gross lifecycle emission of 106 g CO_2/pkm, higher than the emissions of the replaced modes, which range from 43 to 65 g CO_2/pkm, shared e-scooters result in a net increase of emissions. To reduce overall emissions, efforts should focus on reducing e-scooter emissions and promoting their use as a car alternative, improving parking, access, and flexibility to enhance adoption.

De Bortoli (2021) conducted an environmental assessment of shared second-generation e-scooters, focusing on lifecycle emissions rather than market shares or modal replacements. The study estimated an average lifespan of 7,300 km for shared e-scooters. For these vehicles, vehicle production accounted for 79% of lifecycle CO_2 emissions, followed by servicing (9%), infrastructure (10%), and electricity consumption (2%).

Optimized routing, servicing, and using electric vans were shown to reduce emissions by up to 9%, while electricity use remained minimal. The carbon footprint ranking for Paris showed that private mid-range and entry-level e-scooters emit less CO_2 per passenger-kilometer than shared e-scooters, while all e-scooter types emitted less than diesel buses, private motorcycles, cars, and taxis, but more than most other alternatives. Sensitivity analyses indicated that simply extending the lifespan would not be sufficient to make shared e-scooters less emitting than e-public transport in Paris. Overall, shared bikes and e-mopeds were found to consistently outperform shared e-scooters environmentally. Additionally, De Bortoli also noted that in U.S. conditions, shared micromobility modes globally rank between active modes and motorized modes in terms of global warming potential. Public transport presents a higher carbon footprint than in Paris due to a higher carbon intensity of electricity and a lower vehicle occupancy rate; furthermore, the carbon footprint from the infrastructure is also higher in the US (de Bortoli, 2021).

Krauss et al. (2022) found that shared e-scooter trips most commonly replace walking, ranging from 40% in Paris to 64% in Seattle. Subway trips are replaced in 1% (Seattle) to 30% (Paris) of shared e-scooter trips, taxi/ride-hailing in 4% (Berlin) to 12% (Melbourne), and buses in 5% (Düsseldorf/Paris) to 15% (Stockholm). Replacements of private fossil-fuel car trips by shared e-scooters are modest (1 to 7%), while electric car trips and private cycling are rarely replaced (up to 0.7 and 1 to 4%, respectively). The study shows that emissions of shared e-scooters, although on a different level, have a similar relation between use, servicing (repositioning) and total LCA emissions as shared e-bicycles: servicing and scope 3 emissions weigh heavy. Shared electric scooters have use-phase emissions of 2.8 g CO_2/pkm3 which is lower than most motorized mode alternatives, while total life cycle emissions amount to 97.5 g CO_2/pkm. Krauss et al. conclude that shared e-scooters reduce CO_2 emissions compared to the emissions of the modes which would be used otherwise in all six cities, in the non-European ones (Seattle and Melbourne). Overall, shared scooters have higher CO_2 emissions due to production and maintenance from shorter life cycles compared to privately owned vehicles. While shared electric scooters can reduce CO_2 when replacing high-emission vehicles, their total impact depends on their entire life cycle. All the mentioned studies have been summarized in Appendix 2.4.

Towards the electric shared car

Baptista et al. (2014) examine carsharing in Lisbon, Portugal, reporting reduced car ownership, parking demand, and vehicle costs. It further finds that within the carsharing fleet, shifting from conventional shared cars to hybrid and electric vehicles (EVs) can reduce energy consumption by 35 and 47%, respectively, along with CO_2 emissions by approximately 35 and 65%. These results reflect vehicle technology improvement, not account for modal shifts; therefore, the total city-wide emissions would be lower.

Martin and Shaheen (2016) examined the effects of conventional and electric car sharing on vehicle ownership, car miles traveled (CMT), and CO_2 emissions in five U.S. cities. They found that electric car sharing reduced total CMT, while conventional car sharing increased it. In San Diego, conventional car sharing had a more significant CMT reduction than electric, with each shared EV replacing fewer cars (1–7) compared to conventional (2–11). This led to a CMT change of −7% in San Diego versus −6% to −16% elsewhere. Overall, car sharing removed about 28,000 cars, with 25% of electric car users shifting from public transport, 11% from private cars, and 34% from walking. CO_2 reductions were 6% per car-sharing household in San Diego, while conventional systems saw reductions of 4 to 18% in other cities, though specific data for electric carsharing were lacking.

Liao and Correia (2022) found that electric carsharing generates lower emissions per passenger-kilometer than conventional carsharing, partly due to the limited range of battery electric vehicles. While carsharing reduces driving distances and public transport use, it increases walking and encourages more active, sustainable modes. However, the average trip distance for electric carsharing is relatively short (2.7–3 km), indicating that e-bike sharing may be a more suitable alternative for these trips. The study did not provide specific CO_2 reduction percentages.

Jung and Koo (2018) showed that shifting from private to shared electric vehicles—particularly for delivery and one-way trips—can significantly increase usage and reduce emissions. Replacing 50% of gasoline stations with EV charging stations and vehicles can reduce CO_2 emissions by 64% annually, using the Dutch energy mix. Expanding charging infrastructure to 71.1% of gasoline/diesel stations can result in zero emissions from the modal shift. However, the net CO_2 impact also depends on the modes being replaced, as shifts from both private cars and public transit to car sharing may not fully offset emissions if they delay car ownership decisions. All the studies mentioned have been summarized in Appendix 2.5.

In summary, shifting from private cars to shared electric cars and micro-mobility options offers the potential for CO_2 reduction. However, achieving meaningful environmental benefits depends on effectively managing life cycle emissions and integrating these modes within sustainable urban mobility systems.

2.4 Mobility hubs concept, definition and characteristics

In recent years, the mobility hub concept has gained growing prominence in international transport planning as an emerging component of passenger transport systems (Geurs et al., 2022). Mobility hubs provide a sustainable alternative to car travel by integrating various shared mobility options in specific locations (Klanke, 2022). By combining shared services, mobility hubs promote shifts to emerging transportation modes (Aono, 2019) and play a crucial role in urban planning and transport policies (Weustenenk and Mingardo, 2023). Since their inception in Bremen in the late 1990s and the establishment of physical hubs in the early 2000s, mobility hubs have gained global popularity as a sustainable transportation solution (Arnold et al., 2023). While initially focused on emissions reduction, mobility hubs now contribute more broadly to local and national policies (Department for Business, Energy and Strategy, 2022; Weustenenk and Mingardo, 2023).

Recent empirical evidence further underlines the value of integrating shared mobility with public transport. For example, a societal cost–benefit analysis of the Dutch public transport bike system (OV-fiets) demonstrates that bike-sharing integrated with public transport can generate significant societal benefits, including improved first- and last-mile connectivity, increased public transport use, and positive environmental and welfare effects (Mbugua et al., 2025). Such findings reinforce the role of mobility hubs as key enablers of multimodal travel, enhancing public transport performance (Transport for Greater Manchester, 2019) while improving social accessibility (Nottingham City Council, 2020). Core objectives of mobility hubs therefore include equitable access to activities, stimulation of local economic activity, congestion reduction, and the promotion of shared mobility services (CoMoUK, 2019; Plymouth City Council, 2020).

Mobility hubs encompass a wide spectrum of types and scales, ranging from large, high-capacity hubs at major public transport nodes to small-scale, locally embedded facilities (Xanthopoulos et al., 2024). On the one hand, station-area mobility hubs—such as those developed around major railway stations—primarily function as regional or metropolitan interchange points, emphasizing high-quality integration between public transport and shared mobility services, including bike-sharing and carsharing. These hubs typically serve longer-distance and multimodal trips and play a strategic role in work-level accessibility (Torabi kachousangi et al., 2022).

On the other hand, neighborhood mobility hubs are smaller in scale and more closely embedded within residential areas, focusing on short-distance trips, daily activities, and local accessibility (Rongen et al., 2022). These hubs typically offer shared mobility modes that can be used for unimodal trips or function as first-mile solutions connecting users to higher-order public transport stations (Rongen et al., 2022). By doing so, neighborhood hubs provide flexible transport options for residents without access to a private car, supporting car-light lifestyles while facilitating access to medium- and long-distance travel (Rongen et al., 2022). Together, these different hub types illustrate that mobility hubs are not a one-size-fits-all concept but a flexible approach that can be tailored to spatial context, travel demand, and policy objectives.

Despite their growing importance, the concept of a mobility hub remains ambiguous, with no universally accepted definition (Blad et al., 2022; Rongen et al., 2022). Various terms and definitions exist in the literature (Aono, 2019; Claasen, 2019; CoMoUK, 2019; Miramontes et al., 2017; Van Rooij, 2020), reflecting differences in scale, function, and policy context. As an increasing attractive topic, mobility hubs have become central to numerous theses, academic publications, and planning practices, as shown in Table 2.3.

Typically, mobility hubs are defined as recognizable physical locations that offer a variety of amenities and provide a range of shared transport modes while being integrated into public transport networks, thus facilitating multimodal mobility (Aono, 2019; Claasen, 2019; CoMoUK, 2019; Miramontes et al., 2017; Van Rooij, 2020; Blad et al., 2022; Anderson et al., 2017; Bell, 2019; Bösehans et al., 2021; Coenegrachts et al., 2021; Frank et al., 2021; Vianen, 2022; Rongen et al., 2022). Common keywords in these definitions include *strategic locations*, *sustainable multiple transport modes, shared modes, shared mobility services, seamless mobility, mobility services, economic services, node, and place*.

Table 2.3: Examples of mobility hub definitions since 2020.

Examples of definitions used in Master thesis	
Li (2020)	A mobility hub is a physical place that integrates mobility functions and other facilities that benefit the neighbourhood. By providing a variety of sustainable travel options and living facilities, the mobility hub facilitates residents' travel and daily life.
Blad (2022)	The mobility hub is a place where multiple sustainable transport modes come together at one place, providing seamless connection between modes, additionally offering shared mobility, including other features, ranging from retail, workplaces to parcel pick-up points.
Van Gerrevink (2021)	A mobility hub is defined as a place where several (shared) modalities are combined. This could range from a station area including access/egress facilities to a small-scale hub with a few shared vehicles offered.

Vianen (2022)	A mobility hub is a recognizable place which offers a range of transport modes (e.g. carsharing, bike-sharing, bus etc.), but also other services (e.g. postal lockers, neighbourhood library, kiosk etc.). There are different hub sizes, varying from larger hubs like train stations which combine a lot of shared services and transport modes, to neighbourhood hubs which serve needs of people on a local level.
Examples of definitions used in academic publications	
Coenegrachts et al. (2021)	A location where shared mobility is concentrated. The shared mobility hub clusters different new and conventional mobility services at a physical location. Its functions, services, facilities, and infrastructure requirements depend on the local urban context, including the policy goals of the different stakeholders.
Examples of definitions used in the planning practice	
ALICE (2020)	A physical location that enables the transfer to the most optimal modality for the onward journey.
Arup (2020)	In the current transport system, mobility hubs are commonly seen as physical places that connect a variety of transport modes. A mobility hub can be anything from a bus stop and a bike sharing station to an inner-city main train station.
Witte et al. (2021)	A physical link between transport modes that – in addition to its mobility function – can also serve as focal point for spatial development.
Metropolitan Transportation Commission (2021)	Serving as a community anchor, a mobility hub is a welcoming environment that enables travellers of all backgrounds to access multiple transportation options and supportive amenities. Built on the backbone of frequent and high-capacity transit, mobility hubs offer a safe, comfortable, convenient, and accessible space to seamlessly transfer across different travel modes.
Advier (2021)	At a transport hub on neighbourhood level different sustainable and shared transport modes are linked with each other. Preferably, a mobility hub includes carsharing. Mobility hubs provide an easily accessible, visible and recognisable offer for end users. For policy makers, hubs represent a tool to enhance a shift towards sustainable transport and more efficient use of public space. Mobility hubs have primary elements like shared modes, bicycle parking, proximity to public/collective transport, easy access, branding, and secondary elements like storage facilities or meeting points for neighbourhood activities.

reisviahub.nl, (2021)	A hub is more than a transport node where people can transfer between modes. The emphasis is on experience: living climate, recognisability, information, time saving, positive surprise and integration with the environment. It is the ideal place to link several facilities together. Think of facilities for travellers only, such as a kiosk, water tap, Wi-Fi, or transfer point for the hub taxi. But also think of general facilities such as a health centre, a community school, or a shop. In short, a place where everything comes together.
Geurs et al. (2022)	A mobility hub is a physical location where different shared transport options are offered at permanent, dedicated and well-visible and where public or collective transport is available at walking distance.

2.4.1 Role of mobility hubs to reduce CO_2 emissions

Mobility hubs play a critical role in enhancing the effectiveness of shared and emerging transport modes as sustainable alternatives to private car use. Beyond their functional purpose, hubs have the potential to reshape societal attitudes towards shared mobility (Karlsson et al., 2017). In some cultures, private car ownership continues to serve as a symbol of social status, while shared modes are perceived as low-status alternatives (Pojani et al., 2018; Chun et al., 2019). Empirical evidence from Germany suggests that hubs raise awareness and normalize shared mobility as a mainstream alternative (Miramontes et al., 2017). In this sense, mobility hubs act not only as infrastructural interventions but also as cultural and behavioural catalysts.

Functioning as centralized and accessible nodes, mobility hubs facilitate multimodal integration and strengthen the convenience of sustainable travel (Aono, 2019). Rather than directly enforcing behavioral change, they reduce barriers to adopting alternatives by improving connectivity and minimizing dependence on private cars (e.g., Liao and Correia, 2022; Alarcos Andreu, 2017; Miramontes et al., 2017; Pfertner, 2017; Claasen, 2019; Knippenberg, 2019; Van Rooij, 2020). Studies highlight that hubs increase public transport usage, improve first- and last-mile connections, and alleviate parking pressures by consolidating shared vehicles in accessible locations (Blad et al., 2022; Jorritsma et al., 2021; Kim, 2021). Pfertner (2017) reports that 83% of users considered mobility hubs sufficient to eliminate the need for private car ownership, offering convenient access to multiple transport options. Evidence further proofed that mobility hubs facilitate a shift away from private car ownership (Karbaumer, 2018; Liao and Correia, 2022; Storme et al., 2021), while Liao and Correia (2022) found that many users sold or postponed the purchase of cars after adopting hub-based services. These outcomes illustrate the capacity of hubs to enable modal shifts at scale.

From an environmental perspective, mobility hubs address several structural barriers that diminish the carbon-reduction potential of shared mobility. Although emerging modes can reduce emissions when substituting car travel, their benefits are often offset when they replace more sustainable modes, such as walking, cycling, or public transport (Hollingsworth et al., 2019; de Bortoli and Christoforou, 2020; D'Almeida et al., 2021; Reck et al., 2022; Weschke et al., 2022). Campbell et al. (2016), for example, illustrates that bike sharing in Beijing often substitutes bus trips in dense urban districts, while e-bike sharing complements public transport in suburban areas. These findings underscore the importance of context-sensitive hub design in maximizing carbon-reduction outcomes. Moreover, shared micromobility services face challenges such as short vehicle lifespans due to vandalism and misuse, which elevate life-cycle emissions per passenger-kilometre. By offering secure parking, charging facilities, and improved oversight, hubs extend vehicle lifespans, reduce production-related emissions, and mitigate these indirect environmental costs (Luo et al., 2019; O'Kane, 2018).

Another critical dimension lies in reducing the inefficiencies associated with vehicle rebalancing. The frequent repositioning of shared bikes, scooters, or cars to meet fluctuating demand is often carried out with fossil-fuel vans, which can outweigh the operational emission savings of shared fleets. Strategically designed hubs can significantly reduce the need for rebalancing by consolidating vehicles in high-demand areas, while also supporting complementary strategies such as incentivized user returns, bundled fleet operations, and electrified repositioning logistics (de Bortoli, 2021). Collectively, these measures reduce the energy intensity of fleet management and strengthen the environmental case for shared mobility.

Overall, mobility hubs represent a multifaceted solution to urban transport and climate challenges. By integrating diverse transport services, reducing inefficiencies, and improving both user experience and social acceptance, hubs strengthen the carbon-reduction potential of shared mobility. When strategically placed and supported by enabling policy frameworks, hubs can extend beyond niche interventions to become a mainstream contributor to sustainable, low-carbon urban transport systems.

2.5 Discussion and Conclusions

This review synthesizes current knowledge on the role of emerging transport modes—including micromobility, shared mobility, and electric mobility—in reducing urban CO_2 emissions. Using a Life Cycle Assessment (LCA)–based analytical perspective, complemented by the Dynamic Mitigation framework, the analysis shows that while these modes can contribute to decarbonization by displacing private car use, their environmental benefits are not inherent or guaranteed. Instead, net CO_2 outcomes depend on how modal substitution patterns, operational logistics, and vehicle life-cycle characteristics interact within specific urban contexts.

2.5.1 Discussion

The transition of shared and electric mobility from niche applications to mainstream urban transport solutions is a non-linear and conditional process. The reviewed studies demonstrate that emerging mobility modes possess substantial potential to reduce private car dependency, but their realized environmental effectiveness is contingent on managing systemic trade-offs across the transport system rather than on technological improvements alone.

Trade-offs and rebound effects in the CO_2 performance of emerging mobility

A robust finding across the literature is that CO_2 reduction benefits are frequently undermined by unproductive modal substitution. Shared micromobility services often replace walking, cycling, or public transport trips rather than private car travel. When such substitution patterns dominate, net emissions may increase despite low or zero tailpipe emissions. In addition, multiple life-cycle studies document that operational rebound effects—most notably those associated with fleet rebalancing, maintenance, and premature vehicle replacement—can offset or even negate anticipated emission savings.

Empirical evidence indicates that shifts from private cars to shared cars or private electric bicycles yield the most consistent CO_2 reductions. In contrast, shared micromobility systems frequently exhibit higher life-cycle emissions per passenger-kilometer, an outcome largely attributable not to vehicle propulsion technology but to indirect emissions arising from logistics and shortened vehicle lifespans. These findings demonstrate that decarbonization outcomes depend more on system configuration and usage patterns than on vehicle technology alone.

Mobility hubs as systematic integrator of life-cycle emissions

The reviewed literature suggests that mobility hubs *may address* structural factors constraining shared mobility performance, primarily through mechanisms inferred from station-based systems and centralized fleet operations. However, it is important to distinguish between empirically demonstrated effects and mechanisms inferred from related evidence. Life-cycle studies consistently show that vehicle production accounts for a dominant share of emissions in shared micromobility systems, often exceeding 70–90% of total life-cycle CO_2 emissions. As a result, vehicle lifespan emerges as a decisive determinant of environmental performance. While direct empirical studies isolating the CO_2 impact of mobility hubs remain limited, evidence from station-based and centrally managed systems suggests that secure and organized docking environments are associated with lower vandalism rates and longer service lifetimes. These findings support the inference that mobility hubs may contribute indirectly to emission reductions by extending vehicle lifespans and amortizing production-related emissions over greater travel output.

Similarly, multiple studies document that rebalancing operations—particularly when conducted with fossil-fuel service vehicles—represent a substantial source of indirect emissions. Centralized fleet organization and reduced redistribution distances, which are characteristic of hub-based or station-based systems, are consistently associated with lower logistical emissions. While these effects are well documented for station-based systems, their direct attribution to mobility hubs as integrated infrastructures remains an area where empirical evidence is still emerging.

Conceptual implications: mobility hubs as conditional system-level enablers

Beyond operational efficiencies, the review suggests that mobility hubs may function as system-level enablers within broader urban transport transitions. By improving visibility, intermodal accessibility, and spatial integration, hubs have the potential to reduce practical barriers to combining shared mobility with public transport and to support behavioural shifts away from private car ownership. However, evidence for such behavioural effects is largely indirect and context-dependent, drawing primarily on studies of intermodal integration rather than on evaluations of mobility hubs per se.

Accordingly, mobility hubs should not be interpreted as inherently decarbonizing interventions. Rather, their potential contribution to CO_2 reduction appears conditional on their ability to (i) increase substitution away from private car use, (ii) reduce indirect operational emissions, and (iii) support longer vehicle lifespans within shared mobility systems.

Methodological barriers and the standardization gap

A central limitation identified across the reviewed literature is the persistent lack of standardized CO_2 accounting. Differences in system boundaries, functional units, and treatment of indirect emissions significantly constrain cross-study comparability. Moreover, geographical heterogeneity, particularly in electricity generation mixes, introduces substantial variation in the carbon performance of electric and shared mobility systems. Identical interventions may therefore yield divergent outcomes across cities and regions.

These limitations underscore the need for future research to move beyond generalized performance claims. Context-sensitive threshold analyses are required to identify the specific car-replacement rates and operational conditions necessary to offset life-cycle emissions under local energy and mobility contexts. Such analyses would enable policymakers and planners to shift from uniform deployment strategies toward locally optimized mobility hub implementations.

2.5.2 Recommendations for research and policymaking

To advance shared mobility from niche to mainstream, we propose the following recommendations:

Focus on replacing car trips: Cities should place mobility hubs in areas where they are most likely to replace car use (such as the edges of the city). If hubs are only located near existing train stations, they might simply replace walking or cycling instead of removing cars from the road.

Standardized emission data: To fix the lack of clear data found in this review, city authorities should require shared mobility companies to report their total CO_2 impact. This must include not just the trips themselves, but also the emissions from maintenance vans and the vehicles used to move bikes and scooters around.

Incentives for hub-to-hub trips: Policies should encourage users and companies to move vehicles between hubs. This strategy minimizes the logistical burden associated with fleet redistribution—specifically the secondary emissions from service vans. By reducing the intensity of motorized rebalancing, hubs help prevent operational offsets, where the carbon costs of managing the shared system threaten to negate the environmental benefits gained from the modal shift.

2.5.3 Conclusion

This review demonstrates that emerging transport modes can contribute to urban CO_2 reduction, but only under clearly defined conditions. Their environmental performance is shaped by modal substitution patterns, operational logistics, vehicle lifespans, and local energy systems. Mobility hubs emerge from literature not as a guaranteed solution, but as a potentially important enabling infrastructure that may mitigate life cycle and operational inefficiencies when appropriately designed and contextually deployed.

Rather than demonstrating that mobility hubs inherently reduce CO_2 emissions, this review clarifies the conditions under which hubs are most likely to contribute positively to urban decarbonization—specifically when they support high rates of private car substitution, reduce indirect emissions from rebalancing and maintenance, and operate within low-carbon electricity systems. Recognizing these conditions is essential for translating the theoretical potential of emerging mobility systems into sustained, system-wide emission reductions.

Chapter 3:

Passengers Preferences for Shared Access/Egress Transport Modes

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Passengers Preferences for Shared Access/Egress Transport Modes

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Building on the previous chapter's discussion on modal shift and emission reduction, this chapter shifts focus to travel behaviour at multimodal hubs, specifically, passenger preferences for emerging access and egress transport modes at railway stations. First- and last-mile connectivity remains a major challenge for public transport systems, often influencing whether travellers choose sustainable modes over private cars. Shared modes services can fill this gap, but their effectiveness depends on user acceptance, perceived convenience, and accessibility.

This chapter investigates passenger preferences for shared access and egress modes—such as shared bikes, e-scooters, e-steps, and autonomous vehicles—at Delft Campus railway station in the Netherlands. Through a stated preference experiment, the study examines behavioural responses to factors including travel time, cost, availability, weather conditions, luggage handling, and socio-demographic characteristics.

The findings provide valuable insights into the behavioural determinants of mode choice at transit nodes, supporting the design of integrated, user-centric mobility hubs that can enhance public transport utilization.

The chapter is structured as follows: Section 3.2 elaborates on the key factors influencing passenger preferences in first/last mile travel, reviews the limited literature, and identifies the research gaps. Section 3.3 details the research methodology, while Section 3.6 and 3.7 describe the survey design and the stated choice experiment. Section 3.8 presents the data collection and analysis results, followed by market share prediction in Section 3.9. The chapter concludes in Section 3.10.

This chapter is based on the following paper:

Torabi Kachousangi. F., Araghi,Y., van Oort, N, Hoogendoorn, S. (2022) Passengers preferences for using emerging modes as first/last mile transport to and from a multimodal hub case study Delft Campus railway station, *Case Studies on Transport Policy,* Volume 10, Issue 1, 2022, Pages 300-314, ISSN 2213-624X, https://doi.org/10.1016/j.cstp.12.011.

3.1 Introduction

Transport literature highly values public transport (PT) systems as increasing use of this mode (PT) can be the answer to congestion, pollution, and better use of infrastructure (Newman, 1995, HiTrans, 2005, United Nations Economic Commission for Europe, 2015, Yañez-Pagans et al., 2018, Van Oort and Yap, 2021). Public transport systems will be an inseparable part of urban life in the coming years. To have more liveable and sustainable cities, the ongoing challenge of improving PT systems, including the first and last mile of PT trips, should be considered (Van Kuijk et al., 2021). The availability and effectiveness of the access/ egress modes may have essential impacts on the uptake of public transport systems and may persuade more people to shift from private modes to PT. These factors need further and more detailed analysis for the case of small and medium multimodal stations and hubs. Furthermore, there is also a lack of understanding of contextual factors such as the impact of weather conditions and carrying luggage on how people may choose their first last mile modes.

Ridership of public transportation is highly influenced by travel time (Murray et al., 1998 and Murray, 2001), distance, costs (Arentze & Molin; 2013, Yap et al., 2016; Lau and Susilawati, 2021; Van Kuijk et al., 2021), and service-quality attributes (Arentze & Molin; 2013) such as the quality of access and egress (Givoni and Rietveld, 2007; Brons et al.,2009; Abe 2021). The first two factors highly depend on the accessibility of the public transportation system (Goel and Tiwari, 2016). In addition, the first/last mile of the trip plays a determinant role in transportation mode preferences (Wang and Odini, 2012). As a general term, mobility hubs are defined as the main transit access points in multimodal transportation planning processes (Hochmair, 2015). Transport planners have realised that for a hub to thrive, it must offer a seamless multimodal trip. A multimodal trip is more than one mode in a traveller's trip, including walking or cycling, and this change of modes between the main travel modes. A multimodal hub as a type of transit mobility hub refers to a station that is usually served by train or metro, with direct connections to different types of transport modes, such as a car (private and shared), bicycle (private and shared), other public transport and walking, which provides an integrated and a sustainable mobility network (Venhoeven, 2012). Thus, these hubs can offer multiple modes for different users and different travel purposes, where people can transfer from one mode to another directly (Henry and Marsh, 2008).

Shared mobility replaces, complements, and integrates transport modes on urban networks (Kong et al., 2020). In addition, supplying shared-micro-mobility at the last mile benefits transit riders (Baek et al., 2021). Different researchers have argued that new transportation concepts such as bicycle sharing (Wu et al., 2019; Ma et al. 2020),e-scooter sharing (Baek et al. 2021), car-sharing (Correia and Antunes, 2012; Jorge and Correia, 2013) and automated vehicles (Chen et al., 2020; Abe, 2021) are crucial to providing a seamless door to door journey experience to passengers (Scheltes, 2015). The introduction of these new services at the first/last mile of the trip potentially improves the attractiveness of multimodal hubs due to their favourable characteristics, such as flexibility. However, Scheltes and Correia (2017) believe that this access/egress stage is still not well-utilised, and travellers struggle with inconvenient transport modes for the first/last part of their journey.

Although the preferences of travellers on transport modes have been studied (Ohnemus and Perl, 2016; Yap et al., 2016; Shaheen and Chen, 2016; Scheltes and Correia 2017), still there is limited knowledge about automated vehicles (Abe 2021) and shared modes preferences in the first-last mile of the trip (Van Kuijk et al., 2021). It is not clarified yet how passengers' modal choices would differ by introducing emerging modes. In addition, influential factors to modal choice such as the impact of context variables (weather and amount of hand luggage) on travellers' preferences for different types of access/egress modes remain a gap in the literature, which will be discussed in this work.

This research aims to empirically reveal travellers' (stated) preferences regarding potential new access/egress modes connected to a local hub. The objective of this paper is to look at the role of these access/egress modes in passengers demand of multimodal hubs and analyses the preferences of urban rail users for their first-last mile. In this study, one relatively well-known access/egress mode (bicycle sharing) and four emerging access/egress modes, namely shared e-scooters (both standing and sitting), individual automated vehicles, and collective automated vehicles (in the form of driverless vans or minibuses), and their related attributes are considered. Furthermore, we introduce two context variables (weather and amount of luggage) to capture travellers' preferences on different access/egress modes from a local hub under varying conditions. Therefore, this study may add to our understanding of factors contributing to the (re)development of the local hub areas regarding access/egress facilities and services.

To determine people's preferences for new transportation modes for access/egress from hubs, a stated choice experiment as the most suitable method has been performed. A stated choice survey provides a hypothetical situation for respondents, who are required to decide on a preferred mode of transport, even a not existing mode, considering different attributes and contexts from a range of available options.

This study uses the Delft Campus railway station in Delft, a bicycle-friendly city in the West of the Netherlands, as a case of an emerging small multimodal hub that is located close to TU Delft University. This case study aims to see the impact of emerging modes on travellers' choice to use PT and if the contextual situations significantly impact their behaviour. Therefore, this case study aims to evaluate how emerging modes and context indicators impact the modal choice of travellers in multimodal hubs, which help to predict access/egress mode choices of travellers at small and medium stations for a short time distance. Furthermore, with this case study, we aim to provide insight for transport planners and public transport providers on how the merging access egress modes may facilitate higher utilisation of PT.

The paper will outline the characteristics of the multimodal hub concept and passenger behaviours accessing/egressing the station in the literature review section. The case study and survey are discussed in the third section, which presents the methodology of this paper. The analysis of the collected surveys and the discrete choice model results will be discussed in section 4, and conclusions and the discussion will be presented in the last section.

3.2 Literature review

In this research, we seek to find the impact of emerging modes and context indicators such as weather and luggage on the modal choice of travellers in multimodal hubs. We reviewed 40 relevant publications between the years 2010-2021. This section provides a brief review of the different aspects relevant to this topic.

We will first describe the characteristics of a multimodal hub based on literature to understand its essential role in future transport systems. Secondly, the passenger behaviour accessing and egressing from multimodal hubs will be explained in two terms: socio-demographic characteristics and unobserved or latent variables that reveal travel characteristics. Subsequently, we consider the characteristics of the access/egress trip, the impact of weather and luggage on the access/egress trips, and finally, the role of technology; emerging alternative modes and their impact on travellers' access/egress decisions. The aspects considered are relevant and essential for designing the survey in this study.

3.2.1 Characteristics of Multimodal Hubs

A multimodal public transport trip generally consists of three stages. The first and the last stages are described as access and egress miles, and the central part is the middle of the trip. Access modes and egress modes refer to transport modes used in the first part and the last stage of a journey, respectively, which can be walking, cycling, bus, tram, metro, taxi, shared car, and soon collective or personal automated vehicles (Krygsman, 2004, Yap et al., 2016, Shaheen & Chen, 2016).

According to (Bertolini 2008), a hub is composed of two aspects, a (network) node (for interchanges with other types of mobilities) and a place (for serving services for passengers). A multimodal station as a significant node can offer multiple modes for different users and different travel purposes. This primary mode is usually the train or metro, and multiple other modes, such as walking, cycling, cars, and public transport, where people can access from one mode to another directly (Henry and Marsh, 2008).

A multimodal hub is a place where the access/egress services, modes and transportation systems are connected, and interfaces occur among them (Henry and Marsh, 2008). Generally, the idea behind a multimodal hub is to seek optimal travel efficiency by taking advantage of different modes while minimising their negative impacts (Pitsiava-Latinopoulou & Iordanopoulos, 2012). Multimodal hubs may improve community liveability by incorporating land use, demographic, socio-economic, environmental, health, security, and public policy issues together in a holistic transport policy approach (Scott et al., 2013). For instance, providing facilities at a multimodal hub increases access and choice by positively coordinating between different modes (Scott et al., 2013). A well-designed multimodal hub plays a role in developing the station's surroundings and attracting many users and is a catalyst for urban development in metropolises, and medium and small cities (Triggianese et al., 2018).

Generally, multimodal hubs can be divided into three areas: the arrival/departure area of the primary mode, the facilities area, and the access/egress area possibly containing multiple (new) modes. The last two areas can be designed based on the services offered, transportation modes and allocated spaces, and expected hub usage, which means passengers' user preferences and choice behaviour.

3.2.2 Passenger Behaviour Accessing to and Egressing from Multimodal Hubs

Scheltes (2015) states that although the last part of the trip is a relatively small distance, a high proportion of total travel time is spent at this stage. Furthermore, it is mentioned that inflexibility, unavailability, and the absence of a seamless mobility experience for passengers cause considerable disutility in a public transport trip for it to be competitive with a car.

Influential factors to modal choices for accessing and egressing the railway stations are essential (Halldórsdóttir et al., 2017). Therefore, access/egress mode choice has recently been getting more attention in transport literature. However, there is no uniform approach or definition of access/egress modal choice by passengers. It depends on the aim/scope of each research (De Witte et al., 2013). An overview of the selected literature for this study considering access/egress mode choice factors published after 2010 (except for some references regarding carrying luggage) is presented in Table 3.1.

Table 3.1: Overview of literature focusing on access/egress modes

Authors	**Year**	**Country**	**Type of station**	**Multimodal stages (HE / MS / AE)** [1]		**Modes**
Abe	2021	Tokyo	Railway stations	HE, MS, AE	6	Bus, car driver, car passenger, bicycle/motorcycle, walk and AV
Baek et al.	2021	Seoul	Subway	AE	3	Town bus, e-scooter sharing, walking
Kim & Cho	2021	Seoul	-	-	1	shared bicycles
Lau & Susilawati	2021	Malaysia	Light Rail Transit (LRT) and Mass Rapid Transit (MRT	HE, MS, AE	2	Shared Autonomous vehicles, PT
Van Kuijk et al.	2021	Netherlands	Bus & tram	MS, AE	4	shared bicycles, e-bikes, e-scooters, and e-mopeds
Aguilera-García et al.	2020	Spain	-	-	9	Private car, private moped/motorcycle, bike, walking, Public transport, car-sharing, scooter-sharing, bike-sharing, taxi and Ridesourcing
Alonso-González	2020	Netherlands	-	-		Pooled on-demand services
Chen et al.	2020		Metro	HE	1	Autonomous vehicles
Kong et al.	2020	USA	-	-	2	Shared bicycle, PT
Jiao & Bai	2020	Austin, TX	-	-	1	shared e-scooter
Van Mil et al.	2020	Netherlands	Railway stations	HE, MS	1	Bicycle

[1] home-end (HE) stage, main stage (MS) and activity-end (AE) stage can be defined for any multimodal trips.

Yan et al	2020	China	metro station		1	dockless bike-sharing service
Wu et al.	2019	Taiwan	Metro-train stations	-	1	Shared bicycle
Ton et al.	2019	Netherlands	-	-	4	Car, PT, bicycle and walk
Stam	2019	Netherlands	Railway stations	HE, MS, AE	9	Private bicycle, Shared bicycle, Private e-scooter, Shared e-scooter, Private on-board vehicle, Shared car, Bus, Individual on-demand rides, Collective on-demand rides
Bronsvoort	2019	Netherlands	Bus stations	HE, MS, AE	4	Express bus, Bus, shared bicycle, Flexi
Mo et al.	2018	Singapore	Mass Rapid Transit (MRT) station	HE, AE	3	Walking, bus and LRT
Shelat et al.	2018	Netherlands	Railway stations	HE, MS, AE	1	Bicycle
Frei et al.	2017	USA			3	Traditional Transit, car, flex
Halldórsdóttir et al.	2017	Copenhagen	Railway stations	HE, AE	5	Walking, bicycle, car driver, car passenger and bus
Brand et al.	2017	Netherlands	Bus stations	HE, AE	4	Bus, BRT, walking and cycling
Ji et al.	2017	China	Railway stations	HE	5	car, bus, walk, private bike and shared bike
Shaheen & Chen	2016	-	-	-	4	Shared mobility; Car sharing, bike sharing, on-demand ride services, and micro-transit
Yap et al.	2016	Netherlands	Railway stations	AE	4	BTM, bicycle, AV car-sharing and AV automatically driven
Goel & Tiwari	2016	India	Metro stations	HE, AE	7	Walking, bicycle, cycle-rickshaw, auto-rickshaw, 2W, car and bus
Scheltes	2015	Netherlands	Railway stations	HE, AE	1	Automated vehicles
Puello & Geurs	2015	Netherlands	Railway stations	HE	1	Bicycle
Tran et al.	2014	Vietnam	Mass transit stations	HE	4	Walking, bicycle, motorcycle (driver) and motorcycle (passenger)
Ryley et al.	2014	UK	-	-	3	Bus and DRT
Creemers et al.	2014	Belgium	Railway stations, BTM stations	HE, MS, AE	3	Car, BTM and slow
Chakour & Eluru	2013	Canada	Railway stations	HE	4	Drive alone, shared ride, transit and active transportation

De Witte et al.	2013	-	-	HE, MS, AE	-	Different modes
Arentze & Molin	2013	Netherlands	Stations	HE, MS, AE	4	Walking, bicycle, bus/tram and PT bike
Wen et al.	2012	Taiwan	High-speed rail (HSR) stations	HE	8	City bus, train, car driver, car passenger, motorcycle driver, motorcycle passenger, taxi and shuttle bus
Correia & Antunes	2012	Portugal	Carsharing stations	-	1	Carsharing
Wang & Odoni	2012	-	Rail Station	-	1	Different
Martin & Shaheen	2011	Canada and USA	-	-	1	Car sharing
Molin & Timmerman	2010	Netherlands	Railway stations	AE	7	Public transport, taxi, train taxi, PT bike, bike in a train, bike at station and Greenwheels
Martin et al.	2010	USA	-	-	1	Carsharing

The literature that focuses on the home-end and activity-end stages of a multimodal trip can be classified into the following two categories:

Literature focuses on socio-demographic characteristics, such as gender, age, occupation/income, driving license, vehicle ownership, car availability, household size, number of workers, other motorists, season tickets, and type of train user.

Creemers et al. (2014) showed that women tend to use private cars and hesitate to use slow access/egress modes of transport. Ji et al. (2017) noted that women like to use private bicycles rather than public bicycles to access railway stations. Men tend to use buses less on activity-end trips (Halldórsdóha et al., 2017), they prefer to ride motorcycles (Tran et al., 2014). Van Kuijk et al. (2021) concluded that age is considered a reliable determinant for using shared mode in the last mile. Moreover, Yan et al. (2020) discovered a positive correlation between young age and shared bicycles in the last mile. Jiao and Bai (2020) found that young, male, and highly educated people are willing to use shared e-scooters. Although walking and riding motorcycles are more popular for older people as access modes to stations (Tran et al., 2014), Ji et al. (2017) found that shared bikes are not a popular mode among older and low-income groups. On the other hand, Frei et al. (2017) interestingly found that older travellers who earn $150,000 per year are significantly likely to use flexible and traditional transit.

Furthermore, there is a direct relationship between income and the use of private cars as opposed to public transport (De Witte et al., 2013). There is a negative correlation between income and willingness to use shared e-scooters and e-steps (Jiao and Bai, 2020); (Aguilera-García et al., 2020). Full-time students are willing to use buses (Halldórsdóttir et al., 2017) with no preference for bicycles at home-end trips (Puello and Geurs, 2015). While possession of a driving license typically increases private car usage (Creemers et al., 2014), owning a vehicle or car's availability also increases the shares of car use for the first/last mile of the trip (Halldórsdóttir et al., 2017 and Goel & Tiwari, 2016). In addition, motorcycle ownership decreases the probability of walking choice, and car availability also decreases the share of cycling (Puello and Geurs, 2015). De Witte et al. (2013) concluded car ownership is the second determinant for modal choice after the age when a car is available.

Having a season ticket encourages passengers to use public transport since it is valid (Halldórsdóttir et al., 2017). Employees could also be motivated to use public transportation since they provide transit passes (De Witte et al., 2013). Yap et al. (2016) presented that first-class train users prefer to experience automated vehicles (AVs) at stations if they are available. By contrast, bicycles and BTM (Bus, Tram, Metro) are the first preference by second-class train users in general. Finally, families with more children dislike cycling and motorcycles (Tran et al., 2014).

Literature has addressed unobserved or latent variables that reveal travel characteristics such as travellers' attitudes, perceptions, and preferences/habits.

Alonso-González et al. (2020), who studied the attitudes towards demand-responsive transport and mobility-as-a-service, discovered that young users have more positive attitudes towards sharing and multimodal lifestyles in general. De Witte et al. (2013) compared the perception of car use and public transport in terms of freedom, independence, speed, price, protection, and prestige, and concluded that public transport was perceived less favourably. Yap et al. (2016) argued that when examining the adoption of autonomous vehicles (AVs), which are not yet widely used, two psychological factors are particularly important: (1) trust in AV technology and (2) passengers' attitudes towards the sustainability of AVs. They further found that in-vehicle travel time is perceived differently in autonomous vehicles than in manually driven vehicles, with travel time in autonomous vehicles being viewed less favourably. Arentze & Molin (2013) described travellers differently perceiving the time attributes and travel costs. Paulley et al. (2006) argued that waiting time is also differently perceived and affected by comfort, cleanliness, safety, and weather.

In addition, the attitude towards the environment of the hub, the perceived connection of departure stations, and the perceived quality of facilities for bicycles highly promote the use of cycling (Puello and Geurs, 2015). The travel experience in the first and last mile effects on satisfaction and willingness of people to use PT (Van Kuijk et al., 2021).

Passengers usually prefer quality services such as reliability, safety, comfort, health, convenience, and image/status (Arentze and Molin (2013). Drivers who are not satisfied with driving for reasons such as traffic would be potential targets for flexible services, as Frei et al., 2017 noted.

3.2.3 Characteristics of the access/egress trip

De Witte et al., 2013 argued that faster transport modes are preferred for longer distances in general. Thus, increasing the distance to/from transit nodes will increase the shares of motorised transport modes (Stam, 2019). For example, buses are preferred for longer access/egress distances (Mo et al., 2018). In contrast, the choice of PT over the car is directly related to increasing trip distance (Goel & Tiwari, 2016). Molin & Timmermans (2010) found that distance and the probability of walking have an opposite relationship, whereas, with increasing distance, the choice of PT increases. Generally, passengers would travel shorter distances at the last mile by walking; conversely, longer first miles are accepted by cycling (Brand et al., 2017). However, Wu et al. (2019) presented that trips of shorter distances are more likely to be completed by cycling (bike-sharing) and e-step sharing (Baek et al., 2021) relative to other transit services. In general, it can be seen that as the distance increases, the probability of cycling to the railway station decreases (Puello & Geurs, 2015).

Based on a literature review conducted by De Witte et al. (2013), trip purpose is the primary determinant of mode choice. Although different access/egress modes can be selected for different trip purposes such as shopping, leisure and work (Halldórsdóttir et al., 2017), cars and taxi alternatives are generally used in business trips, Greenwheels for recreational trips (Molin & Timmermans, 2010), and shared bikes for school- or work-related trips (Ji et al., 2017). Travelling with a companion decreases the probability of bicycle, walking, and bus choices and increases the chance of car usage (Halldórsdóttir et al., 2017). Moreover, according to the research of Molin and Timmermans (2010), travelling with others increases the choice of slow transport modes and cars.

Departure time determines the access mode to the station (De Witte et al., 2013). Molin & Timmermans (2010) found that the share of public transport and slow transport are decreased in off-peak hours like evening, due to low-level services and lack of convenience.

Generally, distance, travel time, and travel cost have direct mutual effects. (Chakour & Eluru, 2013 and Halldórsdóttir et al., 2017 believed that long travel time negatively affects passengers' modal choice. Ryley et al. (2014) valued cost, travel time, and wait time for DRT as the most valuable attributes to use current modes. Lau and Susilawati (2021) research showed that the use of shared AVs directly relates to waiting time and cost; decreasing waiting time and cost for shared AVs results in increased shared AV ridership. They found that, when shared AVs are available at a low cost, passengers tend to prefer using them for the entire trip rather than solely for first- and last-mile connections, instead of integrating them with local public transport (Lau and Susilawati, 2021). In addition, Ryley et al. (2014) noted that arrival time is an essential factor for a successful DRT service. Halldórsdóttir et al. (2017) found that reductions in walking, cycling, and in-vehicle travel times increased the likelihood of bus services being used as access and egress modes for first- and last-mile trips. Moreover, Frei et al. (2017) highlighted the importance of travel time and argued that a substantial shift from private car use to public transport would increase travel times for former car users.

Wen et al. (2012) stated that the cost of access modes determines the modal choice for the majority. Van Kuijk et al. (2021) found that travel cost negatively affects willingness to use a shared mode in the last mile trip. The value of travel time and costs are captured by the psychological factors as Yap et al. (2016) discussed along with the level of services (e.g. comfort and convenience, safety, protection, and security) (Ortuzar & Willumsen, 2011). However, Jorge & Correia (2013) depicted a direct relationship between service characteristics and demand patterns for car-sharing services.

Chakour & Eluru (2013) use the term availability of transit services by addressing the 'supply' of transit, and they further study the effects of availability on modal choice at both the origin and destination. Other studies refer to the availability of modes as an essential indicator to assess an urban area's commitment to transit (Kriger et al., 2015). McNally (2008) and Jayasinghe et al. (2017) argued that various available modes play a crucial role in planning an urban transportation system and predicting travel demand. Camagni et al. (2002) argued that by increasing mode frequencies, the share of public transport would be increased and the comparative efficiency of public transport. Furthermore, fleet size directly affects the availability of vehicles, especially at railway stations. The availability of bicycles at stations increases the utility of this mode as well (Bronsvoort, 2019). Wang and Odoni (2012) concluded that the unavailability of services at the last mile negatively affects the use of public transport in urban areas, especially for students, seniors, and disabled users.

3.2.4 Impact of weather and luggage on the access/egress trips

Slow transit modes mainly cover the first and the last mile of the trip; accordingly, weather plays a vital role in modal choice as an environmental issue (Keijer and Rietveld, 2000; Rietveld, 2000). Changing weather conditions will change access to transport modes, significantly affecting modal choice since non-motorised modes are considered (De Witte et al., 2013). Besides weather, temporal variations also determine bike-share ridership (Kim and Cho, 2021). Fyrhi and Hjorthol (2009) compared summer activities done mainly by bike and winter activities by walking. Ton et al. (2019) found that summer activities are positively associated with walking, and cycling has no significant relationship. Ton et al. (2019) concluded that weather has a limited impact on active mode use such as walking and cycling.

On the other hand, slow transport modes such as walking and cycling are preferred in dry weather, on familiar routes with no heavy luggage (De Witte et al., 2013 and Molin & Timmermans, 2010). Molin & Timmermans (2010) argued that weather conditions travel companions, and the amount of luggage are the influential and prominent variables in mode choice decisions because of the need for transferring. They identified that carrying heavy luggage on trips increases the need for motorised modes, especially taxi alternatives instead of slow modes, and decreases train and consequently multimodal trips. Regarding the luggage, Frei et al. 2017 pointed to it as a negative attribute for transit commuters who would walk to the station and wait in cold weather or busy transit.

De Witte et al. (2013) concluded that variables such as weather conditions and luggage are often overlooked in mode choice studies, despite evidence from Molin and Timmermans (2010) suggesting that they should receive greater attention in traffic flow simulation models.

3.2.5 Technology; Emerging alternative modes and their impact on access/egress

To improve urban mobility problems, from a technological perspective, the development of cleaner energies and more efficient transportation systems have been considered in recent decades (Martinez & Viegas, 2017). Accordingly, due to the new technological developments in recent years and also environmental concerns, the access/egress transport alternatives have been changed from private vehicles to more shared systems (passengers or vehicles) (Wu et al. 2019), as well as automated mobility (parking less), and electric mobility (Stam, 2019). Lau and Susilawati (2021) found that integrating shared AVs and PT encourages a modal shift from private cars to shared AVs while increasing PT ridership. Similarly, bike-sharing can both compete with and complement public transport and has considerable potential as a first- and last-mile travel option (Kong et al., 2020). Likewise, the provision of AV services for first/last mile travel can facilitate passengers' access to and egress from stations/stops within urban transit networks (Abe, 2021). Chen et al. (2020) assumed that compared to headway-based feeder buses, AVs are more flexible. They emphasised that to reduce walking distance, pickup points should be considered at bus stops and close to parking lots (Chen et al., 2020). Yap et al. (2016) also concluded that introducing automated vehicles specifically for the last mile has potential. Understanding these potentials is essential for sustainable transportation and cities with AVs (Abe, 2021). The fleet size, variety of alternatives, related facilities, and locations are essential for increased hub use.

Besides the classic instrumental variables such as the time people spend during access and egress (waiting time and in-vehicle time), travel cost, and socio-demographic, some new influential factors should be taken into consideration, such as the mode availability and booking time which relates to reliability and flexibility (Bronsvoort, 2019).

Booking factors, as well as departure delay and travel time deviation, negatively impact mode choice. Travellers would like to spend less time on access and egress trips (Bronsvoort, 2019). Jorge and Correia (2013) emphasised that shared vehicles' utility is valued much higher than private vehicles due to less time spent on the road and parking places. So, they could be alternatives to private car ownership (Correia & Antunes, 2012).

Regarding bike-sharing, it is reported that this system decreases the share of private cars in the modal split in the US (Shaheen & Chan, 2016). In the same study, it was found that bike-sharing could be a bus alternative in large cities and an access/egress mode to/from bus stations in smaller cities in the US. Another study showed that the option of cycle-hire facilities promoted bike shares in the last mile distance (Brand et al., 2017).

The emerging access/egress modes such as shared, electric, and automated vehicles are more environmentally friendly, flexible, cheaper, and faster than the current modes. The emerging modes such as bicycle-sharing systems (Brand et al., 2017., Scheltes 2015 and Bronsvoort, 2019, Shaheen & Chan, 2016), E-bikes in stations (Scheltes 2015), and car-sharing programs (Correia and Antunes 2012; Jorge and Correia 2013, Scheltes 2015, Martin et al. 2010, Martin and Shaheen, 2011), as well as the short term application of automated vehicles (Scheltes 2015 and Yap et al. 2016), can compete with private cars.

Although there are different influential factors on passenger preferences regarding access-egress modes, among the mentioned factors, the impacts of travel time, travel cost and availability of emerging modes in different weather conditions and carrying/no luggage is not thoroughly investigated at multimodal hubs, which is the aim of this research.

3.3 Methodology

3.3.1 The research approach

The research approach is formulated to address the main research question which is defined as how emerging modes and context indicators impact the modal choice of travelers in a multimodal hub. This case study may help predict access/egress mode choice decisions at stations. To reach the answer, a literature review has been undertaken as a first step to find influential factors on modal choice at multimodal hubs. Then, a stated preference survey was designed based on five alternatives, three attributes, and two contextual situations and conducted at Delft Campus train station as an example of a small-medium multimodal station with high demand for passengers, accessing the Technical University nearby.

A stated choice survey was selected to determine people's preferences for new modes of access/egress from hubs. Stated choice experiments are widely used in transport literature to understand travellers' choices regarding various modes. Respondents who receive hypothetical choice situations (Louviere et al., 2000; Train, 2009) are required to decide a preferred transport mode, considering total travel time, travel cost, and availability of modes from a range of available options. This method was selected for several reasons. Firstly, the new transport modes are not yet available for daily use. There is no available data on the revealed preferences of people. Secondly, our research intends to include context scenarios such as weather and luggage to test the impact of these context effects on mode choices. Stated preference offers an opportunity for the researcher to create context effects for respondents and test the impact on people's choices.

The most common (and simplistic) model to extract the participants' choice behaviour in the stated preference studies is the Multinomial logit (MNL) model. These models are based on the theory of utility maximisation and the assumption that the respondents maximise their utility when choosing among alternatives in a given choice set. In MNL, the assumption of independence of irrelevant alternatives (IIA) is considered (McFadden, 1986).

However, given the similarities (and thus expected correlations in choice behaviour) among some alternatives in our stated experiment, we apply Nested Logit (NL) models. In these models, the assumption of IIA is relaxed by allowing correlation between the non-observed utilities of groups of alternatives (Hensher et al., 2005)

3.3.2 Selection of Delft Campus station (in the Netherlands) as a case study

Scheltes (2015) studied the modal split of the access/egress trips for the coming years in the Netherlands and found that almost half of people are interested in new, emerging, and future modes. This study evaluates how emerging modes affect the modal choice of travellers in a multimodal hub which helps to predict access/egress mode choice decisions at stations.

The Netherlands has one of the densest rail networks globally, transferring more than 1.2 million passengers per day (Van Hagen & Exel, 2012), travelling 21.6 billion kilometres by public transport users in 2014 (CBS, 2015). Currently, up to 17% of these trips are considered multimodal trips, using at least two different transport modes for medium-distance transferring (20-40 km) between urban areas in the Netherlands (Van Nes et al., 2014). Moreover, more than half of them (61%) are covered by train as the principal transport means (Kennisinstituut Voor Mobiliteitsbeleid, 2014). For this reason, the role of railway stations as transit nodes is crucial and well-investigated by several researchers (see, for example, Molin & Timmermans, 2010; Puello & Geurs, 2015; Shelat et al., 2018; Van Mil et al., 2020 and Yap et al., 2016).

Depending on trip direction (home-end and activity-end), bicycle, walking, and public transport are used differently in the Netherlands. According to Kennisinstituut Voor Mobiliteitsbeleid dataset 2017, at the home-end trip, the modal split is bicycle at 43%, walking at 23%, and public transport 19%, and at the activity-end trip, cycling is decreased to 13%, and walking and public transport are increased to 45% and 33% respectively. Based on these percentages and the decreasing trend of classic public transport modes such as bus, tram, and metro, it is assumed that the transportation sector should provide more transport alternatives in the last mile of trips (Figure 3.1).

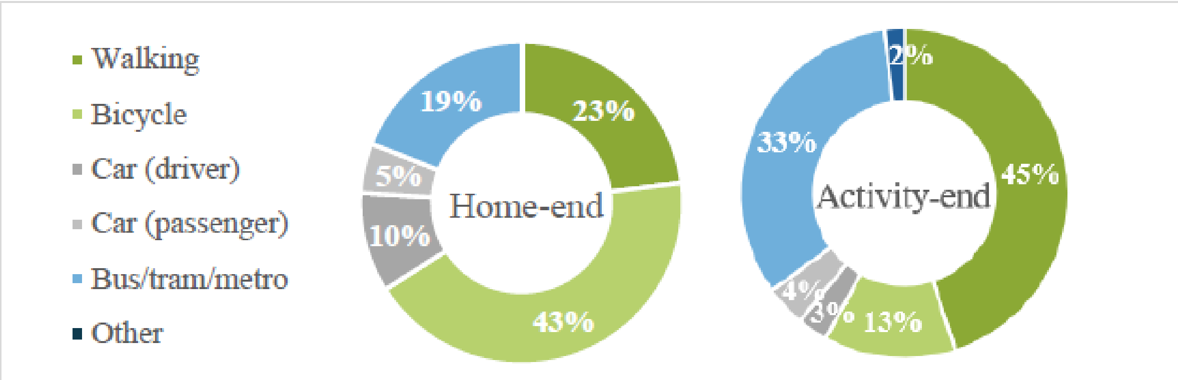

Figure 3.1: Modal split (2014) of the 20 busiest railway stations in the Netherlands (Kennisinstituut Voor Mobiliteitsbeleid, 2017).

In recent years, the Dutch national railway operator, Netherlands Spoorwegen (NS), has introduced two shared mobility services at railway stations, 'OV-fiets' (a bike-sharing system) and 'GreenWheels' (a car-sharing system). Evidence shows that shared mobility services have become increasingly popular in the Netherlands, with their use growing by 23% in 2017 (CROW-KpVV, 2017). Furthermore, 8,627 autonomous electric vehicles (AEVs) were registered in the Netherlands in 2017 (Rijksdienst Voor Ondernemend Nederland, 2018).

Figure 3.2 shows Delft Central and Delft Campus train stations, including access and egress passenger flows. Delft-Campus train station which ProRail, (2012) introduces as a so-called 'Basis station [2]' with around 5000 passengers per working day (Boor, 2019), has connections only to bicycles, shared bicycles, and car parks, and can be considered a small hub. It is one of the two train connections to Delft and the central train station for Delft University of Technology (TU Delft). Due to its proximity to the University and the science park, the Delft Campus train station can be developed as an important multimodal hub that is considered the case study in this research. Figure 3.3 shows the Delft Campus train station.

[2] ProRail named stations with 1000-10,000 passengers per day as 'basis station' in The Netherlands (Spoorbouwmeester, 2012).

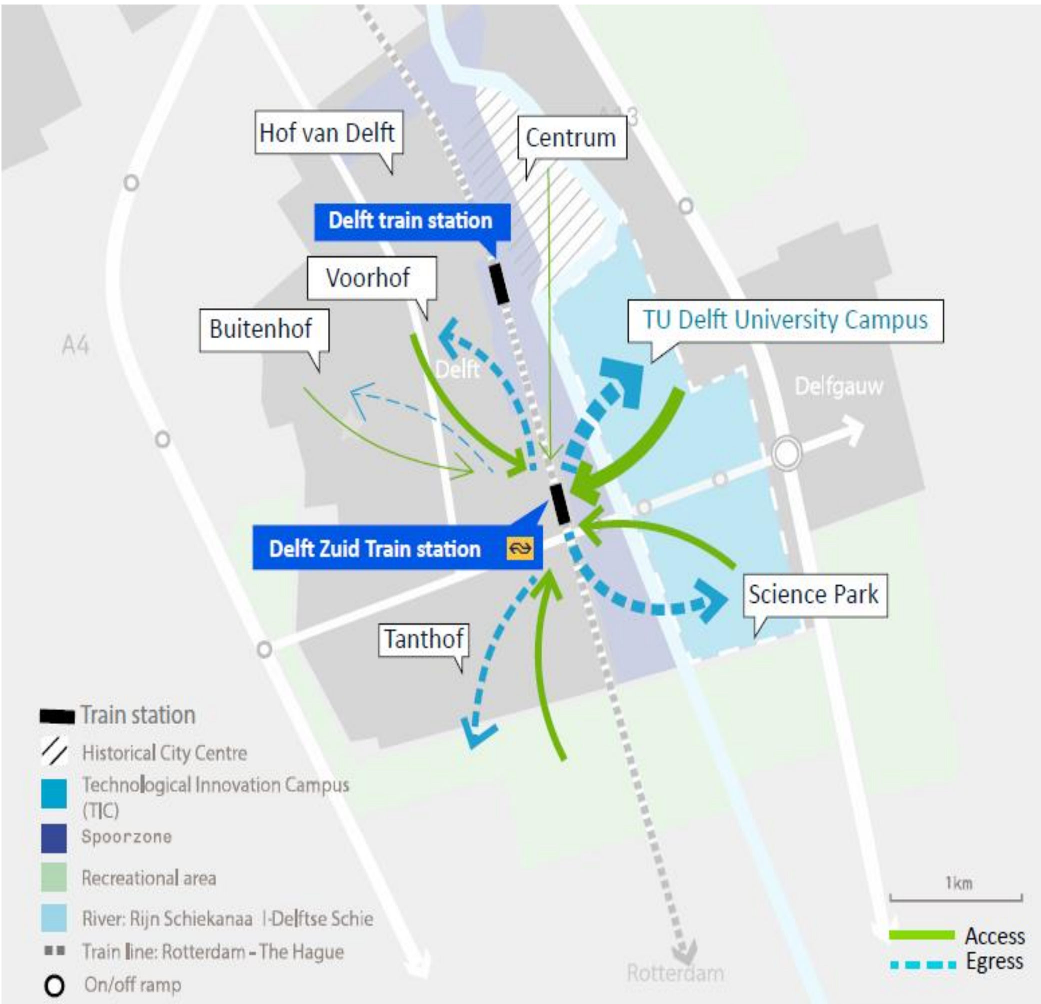

Figure 3.2: Map of Delft presents Delft Central and Delft Campus train stations, including access/egress passengers (Boor, 2019).

Figure 3.3: Old Delft Campus train station, named Delt Zuid station.

Although approximately 35% of daily users of Delft Campus station are TU Delft University students or staff, the public transport connections between Delft-Zuid and the university campus are not optimal. Figure 3.4 provides additional information on the mode share in this station (https://dashboards.nsjaarverslag.nl/reizigersgedrag/delft-zuid, 2019). Walking and cycling are the main access/egress modes in this 2-kilometre walking distance, and the lack of public transport modes (Scheltes and Correia, 2017) makes it an exciting candidate small hub at which to ask the users and travellers what they would foresee as suitable access/egress modes in the future.

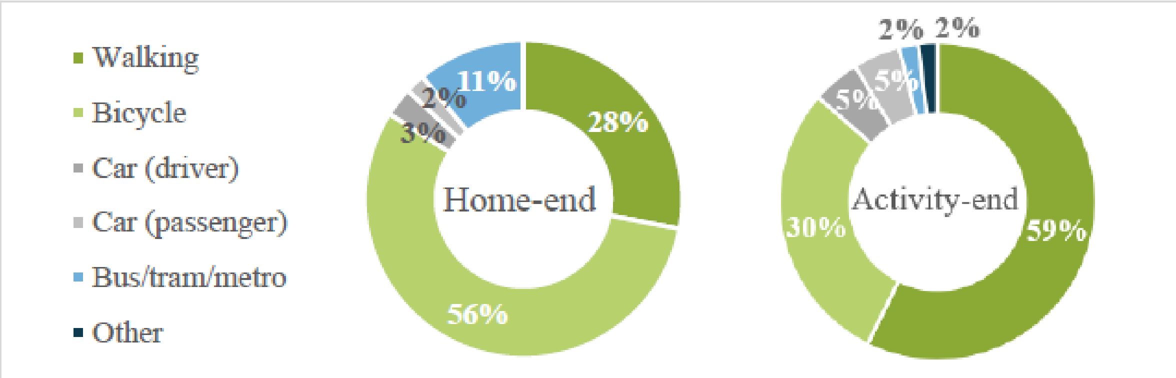

Figure 3.4: Current access/egress modal split in Delft-Campus train station (NS, https://dashboards.nsjaarverslag.nl/reizigersgedrag/delft-zuid, 2019).

3.3.3 Survey and sample

This paper explores people's preferences for adopting bicycle sharing, shared e-scooters (both standing and sitting), individual automated vehicles, and collective automated vehicles among passengers. The Delft-Campus train station is selected as an example of a small-medium multimodal station. A survey was conducted to capture influential factors socio-economic, travel-related, behavioral, and personal preferences in this study that are not captured through revealed data.

Our survey was conducted in an online survey in English and Dutch. The flyers, including QR codes, a link to access the survey, and a short explanation of the purpose of the research, were distributed at Delft-Campus station among travellers who access or egress from the station between 18 June and 1 July 2019, Figure 3.5.

The questionnaires begin with a short introduction about emerging new modes such as access and egress modes combined with the train in Delft-Campus station. This travel demand survey was conducted in three parts: 1) reveal preferences, 2) stated choice experiment and 3) socio-economic characteristics in Delft Campus train station as a case study. Only respondents who travelled via this station were allowed to answer the questionnaire.

The first part was presented to participants to collect data about the current situation related to the first/last trip, such as the trip's purpose, the approximate distance between the origin and the destination, position (access or egress stage), and the modes of transportation they used. This part of the experiment aimed to find out the revealed preferences of the subject. The questionnaire ended by asking socio-economic characteristics of the respondents. Table 3.2 shows these socio-economic variables and categories.

Figure 3.5: The survey flyers include two QR codes, Dutch and English.

Table 3.2: Overview of socio-economic variables and their categories used in the experiment.

Socio-economic variable	Categories					
Birth year						
Gender	Female	Male	Others	-	-	-
Gross income (€/year)	<€10.000	€10.000-€39.999	€40.000-79.999	>€80.000	I do not know	Others
Education level	≤Pre-vocational secondary	Secondary education (MBO)/ pre-university	≥University education (HBO, WO)	Others	-	-
Most frequent trip purpose	From/to work	Education/ business	School/ study	Social/recreation/ sports	Healthcare	Others
Origin/ destination	TU Delf	Schieweg Noord	Schieweg Zuid	Voorhof	Tanthof oost	Others
Transport stage	Access	Egress	-	-	-	-
Current main transport mode	Walking	Private Bike	Shared Bike	Car (driver)	Car (passenger)	Others

3.3.4 Stated choice experiment

The second part of the questionnaire featured a stated choice experiment. At the beginning of the second part, which was about future transportation modes and trips, five new transport mode options were introduced in an overview Table 3.3 and presented in Figure 3.6.

Although it would be interesting to examine how emerging modes fare against more traditional modes (e.g. walking), this research only looks at the relative preference to find their potential for future stations. The respondents were further informed that the following condition applies to the modes in Table 3.3:

- Walking and private bicycles are out of the scope since we would know passengers' opinions regarding emerging modes.
- The modes can be booked via a mobile App before taking the trip.
- They (in the case of the first three modes) can be left anywhere (dockless station) as long as it is in an admissible region (geofencing).
- The availability of transport modes is different. Availability was presented as the probability of finding a mode present when the passenger arrives with the primary mode and wants to shift mode and egress from the station. For instance, if the availability is set to 90%, the respondent can find the mode at 90% upon arrival at the station, while 10% of the time, it is not available at the station.

The additional information regarding waiting times until the next available mode can be checked via a mobile app.

Table 3.3: Overview of the alternative characteristics.

Shared modes	Characteristics
	***Shared (E)bike***; can be used by several people at different times.
	***Shared (E)step***; can be used by several people at different times. You have no seat; you should stand in an open area and pedal to move normally.
	***Shared (E)scooter***; can be used by several people at different times. You have a guaranteed seat in an open area, and you do not pedal to move.
	***Individual Automated Vehicle***s; can be used by several people at different times. It looks like a private taxi (flexible route, flexible schedule) but is driverless and cheaper. You have a guaranteed seat.
	***Collective Automated Vehicle***s; can be used by several people at the same time. The shuttle has a flexible route and flexible schedule and is cheaper than taxis due to being driverless. You are inside but do not have a guaranteed seat.

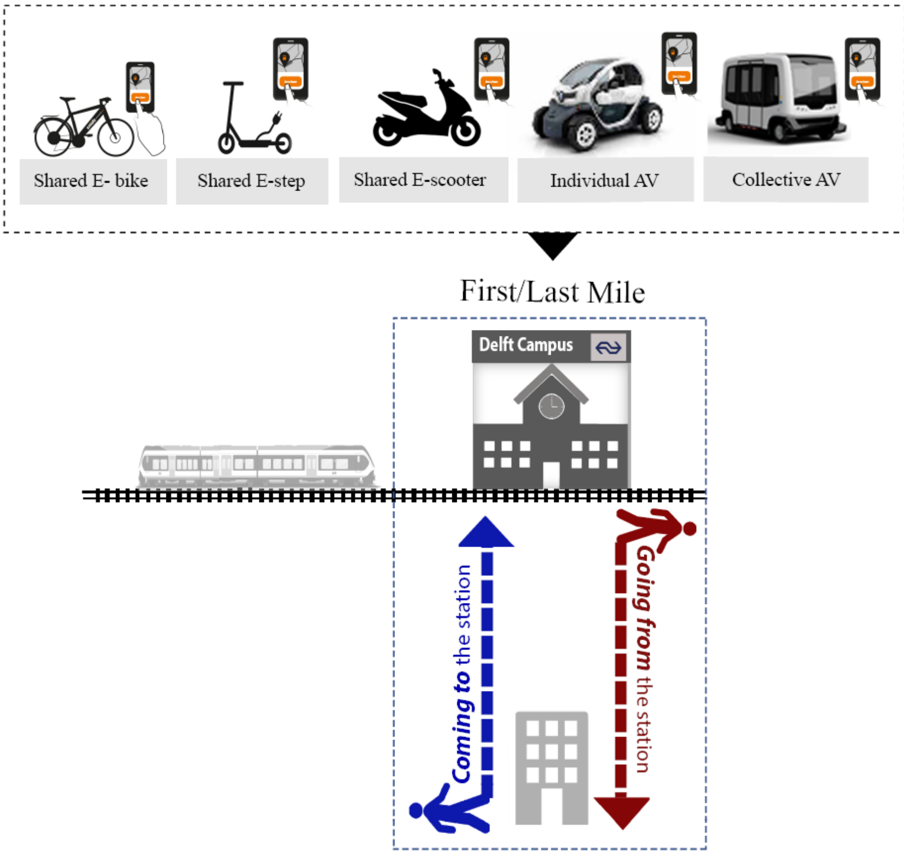

Figure 3.6: Overview of trip future alternatives incorporated in the SP experiment.

When the choice sets were offered to the respondents, a different contextual situation (i.e., scenarios) was also introduced to the respondents to see how these contextual situations would play a role in respondents' choices for alternative access/ egress modes.

Each contextual situation is composed of a weather element and a luggage element. Six different contextual situations were developed (Table 3.4), which are as follows:

1) Imagine that the weather is sunny and you do not need to carry any luggage.

2) Imagine that the weather is rainy, but you do not need to carry any luggage.

3) Imagine that the weather is cold (less than 5 °C), but you do not need to carry any luggage.

4) Imagine that the weather is sunny and you need to carry luggage of 10kg or more.

5) Imagine that the weather is rainy and you need to carry luggage of 10kg or more.

6) Imagine that the weather is cold (less than 5 °C) and you need to carry luggage of 10kg or more.

Therefore, participants were asked to decide which mode they prefer as an access-egress mode for their trip to/from Delft Campus station based on the attributes and characteristics of the five alternative transport modes plus considering one of the six contextual situations (Scenario) that was shown in Table 3.4. The contextual situations were randomly distributed to the respondents, but we made sure that the contextual situations were equally distributed among respondents.

Table 3.4: The context effects were provided for the respondents.

Contextual Number	**Context conditions Weather situation + Luggage**		
Context 1	Sunny	+	No Luggage
Context 2	Rain	+	No Luggage
Context 3	Cold ≤ 5◦c	+	No Luggage
Context 4	Sunny	+	With Luggage ≥10kg
Context 5	Rain	+	With Luggage ≥10kg
Context 6	Cold ≤ 5◦c	+	With Luggage ≥10kg

3.3.5 Alternatives and attributes and choice sets

Considering all alternatives and attributes in a stated preference experiment provides many choice sets that are not practical. Three different instrumental attributes, such as total travel time, travel cost, and availability of modes in three corresponding attribute levels, have been used in the SP experiment, disaggregated by different modes (Table 3.5). To make alternatives more credible and imaginable for respondents, most attribute levels came from literature or existing services (Bronsvoort, 2019). The five alternative modes and three attributes were selected not to exceed the cognitive load of respondents in the experiment. This would allow respondents to compensate for the attributes and weigh the alternatives appropriately even though there is a chance that respondents may use simple heuristics to make the choices (e.g. always choosing the lowest costs fastest mode, or the most modern mode).

Table 3.5: Overview of attributes and attribute levels used in the SP experiment

Attribute	**Attributes levels**		
Travel cost-shared (e) bike	€ 0.50	€ 1.00	€ 1.50
Travel cost-shared (e) step	€ 1.00	€ 1.50	€ 2.00
Travel cost-shared (e) scooter	€ 1.50	€ 2.00	€ 2.50
Travel cost-shared individual AV	€ 3.00	€ 4.00	€ 5.00
Travel cost-shared collective AV	€ 2.50	€ 3.00	€ 3.50
Travel time shared (e) bike	4 min	6 min	8 min
Travel time shared (e) step	3 min	5 min	7 min
Travel time shared (e) scooter	3 min	5 min	7 min
Travel time shared individual AV	4 min	6 min	8 min
Travel time shared collective AV	5 min	8 min	11 min
Availability shared (e) bike	70 %	80 %	90 %
Availability shared (e) step	70 %	80 %	90 %
Availability shared (e) scooter	70 %	80 %	90 %
Availability of shared individual AV	80 %	90 %	100 %
Availability of shared collective AV	80 %	90 %	100 %

Attribute levels have been obtained by looking at the overall market values when conducting surveys for the known modes (i.e. shared bike, E-bike, scooter). For the other less known modes to the markets (i.e. AVs), recent transport literature has been used to obtain the cost and travel times for AVs where they are considered for similar access /egress purposes, for instance, the study of Yap et al. (2016), and Ashkrof et al., (2019).

The travel cost of an alternative denoted the paid cost for using a specific means during the trip for renting or parking, and they are based on prices at Dutch stations. The lowest and highest prices are assumed for shared bikes (€0.5, €1, €1.50) and individual AVs (€3, €4, €5) respectively. Due to some maintenance and the battery, the cost of e-step and e-scooter was considered as more than the cost of bike-sharing. AVs are not yet operational in the Netherlands, but these prices have been extracted from recent studies (Yap et al., 2016, Scheltes, 2015 and Scheltes and Correia, 2017).

Total travel time, defined as door-to-door travel time including waiting time, was calculated based on distance and speed using Google Maps. It is assumed that shared e-step and e-scooter are the fastest modes (3min, 5min, 7 min), and collective AVs take the most time (5min, 8min, 11 min).

The attribute of 'availability' is rarely used in terms of varied transit modes in the literature and mainly uses car ownership. Here, availability denoted the accessibility of the alternatives. Nguen-phuoc et al. (2018) used attribute levels of 'yes' and 'no' for ownership/availability of motorcycles and bicycles in their studies. In our choice experiment to present the comparative attribute, we would develop and extend the availability attribute level into availability percentage, and probability of finding a mode upon arrival at the station. 90% availability means that once a passenger arrives at the station, they can successfully access a mode 9 out of 10 times. 100% availability is provided only for AVs to investigate whether the increasing availability of AVs for the last mile can specifically make them more attractive to passengers.

The choice sets in the SP survey were based on an efficient design since they are preferred to the traditional orthogonal designs. These designs are developed to minimise the elements of the AVC [Asymptomatic Variance-Covariance] matrix for the design (Bliemer & Rose, 2009, p. 611), and to minimise the standard errors (D-error). These designs were constructed using the Ngene software (ChoiceMetrics, 2012). To develop efficient designs, some priors are needed. These preliminary (estimated) values of the coefficients (Rose et al., 2008) were obtained from a pilot study for access-egress modes that assumed no prior estimates and used orthogonal designs.

Since it was challenging to obtain priors from a pre-test or another study, we conducted our pilot study to obtain priors for efficient design. The pilot survey was performed before the primary survey, and then the efficient design was generated. There was no bias in selecting the respondents for the pilot, and the pilot was performed among the random passengers at the Delft campus station.

The pilot study used an orthogonal design and was collected from 57 fully completed surveys. The priors were generated based on the MNL model (fitted on the pilot sample), and the coefficients were used to develop the primary survey's efficient design.

Given five alternatives, three attributes, and three levels (Table 3.5), three weather conditions, and two luggage conditions, a total of 36 choice scenarios (choice sets) were generated. One of the design efficiency measures provided by Ngene, namely the S-estimate, calculates the minimum sample size required to obtain statistically significant coefficients at the 95 % confidence level. For the selected design, the S-estimate was 6.8, indicating that approximately 245 completed choice observations were required. To ensure adequate statistical power, the complete design was repeated seven times, resulting in a target of 252 completed choice observations.

To keep the questionnaire completion time manageable, the design was blocked such that each respondent was presented with only six of the 36 choice sets. Furthermore, each respondent was assigned a single contextual setting (i.e., a fixed combination of weather and luggage conditions) to minimize confusion and reduce cognitive burden. Participants were asked to choose among the five alternatives, and no opt-out option was provided. Figure 3.7 presents an example of a choice set, illustrating the combination of attribute levels across all alternatives within a specific contextual setting. Figure 3.7 shows an example of these choice sets, the combination of attribute levels and all alternatives in a specific context.

Scenario E3	 Bike sharing	 E-step sharing	 E-scooter sharing	 Individual AV	 Colective AV
Travel Time	6 min	3 min	3 min	6 min	11 min
Travel Cost	1.5 euro	1 euro	1.5 euro	5 euro	2.5 euro
Availability	80%	70%	90%	90%	100%

Figure 3.7: Example of giving a choice set to respondents in the survey.

3.4 Data collection and analysis results

In this section, we provide descriptive statistics of the collected data and contemplate the representativeness of the sample that the survey has obtained. Afterwards, we present two MNL models (with and without socio-economic parameters) to demonstrate the choice preferences of the respondents in choosing access/egress modes from a small multimodal hub in the presence of context indicators.

In order to relax the IIA assumption of the MNL models, we introduce two NL models (again, with and without socio-economic parameters). Afterwards, we discuss the model fit of these logit models and evaluate which model can better describe and predict respondents' choices on access/egress modes, given the two context indicators. Furthermore, the market share is predicted, and the elasticities of different transport modes are calculated.

3.4.1 Data collection

In total, 480 people started the online survey, and from those, 293 respondents completed the survey (61% completion rate) with an average time of approximately 14 minutes. This equals 1758 filled choice sets, which is much higher than the minimum required (i.e. 252).

Table 3.6 compares the socio-economic variables between our sample of respondents and the Dutch population from NS Klimaat VI Personenonderzoek (NS, 2019). To analyse socio-economic characteristics, it should be considered that the experiment has been performed at Delft Campus station, which is in the neighbourhood of TU Delft.

Regarding the socio-demographic characteristics of the sample, it contains higher shares of young (82% <39 years), university-educated (84%), and low economic level 31% <19.999 euro) users who travel most often for work/school-related purposes (68%) compared to the general Dutch sample. Looking further into the general Dutch sample shows an over-representation of respondents aged 40 to <64 years (45%) who are not highly educated and travel for leisure-related purposes. The table compares current modal split transportation modes with the NS modal split figures last at the access and egress stages.

Although we have made every attempt to sample passengers arriving at the Delft campus station randomly, the final sample may be biased, since many passengers at this station are heading to a particular destination (Delft Technical University) which might not represent the population of Delft (or The Hague or Rotterdam).

Delft-Campus train station is located close to TU Delft University. It is the largest and oldest public technical University in the Netherlands and one of the highest-ranked universities in the world. So, in the sample, TU Delft University has a dominant role for people who use this station in terms of socio-economic characteristics and trips and travel modes, and where the only available public modes are shared bikes (such as OV fiets and Mobike). The sample is reflected in no shares of BTM and a small share of cars and shared bikes. On the other hand, respondents much more often use private bikes for access and egress trips, 51% and 50% respectively. Compared with the overall model split in the Netherlands, BTM allocated a 24% share of transportation modes at access and egress trips. Generally, NS reported bikes (30%) are used as the first preference of travellers on home-based trips and 58% walking share on activity-based trips.

Table 3.6: Comparison between sample and NS customer population for different socio-economic variables.

Socio-economic variable	Category	Share sample	NS customers
Last trip purpose	From and to work	38 %	14 %
	Business	8 %	6 %
	School/ study	30 %	8 %
	Social/recreation/sports	19 %	58 %
	Healthcare	1 %	-
	Other	3 %	14 %
Age	<20	3 %	-
	20 to ≤39	82 %	31.7 %
	40 to ≤64	10 %	45.8 %

	65 to ≤79	4 %	17 %
	80≤	-	5.5 %
Gender	Female	44 %	53 %
	Male	54 %	47 %
	Other	2 %	-
Education level	Pre-vocational secondary education or below	1 %	27 %
	Secondary vocational education or pre-university education (VWO)	10 %	39 %
	University education (HBO, WO) or above	84 %	35 %
	Other	4 %	-
	I prefer not to say	2 %	-
Total family gross annual income	Less than 19.999 euro	31 %	-
	19.999- 39.999 euro	16 %	-
	40.000-59.999 euro	11 %	-
	60.000-79.999 euro	7 %	-
	More than 80.000 euro	7 %	-
	I don't know or prefer not to say	29 %	-
	Average income (€/month)		€ 1,830
Position	I am Coming To Delft Campus station (access)	66 %	-
	I am Going From Delft Campus station (egress)	34 %	-
Access mode	Walk	33 %	22 %
	Private bike	51 %	-
	Shared bike	5 %	-
	Bike (private / shared, folding)	-	30 %
	BTM	-	24 %
	Car (private / shared, driver/passenger)	7 %	21 %
	Other	4 %	3 %
Egress mode	Walk	34 %	58 %
	Private bike	50 %	-
	Shared bike	6 %	-
	Bike (private / shared, folding)	-	8 %
	BTM	-	24 %
	Car (private / shared, driver/passenger)	4 %	7 %
	Other	6%	4%

3.4.2 Discrete choice model results

We first estimated a main effect only MNL model (i.e. no interaction effects) and then the full MNL model (i.e. with main and interaction effects). The main effect parameters (the three attributes) were significant (the third attribute was significant at $p<0.10$), and they have the right sign, i.e. travel time and ticket price were negative, and availability had a positive sign.

The initial model was compared with the full model via the likelihood-ratio test. This test indicated that the complete modal (final log-likelihood: -2283.86) with interaction effects fitted the data significantly better than the initial primary effect model (final log-likelihood: -2432.21). The likelihood-ratio test with 18 degrees of freedom for the 18 interaction effect parameters that are estimated is found to be well significant, $\chi2=298>34.80$, (d.f.=18, p=0.01). Therefore, the context effects interacted significantly with the three attributes.

As explained before in section 3.4 (and shown in Table 3.4), six contextual situations are imposed on the choice sets. These six contextual situations (scenarios) are effect-coded, as shown in Table 3.7.

Table 3.7: The effect coding of the contextual situations (for a full explanation of the contextual situation see Table 3.4 and Section 3.4)

Contextual situation	Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5
Context 1	1	0	0	0	0
Context 2	0	1	0	0	0
Context 3	0	0	1	0	0
Context 4	0	0	0	1	0
Context 5	0	0	0	0	1
Context 6	-1	-1	-1	-1	-1

The addition of the demographic variables to the MNL model also proved to be a significantly better-fit model compared to the MNL model without demographic explanatory variables. We will not discuss the MNL model further because the NL model shows a better fit, judging by the adjusted R2 and the likelihood-ratio test (adjusted R2 for MNL was 0.196 and MNL with socio-economic was 0.236 and that of NL was 0.201 and 0.241, respectively). Therefore, we provide further detailed descriptions of the interaction of the context indicators with the main attributes in the next section.

3.5 Nested Logit (NL) model

Based on the formulation of the alternative access egress modes, we hypothesised that the currently available access and egress modes (shared bike, e-step, and e-scooter) might have commonalities, and the same would be valid for the two AV alternatives. Thus, we tested this hypothesis with two nested logit models. Table 3.8 shows the estimated parameters for an NL only (model A) and the other with an NL model plus socio-economic (model B) variables. In these models, the three modes (Bike sharing, E-step sharing, and E-scooter sharing) are nested with each other as "Non-AV" nests, and the two alternatives of Individual AV and Collective AV are nested as “AV” nests.

The nested parameter (0.55) is significant (t-value= 4.04) compared with the MNL model. This means that the nesting of the alternatives has successfully captured commonalities among the alternatives within the nests. The nested parameter indicates the level of correlation between the error components of the alternatives within the nest. Since the parameter is getting close to zero, there is more correlation between the unobserved components of the alternatives within the nest (Train, 2009).

Table 3.8: The parameter estimates of the two NL models.

Main effects	NL (model A)		NL+ Socio-economic (model B)	
	Estimate	t-value	Estimate	t-value
ASC shared (E) bike	0	(Fixed)	0	(Fixed)
ASC shared (E) step	-0.275**	-4.70	-0.229*	-1.89
ASC shared (E) scooter	-0.350**	-4.02	-0.116	-0.84
ASC Individual AV	0.160	0.81	0.0691	0.21
ASC Collective AV	0.081	0.49	-0.668	-1.62
Travel time	-0.109**	-8.45	-0.117**	-8.33
Travel cost	-0.614**	-9.67	-0.644**	-9.43
Availability	0.00537**	2.41	0.00564**	2.5
Interaction effects				
Travel time * context 1 (Sun + No Lug)	-0.0927 **	-3.13	-0.0787 **	-2.65
Travel time * context 2 (Rain + No Lug)	0.0172	0.91	0.00179	0.09
Travel time * context 3 (Cold≤5◦c + No Lug)	0.0099	0.48	0.0175	0.82
Travel time * context 4 (Sun + Lug≥10kg)	0.0189	0.82	0.0141	0.59
Travel time * context 5 (Rain + Lug≥10kg)	-0.019	-0.95	-0.0184	-0.84
Travel time * context 6 (Cold≤5◦c + Lug≥10kg)	0.0664	-	0.06371	-
Travel cost * context 1 (Sun + No Lug)	-0.732 **	-8.40	-0.662 **	-7.62
Travel cost * context 2 (Rain + No Lug)	0.260 **	5.24	0.207 **	3.91
Travel cost * context 3 (Cold≤5◦c + No Lug)	0.0166	0.29	0.0105	0.18
Travel cost * context 4 (Sun + Lug≥10kg)	-0.089	-1.59	-0.0683	-1.17
Travel cost * context 5 (Rain + Lug≥10kg)	0.217 **	4.00	0.169 **	2.78
Travel cost * context 6 (Cold≤5◦c + Lug≥10kg)	0.327	-	0.3438	-
Availability * context 1 (Sun + No Lug)	0.0081 **	2.91	0.0078 **	2.77
Availability * context 2 (Rain + No Lug)	0.00657	1.41	0.0051	1.07
Availability * context 3 (Cold≤5◦c + No Lug)	-0.0139 **	-2.44	-0.0134 **	-2.31
Availability * context 4 (Sun + Lug≥10kg)	0.0002	-0.05	0.0009	-0.02
Availability * context 5 (Rain + Lug≥10kg)	0.0009	0.21	0.000396	0.09
Availability * context 6 (Cold≤5◦c + Lug≥10kg)	0.0010	-	0.00096	-
Socio-economic variables				
Age above 26 and under 45- shared (e) step			0.234 **	3.14

Age 26 and younger- shared (e) scooter		-0.193 *	-1.87
Age above 26 and under 45-shared (e) scooter		0.205 **	2.38
Age above 45- shared (e) scooter		-0.012	-
Age 26 and younger- Individual AV		-0.391 **	-2.39
Age above 26 and under 45- Individual AV		0.513 **	4.08
Age above 45- Individual AV		-0.122	-
Age above 26 and under 45- Collective AV		1.13 **	7.55
Female- shared (e) scooter		0.165 **	2.83
Low Education- shared (e) scooter		0.549 **	2.69
Middle-income- shared (e) scooter		-0.237 **	-2.57
Low-income- Individual AV		-0.359 **	-2.77
Middle-income- Individual AV		-0.517 **	-4.29
High-income- Individual AV		0.876	-
Low-income- Collective AV		-0.444 **	-3.75
Middle-income- Collective AV		-0.444 **	-4
High-income- Collective AV		0.888	-
Nest parameter, λ		Nest Value	t-value
Non-AV nest (shared (e) bike, shared (e) step, shared (e) scooter)		1.00	(Fixed)
AV nest (Individual AV, Collective AV)		0.55	4.04
Model fit			
Initial log-likelihood	-2868.02	-2790.76	
Final log-likelihood	-2269.70	-2068.52	
R2	0.209	0.259	
Adjusted R2	0.201	0.241	
	Compared to the model a	Compared to the model b	
likelihood-ratio test	χ^2=28 > 6.63 , d.f =1 p=0.01	χ^2=30 > 6.63 , d.f =1 p=0.01	

3.5.1 Interaction of travel time with context indicators

The interaction of travel time with context indicators provides exciting results. We observe that the utility slope increases for two interactions: 'sunny + luggage' and 'cold ≤ 5 ◦C + luggage' contexts. The significant issue here is that the increase in the slope of utility probably indicates that with the presence of luggage, there is again in using the five alternative modes to access or egress from the station versus not using these modes. Therefore, the longer travel time to access or egress the station is acceptable for passengers with luggage.

It should be mentioned that there is an exception in our finding, and that refers to rainy weather conditions. Surprisingly, the utility slope decreases from the 'Rain + No Lug' condition to "Rain + Lug≥10kg". This result is not consistent compared with the other two contexts. Furthermore, only one interaction effect, namely travel time and "Sun + No Lug", was significant (t-value = -3.13 or -2.65) in our analysis. Therefore, no generalisation to the entire population can be inferred. Nevertheless, the findings provide insight into how passengers' utility curve changes with travel time and using the alternative modes under different weather situations and carrying luggage.

3.5.2 Interaction of travel cost with context indicators

We observed exciting findings by examining the ticket price with context effects indicators. First and foremost, interactions of context effects with the ticket price attribute were significant in most cases.

Looking at the interaction effects, there is a gain in utility slope when combining the ticket price with the context 'Sun + Lug> 10 Kg' compared to when there is no luggage and the weather is sunny. The gain in utility slope also happens when it is 'cold ≤ 5◦C + Lug>10 kg' compared with cold and no luggage. The findings indicate that passengers with luggage are more willing to pay the ticket price and use the transport modes than passengers without luggage. However, this finding is not valid for people with luggage (>10kg) who want to access or egress from the station in rainy weather. There is a slight drop in utility slope when people have luggage compared with when they do not.

Another critical finding here is that, in general, people are more willing to pay the ticket price (positive utility slope) when the weather is rainy or cold (with or without luggage).

3.5.3 Interaction of availability with context indicators

For the interaction of the availability and the context effects, we see a drop in utility slope when examining the availability with the context 'Sun + No Lug' compared to when there is luggage and the weather is sunny. The drop in utility slope also happens when 'Rain + No Lug' is compared with 'Rain + Lug>10Kg'. These results suggest that passengers without luggage are more sensitive to the availability of the next mode when accessing or egressing a station.

It is surprising and counterintuitive that there is a loss in utility slope (-0.0139, or -0.0134) when the weather is 'Cold ≤ 5◦C +No Lug'. This may be related to sampling errors.

3.5.4 Impact of demographics

We tested the impact of the following socio-economic indicators in Model B and Model D: age, gender, income, and level of education. Several of these indicators were significant, providing more insight into their underlying impact on the utility obtained from each alternative than the bike alternative. Bikes are set as default for these socio-economic indicators. Here, we will contemplate only those socio-economic indicators that are significant.

In model B, younger (<26) respondents gained less utility from shared e-scooters and individual AVs. However, the middle group of respondents (between 26 and 45) gained more utility from all alternatives than bikes. The senior group of respondents (>45) gained slightly less utility from shared e-scooters and individual AVs.

Regarding the gender indicator, women gained utility from shared e-scooters compared to shared bikes.

The respondents' education level indicated that those with a high school or lower level of education gained utility from shared e-scooters. However, middle and higher-education passengers were not willing to use shared e-scooters. Income has probably played an essential role in the utility of the respondents for the two AV alternatives. This claim is based on the estimated parameters and their t-value. Low- and middle-income respondents both lost utilities from the two AV alternatives. However, the high-income group gained utility from the two AV alternatives. The middle-income group also lost utility from the shared E-scooter alternative compared to the shared bike alternative.

3.5.5 Prediction of the market share

One of the critical initial steps to estimate the market share of the new modes is to calculate the value of time (VOT) for the respondents. We used the NL models to generate the VOT since they fit better than the MNL models. VOT is calculated by $\frac{\beta_{travel\ time}}{\beta_{ticket\ price}}$ = -0.117/-0.644=0.181 euros per minute or around 10.9 euros per hour (based on model B) for an access/egress trip. This is in the range of other access egress studies (Yap et al., 2016).

3.5.6 Market share

The NL model estimates the market share (choice probabilities) of the five alternative access and egress modes based on estimated coefficients (Betas). It should be mentioned that this market share prediction is under the assumption that the presented modes in the experiment are the only available modes and do not consider traditional modes (e.g. walking, private bicycle or regular bus), which is the limitation of this research. These market shares are provided in Table 3.9.

Table 3.9: The predicted average probability of different alternatives based on model B (NL+ socio-economic).

Alternatives	Average probability from model B
Shared (E) bike	0.589 (59%)
Shared (E) step	0.214 (21.4%)
Shared (E) scooter	0.095 (9.6%)
Individual AV	0.043 (4.3%)
Collective AV	0.057 (5.7%)

As shown in Table 3.9, the first multimodal hub option would be shared bikes (with 59% market share). Multimodal hubs (at least in the Netherlands) should reserve significant access/egress modes for shared bicycles. Based on model B, AVs (individual and collective) would collectively meet 10% demand for access/egress modes if they were present today. Model B also estimates reasonably high demand for motorised modes, especially shared e-step (21.4%) and e-scooters (9.6%), representing one-third of the market share. However, we need to emphasis that these predictions are based on a relatively biased sample towards the higher educated and relatively young sample of respondents and may not be extrapolated exactly to the total population.

3.5.7 Elasticities

By calculating elasticities, one can predict the percentage of market share one mode may lose by increasing travel time or travel cost by a specific percentage. In our case, we have increased time and cost by 10% and estimated a decrease in the market share of that given mode. Table 3.10 presents direct elasticities per mode based on model B.

Based on elasticities in Table 3.10, shared bikes will not be mainly affected by time or cost increases. On the other hand, individual or collective AVs are the most elastic alternatives from a cost perspective. Individual AVs may lose a much more significant market share than collective AVs, given a negative percentage change of -3.32 and -2.54. Comparing cost and time, we can observe that for these access/egress alternatives, the cost attribute has an enormous impact on AVs than the time attribute. This has important implications for AV producers and operators in the future since they need to keep costs competitive with incumbent modes.

Table 3.10: Direct elasticities per mode based on model B.

Alternatives	Model B Time Elasticity	 Cost Elasticity
Shared (E) bike	-0.366	-0.350
Shared (E) step	-0.703	-1.065
Shared (E) scooter	-0.803	-1.834
Individual AV	-0.882	-3.322
Collective AV	-1.129	-2.617

3.6 Conclusion and discussion

Currently, a limited set of modes has been used in stations but, in the future, there is ample potential for using emerging modes for better access/egress at multimodal hubs while also increasing the sustainability of travel. Recently, access/egress transport modes for the first/last mile of public transport trips have been attracting more attention in research and practice. By studying user characteristics of the emerging modes and travellers' preferences on the first/last mile trip modes, this paper provides insights regarding the share of these new modes, which can be valuable for dynamic design for every multimodal hub considering passengers' demands and behaviours.

We investigated the potential of emerging transport modes as new access/egress modes at a small-hub train station (Delft-Campus in the Netherlands). We obtained passengers' preferences towards different travel attributes (travel time, travel costs, availability of different modes) and investigated the impact of weather and carrying luggage on travellers' choices for the access and egress modes. We conclude that travel cost is more important than travel time. Further, the importance of the availability of transport modes is inconsiderable.

The models show that the use of (individual and shared) AVs is positively valued as first/last mile transport modes compared to other alternatives. This case study's findings also provide insight into how passengers' utilities change with different weather conditions and the presence or absence of luggage. We can also contemplate that when it is cold (e.g. ≤5◦c) or rainy, people are more willing to pay the higher ticket price for using AVs and tolerate longer travel time to use more comfortable access/egress modes.

The middle group of respondents (between 26 and 45) gained more utility from all alternatives than bikes regarding socio-economic demographics. Passengers who are middle-aged or with a low/middle education level or female are more likely to use motorised vehicles, especially shared e-scooters. In contrast, the older passengers or high-income groups gained utility by choosing the AV alternatives. Low-middle income groups also lost utility from the shared e-scooters and AV alternatives compared to the shared bike alternative.

Looking at the potential market share of the alternative access and egress modes, it seems that the demand for shared bikes is strong, and it would be the first option at small multimodal hubs, even by increasing 10% of its travel costs. Our model predicted more market share for the motorised modes, especially shared E-step (21.4%) and E-scooters (9.6%), constituting one-third of the future market share.

AVs are more likely to increase the utility of high-income and highly educated segments of society, an exciting mode for the first/last mile trip in coming years. However, the sample increases by 10% travel time, and cost drastically reduces the AVs' demands.

Given the sampling limitations and bias (i.e. highly educated and young population), one should caution against making general forecasts for public policy. The modal share and the market predictions are a product of our sample and thus are indicative results and may not be generalisable for the wider public, which is a significant limitation when using these results.

In conclusion, as general policy advice, besides characteristics of travellers, trips, modes, and built environment, the impacts of technology-emerging alternative modes should be given more attention by policymakers, planners, and designers in the coming years. It can be generalised that although emerging modes with their characteristics affect modal split and passenger preferences differently, a good combination of emerging modes at stations, besides walking, cycling, and buses, can provide attractive multimodal hubs. However, these modes need to be timewise and incredibly price-wise competitive with the current access/egress modes, especially short-distance trips. This means that introducing emerging modes and increasing their utilisation may require some support from authorities to get them fully active and functional.

As the general advice for bicycle-friendly countries like The Netherlands or countries with suitable topology, future small-sized multimodal hubs should supply and reserve at least half of their access/egress modes only for shared bicycles as the first option and then consider other emerging modes as well. This calls for the designers and station owners/operators to pay more attention to bikes and e-bike facilities.

Our study explored travellers' preferences for using five emerging modes as first/last mile transport at a multimodal trip. It is recommended to explore the impacts of the emerging modes on the spatial design of multimodal hubs for future research.

Chapter 4:

Residents' Preferences Regarding Shared Mobility in Car-Free Zones

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While the previous chapter addressed shared mobility for first/last-mile connectivity at multimodal hubs, this chapter expands the analysis to inner-city environments undergoing transitions toward car-free areas. In dense urban areas, private car dependence exacerbates congestion, inefficient land use, and reduced liveability. Promoting shared mobility in these settings offers a pathway toward sustainable and accessible transport alternatives; however, the behavioural responses of residents within actively transitioning car-free zones remain insufficiently understood.

This chapter investigates residents' preferences for shared electric mobility modes — (e-) bikes, scooters, cargo bikes, and cars — in Delft's inner city, which is gradually transforming into a car-free area under the "Mobility Plan 2040." A stated choice experiment examines how travel cost, walking time, socio-demographic characteristics, and trip purpose influence the adoption of these modes, while an "opt-out" option captures avoidance behaviour. A Mixed Logit model is applied to account for preference heterogeneity, estimate the Value of Time (VoT), and quantify the effects of attributes and socio-demographics on mode choice. Rather than forecasting demand, the experiment is used as a behavioural diagnostic of an urban transition in progress, identifying where and for whom the offered shared modes are not yet acceptable substitutes for residents' trips.

The chapter is structured as follows: Section 4.1 introduces the relevance of shared mobility in car-free zones and the associated research gaps. Section 4.2 reviews literature on car-free areas and modal shift dynamics. Section 4.3 describes the research methodology. Sections 4.4 through 4.6 cover descriptive statistics, survey design, and data collection. The main results are presented in Section 4.7, with conclusions in Section 4.8.

This chapter is based on the following papers:

Torabi Kachousangi. F., Araghi, Y., Hoogendoorn-Lanser, S., van Oort, N., & Hoogendoorn, S. (2024). Residents’ Preferences regarding Shared Mobility in Car-Free Zones: The Case of Delft’s Inner City. *Transportation Research Interdisciplinary Perspectives,* 38, 102120. https://doi.org/10.1016/j.trip.2026.102120

4.1 Introduction

Global urbanization and growing car dependence continue to intensify traffic congestion, air pollution, and reduced urban liveability (UN-Habitat, 2020; van Arem et al., 2022; Geržinič et al., 2024). A core illustration of this inefficiency is the disproportionate share of urban space devoted to private vehicles—most of which remain unused for over 90% of the time—creating structural barriers to sustainable spatial development (KiM, 2018). These challenges underscore the need for a fundamental shift in mobility patterns and the reallocation of urban space away from private car use.

Addressing car dependency has therefore become a central challenge for policymakers, demanding carefully tailored solutions. These strategies must simultaneously enhance urban mobility while effectively mitigating traffic congestion (Tate et al., 2025). Transportation and land use planning are inherently interdependent: transport decisions shape patterns of land development, while existing land use strongly influences travel demand and activity (Litman, 2025). Changes in travel behaviour induced by land use management strategies can simultaneously address urban challenges and support a wide range of planning objectives (Litman, 2025). At the same time, emerging transport technologies, such as shared micromobility services and electric mobility, offer potential alternatives to private car ownership, though their long-term implications for travel demand, urban form, and parking requirements remain uncertain (Shaheen et al., 2020).

In response, cities are increasingly pursuing two complementary pathways:

1. the implementation of car-free, car-reduced, or car-independent areas to reclaim public space and promote sustainable mobility (Nieuwenhuijsen, 2020; van Arem et al., 2022; Aumann et al., 2023; Brownrigg -Gleeson et al., 2025), and
2. the expansion of shared mobility systems (e-bikes, e-scooters, shared cars, cargo bikes) as flexible, low-carbon mobility alternatives (van Marsbergen et al., 2022; van Arem et al., 2022; Zhou et al., 2023; Geržinič et al., 2025; Torabi Kachousangi et al., 2025).

Although existing studies examine either the impacts of car-free zones or the role of shared mobility in urban areas, there is limited research on how shared mobility functions within newly implemented car-free environments. This gap is particularly relevant for policymakers, as it highlights the need to consider shared mobility alongside conventional modes such as walking, cycling, and public transport. Integrating shared mobility into car-free planning may therefore enhance accessibility and support a more comprehensive transition toward sustainable urban environments.

The Dutch planning context is particularly conducive to such transitions. Dense historical city centres, a strong cycling culture, and national policy shifts toward mobility hubs and car-free areas create favourable conditions for reducing car dependency (Torabi Kachousangi et al., 2025). While previous studies demonstrate the potential of car-free strategies to improve environmental quality and urban liveability (Nieuwenhuijsen, 2020; Geurs & Münzel, 2022; van Arem et al., 2022; Aumann et al., 2023) and highlight the role of shared mobility in supporting modal shift (van Marsbergen et al., 2022; van Arem et al., 2022; Zhou et al., 2023), they also reveal societal resistance (Pojani et al., 2018; Chun et al., 2019). Achieving a successful transition therefore requires not only infrastructural changes but also a deeper understanding of residents' behavioural responses and preferences. Research on mobility transitions shows that behavioural factors strongly influence attitudes toward shared mobility and reduced-car environments (Selzer & Lanzendorf, 2022; Torabi Kachousangi et al., 2025).

Existing literature on car-reduced and car-independent neighbourhoods in Europe (e.g., Aumann et al., 2023; Sprei et al., 2020; Basu & Ferreira, 2020) primarily explores environmental improvements, changes in space allocation, or public support for car-free planning. However, little is known about the behavioural mechanisms driving individual adoption—or rejection—of shared mobility within actively transitioning car-free contexts. Conventional choice models often investigate mode substitution (e.g., from private car to cycling or shared modes) but rarely incorporate non-participation or avoidance behaviour, where individuals choose not to travel at all under new mobility conditions. Furthermore, the social dimension of shared mobility remains underexamined: recent studies show that despite policy support, shared modes are not equally appealing across demographic groups, reflecting concerns related to comfort, identity, safety, or social norms (Geržinič et al., 2025; Selzer & Lanzendorf, 2022).

This omission creates a critical gap: residents who avoid shared mobility—even when high-quality infrastructure is available and policies are supportive—remain largely invisible in planning practice. Understanding the determinants of this opt-out behaviour, alongside socio-demographic variability in shared mode preferences, is essential for designing inclusive car-free mobility transitions.

This study is grounded in the behavioural-economic framework of Random Utility Maximisation (RUM) theory, which assumes that individuals choose the alternative that provides the highest perceived utility among a discrete set of options. In this context, residents evaluate shared mobility alternatives based on observable service attributes, such as travel cost and walking access time, as well as their own socio-demographic and trip-related characteristics. This theoretical perspective also motivates the use of a Mixed Logit model, which allows for preference heterogeneity across individuals and avoids the restrictive substitution patterns of simpler choice models. In addition, the study draws on the shared mobility acceptance literature, which suggests that behavioural, social, and contextual factors shape both the attractiveness of shared modes and the likelihood of rejecting them altogether. Accordingly, the opt-out alternative is interpreted as reflecting insufficient perceived utility of the offered shared modes for the recalled trip under the stated conditions.

This study responds to this gap by examining how residents evaluate shared electric mobility as one element within a broader car-free transition package in Delft's inner city. Rather than treating shared mobility as a stand-alone solution, we use a stated choice experiment to diagnose when shared modes are perceived as acceptable substitutes for a recently made trip and when they are not, given key service attributes (price and access distance) and heterogeneous resident characteristics. Crucially, the experiment includes an opt-out alternative to capture cases where none of the offered shared modes is considered a viable substitute for the recalled trip under the stated conditions. This allows us to identify potential accessibility and acceptance barriers that remain largely invisible when analyses assume universal mode substitution. We estimate Mixed Logit models to account for preference heterogeneity and to derive policy-relevant measures (e.g., sensitivity to distance access) that can inform the design of inclusive car-free transition strategies. We treat the stated choice experiment not as an end but as a behavioural diagnostic instrument for an urban transition in progress. The opt-out alternative is read through the lens of transition research: it identifies residents for whom the emerging car-free mobility system does not yet provide an acceptable option, making visible the social unevenness of the transition rather than merely estimating substitution elasticities. Modal choice is thus one component of a broader transformation—alongside the reallocation of public space, land-use change, and governance—and our contribution is specifically to its behavioural-acceptance dimension.

The findings provide planners and policymakers with evidence on how shared mobility can support the transition toward car-free, liveable urban environments. By identifying which resident groups are inclined to adopt shared modes—and why—the study offers actionable insights for designing accessible, inclusive, and socially equitable private car-free mobility systems.

4.2 Research background

This section provides a literature review that establishes the conceptual and empirical foundations of the study. It focuses on two core strategies central to our research, the creation of car-free areas and the role of shared mobility in modal shift and clarifies how these strands of literature inform the study's research gap and analytical approach.

4.2.1 Car-free zones: unlocking sustainable urban mobility

Sustainability principles have gained prominence in urban and transport planning, aiming to reduce car dependence (Buehler et al., 2017). The persistent reliance on privately owned, fossil fuel-powered vehicles remain a primary challenge to sustainable urban mobility in European cities, contributing significantly to greenhouse gas emissions, poor air quality and severe congestion (Ceccato et al., 2024). This car-centric paradigm also results in substantial spatial inefficiencies, evidenced by the vast amounts of public land dedicated to regulated parking and traffic infrastructure, thereby limiting opportunities for more sustainable urban uses (van Arem et al., 2022; European Parking Association, 2024).

In response, urban planning is shifting from a private car-dominated model toward one that greatly limits or eliminates private car use, fundamentally aiming to address environmental degradation, public health challenges, and social inequities (Gundlach et al., 2018; Aumann et al., 2023). These interventions take multiple forms, including pedestrian-only areas, low-traffic zones, car-free areas, car-independent neighbourhoods (Erturan & Aksel, 2024), as well as what the literature describes as car-lite or low-car(bon) developments, private-car-restricted and mobility-served neighbourhoods, and areas governed by low or maximum parking requirements (Basu & Ferreira, 2020; Sprei et al., 2020). Removing car-oriented infrastructure in these contexts frees considerable urban space, enabling the expansion of public areas and green spaces for pedestrian use (Nieuwenhuijsen and Khreis 2016). Consequently, these environments reclaim urban space for diverse residents to move safely and comfortably, without the barriers posed by motorized traffic (Erturan & Aksel, 2024). Concepts like the 15-Minute City prioritise integrated land use, walkable urban density, and the fundamental redistribution of urban space away from private motorised transport to favor active and public transport modes (Christidis et al., 2024; Wang et al., 2024; Brownrigg-Gleeson et al., 2025).

The successful creation of genuinely private car-free zones requires a rigorous combination of prohibitive (push) and facilitative (pull) measures. Push measures—such as Urban Vehicle Access Regulations (UVARs) (Ogunkunbi & Meszaros, 2022), including Low Emission Zones (LEZs) (Fransen et al., 2023)—play a critical role in reducing the presence of pollutant vehicles and initiating shifts in travel behaviour (Ceccato et al., 2024). However, these interventions primarily function as preparatory steps for the broader objective of reallocating street space. Effective implementation relies particularly on strong pull factors: substantial investments in high-quality public transport, dedicated cycling and walking infrastructure, and the expansion of shared mobility systems. While push policies constrain car use, pull measures enable sustainable mobility choices in everyday life. Reviews of complex interventions show that integrating both approaches is most effective in achieving the modal shift required for a car-free urban fabric.

Empirical evidence confirms the transformative potential of car-free planning: neighbourhoods explicitly designed for car independency exhibit structurally lower levels of car ownership and usage, with residents showing a higher propensity to adopt non-motorised and collective transport options (Aumann et al., 2023). However, the successful implementation of this transition is highly contingent on key social and governance factors. This includes effectively managing behavioural change, ensuring spatial and social accessibility for all user groups, and establishing inclusive governance to maintain public acceptance of radical spatial changes (Torabi Kachousangi et al., 2025). Importantly, public acceptability has been identified as a critical condition for the successful adoption of access regulations and alternatives to private car use (Ogunkunbi & Mészáros, 2022).

Despite the clear benefits and growing global implementation of these low-car and car-free models, research remains fragmented. There is limited empirical evidence on how such complete spatial strategies systematically influence mobility behaviours, accessibility outcomes, and modal shift across varied urban contexts. This gap underscores the need for studies that rigorously analyse the effectiveness of dedicated car-free zones within the wider transition towards a sustainable urban mobility system.

4.2.2 Role of shared mobility in modal shift

Reducing the number of vehicles on the road and promoting shared mobility options are essential for achieving sustainable transportation goals (Zhou et al., 2023). Shared mobility refers to various shared services such as (electric) carsharing, bike-sharing or any other shared means of transport (Shaheen et al., 2016), utilised on an 'as-needed' basis (Machado et al., 2018; Shaheen et al., 2017). These services serve as primary modes of transport and provide crucial first/last-mile connectivity at public transport stops (Geržinič et al., 2025; Humm, 2020; Stam et al., 2021). However, the effective integration of these services with public transport systems remains complex, as it involves challenges related to physical infrastructure, institutional coordination, and digital systems (Brown & Van Oort, 2026). Smart mobility options operate independently of private car ownership and offer substantial, yet still largely untapped, potential to supplement or even replace car-based travel while requiring significantly less space (van Arem et al., 2022; Zhou et al., 2023; van Marsbergen et al., 2022). Shared mobility services such as (electric)- bike sharing, scooter sharing, cargo bike sharing, and carsharing hold promise for reducing car dependency. However, empirical evidence also highlights that the substitution dynamics are not uniformly beneficial; for example, e-scooters frequently replace walking or public transport rather than private car trips in several European cities, raising concerns about their overall sustainability. Indeed, some cities have scaled down or discontinued public e-scooter programs due to safety, clutter, and limited environmental benefits.

Despite these concerns, recent studies still report meaningful substitution potential under favourable spatial, regulatory, and pricing conditions. For instance, micromobility modes such as e-bikes and e-scooters can replace approximately 30% of short car trips in dense urban centres (Fitt and Curl., 2019). Conventional shared bikes are particularly suitable for trips between 1 and 1.6 km and have been shown to substitute for car use and public transport (Reggiani et al., 2023; Boor, 2019; Shen et al., 2018; Abduljabbar et al., 2021). Moreover, e-scooters demonstrate substitution effects for short-distance car trips when supported by appropriate infrastructure and integrated pricing strategies (Torabi Kachousangi et al., 2022; Torabi Kachousangi et al., 2025; Van Kuijk et al., 2022; Masoud et al., 2019; Hollingsworth et al., 2019; PBOT, 2019). Taken together, these findings suggest that while unintended mode shifts may undermine sustainability outcomes, shared micromobility can still contribute to reducing car dependency when aligned with targeted local mobility policies.

Shared cargo bikes offer a sustainable alternative for transporting goods and toddlers (Becker & Rudolf, 2018; Fishman et al., 2013; Zademach & Musch, 2016), with studies showing substitution for up to 46% of car trips (Becker & Rudolf, 2018).

The availability and convenience of carsharing services encourage the transition from private car ownership (Liao et al., 2020; Nijland et al., 2015). Frequent carsharing use substantially reduces reliance on private cars, with each shared car potentially replacing up to 16 privately owned cars (Schreier et al., 2021). Introducing shared electric vehicles further enhances sustainability benefits and promotes a shift toward active transportation (Martin & Shaheen, 2016; Liao & Correia, 2022).

However, societal values highly affect shared mobility perception and acceptance, making it challenging to shift from privately owned cars to shared alternatives (Geurs & Münzel, 2022; Pojani et al., 2018; Chun et al., 2019). For instance, shared mobility is sometimes perceived as an option for lower socioeconomic groups, while vehicle ownership is associated with higher status (Pojani et al., 2018; Chun et al., 2019). Moreover, adoption and usage are highly influenced by socioeconomic characteristics, trip characteristics, and contextual variables (Torabi Kachousangi et al., 2022; Van Kuijk et al., 2022). To ensure an equitable and inclusive mobility transition, it is particularly critical to address the needs and limitations of the ageing population. Therefore, to effectively design inclusive strategies, it is essential to understand how actual and perceived mobility limitations shape individual choices, especially the decision to opt-out of a trip entirely.

4.3 Research methodology

We have developed a stated choice experiment to address residents' intentions to use shared mobility services and the potential to reduce private car use by introducing car-free areas and shared mobilities in inner cities. This experiment aims to reveal residents' preferences for these services. The city centre of Delft, which serves as an example of a car-free zone, has been selected as the case study for this research.

4.3.1 Case study: Delft inner-city (in The Netherlands)

Delft is a small, medium-sized historic city with around 103,500 inhabitants in the Netherlands. Delft will continue to develop in the coming decades, and the municipality is ambitious to add 15,000 homes and 10,000 jobs by 2040. This city's growth by about 30% by 2040 will negatively affect its accessibility and mobility if suitable measures are not taken.

The historic downtown was designed for pedestrians. However, cars gradually took over the streets. With the implementation of low-traffic programs in the 1990s, car traffic started reducing in the inner city. This positive development creates more space for public activities. The Delft Mobility Program 2040 and Environmental Vision Delft 2040 aim to improve accessibility and increase sustainability in Delft by accelerating the mobility transition from private cars to more public transport modes and making an utterly car-free city centre in 2040 (Gemeente Delft, 2021a,b) (Figure 4.1).

These reports have mentioned that the disappearing parking spaces should be compensated for by introducing mobility hubs and appropriate transport and facilities. Offering shared mobility (shared cars and shared bicycles) in public spaces (mobility hubs) offers opportunities to reduce car ownership and use sustainable transport modes, making the transport network more sustainable (Gemeente Delft., 2021a, b) (Figure 4.1).

We have selected Delft city centre as our case study because it has already taken significant steps towards becoming a low-car or even car-free city centre. The existing policies in Delft, such as the Delft Mobility Program 2040 and the Environmental Vision Delft 2040, actively promote the transition from private car usage to shared modalities and public transport. Furthermore, the availability of shared mobility options, such as shared cars and bicycles, makes Delft a potentially good candidate to study the impact and feasibility of a car-free and shared mobility-focused urban environment.

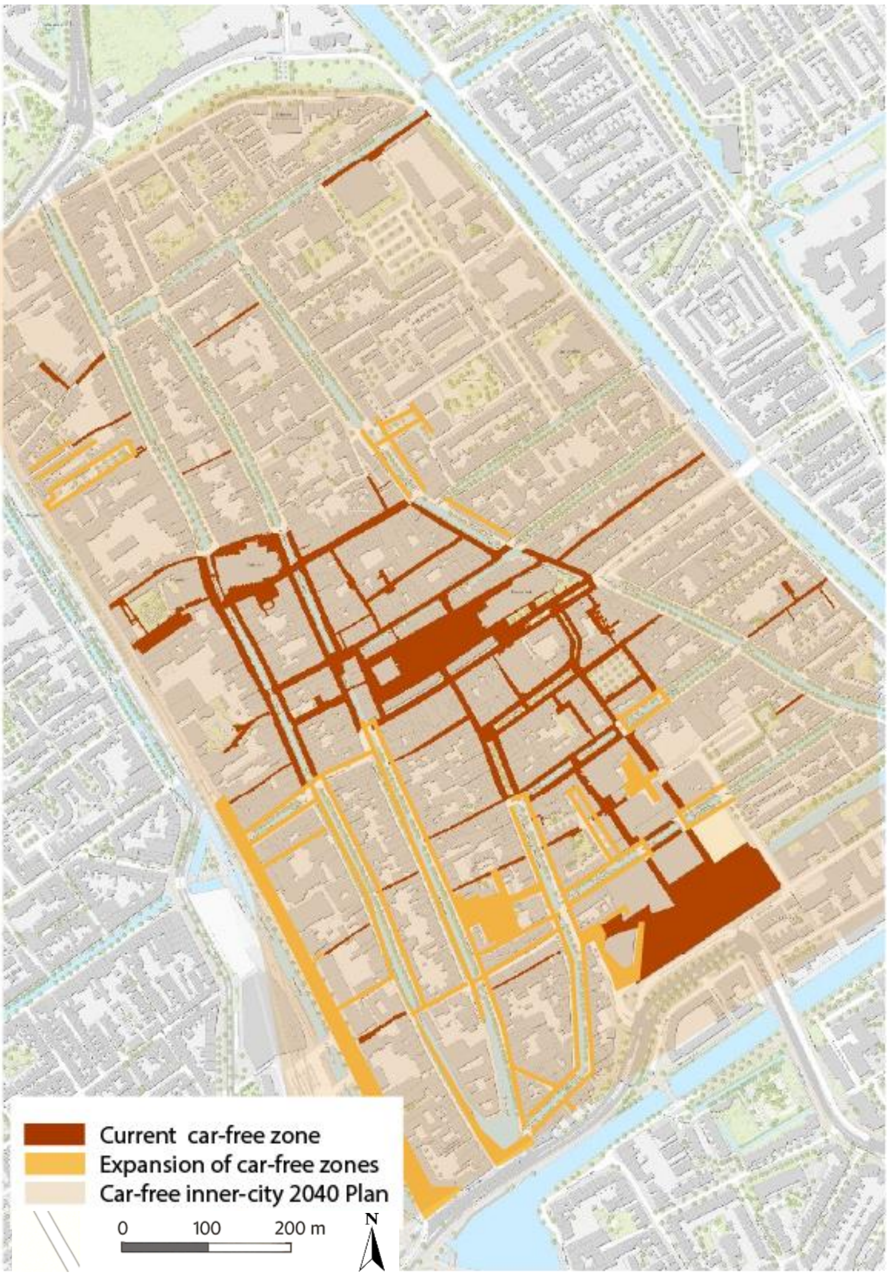

Figure 4.1: Current and proposed car-free zone in the Delft inner city (source: Gemeente Delft, 2021; edited by the author).

4.3.2 Survey overview

To identify the factors influencing these attitudes and to capture both current and potential future-mode choice behaviour, an online survey was conducted consisting of two main components. The first part collected background information, including socio-demographic characteristics and general travel behaviour of Delft's inner-city residents. The second part contained the stated choice experiment, which forms the analytical basis of this study. This survey (English and Dutch versions) was advertised on Delft Municipality's social media pages (Facebook and Instagram) between November 14 and December 7, 2022, and was only accessible to inner-city residents. As recruitment relied on municipal social media, the sample should be interpreted as a convenience sample that may overrepresent digitally engaged residents; accordingly, we frame the findings as behavioural diagnostics within this context rather than population-representative forecasts. This focus was intentional, as the Delft Mobility Plan 2040 specifically targets the city centre. The survey began with a brief explanation of the study's purpose and context, including an introduction to shared mobility in Delft's inner-city, the rationale for the municipality's interest in residents' travel preferences, and information on how the survey results would be used to support future mobility planning.

Part 1: Background information (Revealed Preferences)

This survey aims to capture the level of familiarity of residents with shared modes, car dependency, and socioeconomic characteristics. Firstly, they were asked about their shared experience modes and willingness to use them instead of private cars. Then, respondents were asked to consider their recent max 20 km distance trip from Delft inner-city and specify the means of transport used and other information regarding trip purposes, destination, and travel companions. Finally, some general questions about gender, age, family status, education level, income, driver's license possession and owning cars were raised. According to the literature review, all these factors could influence mode choice.

Part 2: stated choice experiment

A stated choice experiment was performed in this study to examine the substitution potential of shared modes for private cars. Twelve choice sets were generated based on four potential alternatives for private cars: 1) shared (e) bike, 2) shared (e) scooter, 3) shared (e) cargo bike, 4) shared (e) car, and 5) opt-out, and two attributes; 1) travel cost and 2) walking time to shared modes. These modes were selected because past studies (e.g. Torabi kachousangi et al. 2022; 2025; Nijland et al. 2015) have identified shared bikes, scooters, and cars as potential alternatives for private cars in the Netherlands. While cargo bikes are becoming increasingly popular there, the potential of shared cargo bikes has not yet been extensively studied (Rickmers, 2022). Our study aims to investigate the potential of all these shared modes in the city centre, exploring their viability for reducing car dependency and enhancing urban mobility. This makes them suitable options for exploring the transition towards sustainable urban transport systems. Moreover, the inclusion of an "opt-out" option allows the model to capture both the participation and mode choice decisions, accounting for possible reluctance toward shared mobility. This option also makes the choice process more realistic by enabling individuals to opt-out of shared modes altogether.

Regarding attributes, travel cost and walking time to reach shared modes are essential factors influencing modal choice based on literature. These are considered with two corresponding attribute levels in our SP experiment. The travel cost attribute levels were based on the pricing structures of major shared mobility operators active in the Dutch market, including Felyx and Check for shared e-scooters, Donkey Republic for shared e-bikes, Cargoroo for shared cargo bikes, and Greenwheels and MyWheels for shared car-sharing services. These sources reflect the prevailing per-minute tariffs in the Netherlands during 2022, providing realistic and policy-relevant ranges for the stated choice experiment. Besides, walking time, denoted as the maximum distance to reach the first shared mode, has been estimated to range between 2 min and 10 min, as shown in Table 4.1. The selection of alternatives and attributes are all based on the importance mentioned in literature.

Table 4.1: Overview of attributes and attribute levels used in the SP experiment.

Attributes	**Attributes levels**	
Travel cost-shared (e) bike	€ 0.10/ min	€ 0.30/ min
Travel cost-shared (e) scooter	€ 0.20/ min	€ 0.40/ min
Travel cost-shared (e) cargo bike	€ 0.20/ min	€ 0.40/ min
Travel cost-shared (e) car	€ 0.50/ min	€ 0.70/ min
Walking distance to access shared (e) bike	1 min	3 min
Walking distance to access (e) scooter	1 min	3 min
Walking distance to access shared (e) cargo bike	3 min	7 min
Walking distance to access shared (e) car	7 min	10 min

To design the choice sets, an efficient design was generated using Ngene software. Unlike orthogonal designs, efficient designs require prior information on parameter estimates; therefore, two pilot studies based on orthogonal design were conducted to obtain preliminary coefficient priors. Using these priors, the final efficient design was constructed for the main survey, comprising five alternatives, two attributes (travel cost and walking time), and two attribute levels, resulting in 12 choice sets in total. A sample is shown in Figure 4.2.

Choice Set A1	 Shared (e) bike	 Shared (e) scooter	 Shared (e) cargo bike	 Shared (e) car
Cost per minute	0.10 euro	0.20 euro	0.40 euro	0.70 euro
Walking Time to shared modes	3 min	3 min	3 min	7 min

1) Shared (e) bike 2) Shared (e) scooter 3) Shared (e) cargo bike 4) Shared (e) car 5) I'd not travel with these shared modes

Figure 4.2: Example of giving a choice set to respondents in the survey.

To minimise cognitive burden and survey fatigue while maintaining statistical validity, the design was blocked into two groups of six choice sets. Each respondent was randomly assigned to one block and thus evaluated only six choice sets, which is consistent with standard practices in stated choice experiments (Hensher et al., 2015). This approach balances efficiency and respondent engagement, ensuring high-quality responses without compromising the design's robustness.

Participants were instructed to recall their most recent trip (within 20 km of Delft's inner city) and to indicate, for that specific trip, whether they would use one of the offered shared electric modes or none of them ("I would not travel with these shared modes"). The alternatives were deliberately restricted to shared modes because the motivating policy question—how mobility hubs and shared fleets can compensate for reduced private-car access under the Delft Mobility Plan 2040—concerns the shared offer specifically; walking and cycling are already dominant and unconstrained in the inner city. Accordingly, the opt-out denotes non-acceptance of the shared substitution for that trip and does not imply that the respondent would forgo the trip or be barred from using a private car or other non-shared mode. This framing means that respondents reconsidering an already-sustainable trip (e.g., walking or cycling) can rationally opt-out, while the transformative question—substituting a car trip—is captured directly by the car-based sub-sample analysed in the descriptive analysis of opt-out behaviour (Section 4.1.4, Table 4.5- 4.6).

We analysed the stated choice (SP) experiment using discrete choice models within the framework of Random Utility Maximisation (RUM) (Train, 2009). Under this framework, individuals are assumed to choose the alternative that provides the highest utility among the available options, where utility is a function of observable attributes and unobserved factors.

We selected the Mixed Logit (ML) model for our analysis as it offers greater flexibility and behavioural realism compared to the standard Multinominal Logit (MNL). Unlike the MNL, which is constrained by the Independence of Irrelevant Alternatives (IIA) assumption, the ML relaxes this assumption and allows substitution patterns to vary across alternatives (Train, 2009; McFadden & Train, 2000). This flexibility is particularly important in our context, as travel behaviour is unlikely to follow strictly proportional substitution, and individuals exhibit heterogeneous sensitivity to cost and accessibility (Hensher et al., 2015).

Moreover, the ML captures unobserved preference heterogeneity by treating key parameters as random, thereby accounting for individual differences in tastes and sensitivities that cannot be explained by observed socio-demographic variables alone. Incorporating this heterogeneity improves both model fitness and interpretability, yielding a more accurate representation of travel behaviour.

The models were estimated in R (RStudio) using simulation-based maximum likelihood with the Apollo package (Hess & Palma, 2019), a flexible and widely used framework for discrete choice analysis. To perform numerical integration and improve simulation accuracy, we employed 1,500 Halton draws, which provide more efficient coverage of the parameter space than purely random draws. The random parameters, particularly for travel cost and walking time, were modeled using exponential distributions to ensure effects consistent with behavioural expectations, thereby capturing heterogeneity in sensitivity across individuals. 138 respondents each evaluated six choice sets, giving 828 panel observations. Mixed Logit pools information across all observations and respondents, and the random coefficients are identified from within-respondent variation across the six repeated choices; the attribute and heterogeneity estimate therefore do not rest on the non-opt-out sub-sample alone. Because the opt-out share is a share of choices (531 of 828) rather than of respondents, the four shared modes are still chosen in 297 observations distributed across the majority of respondents.

This estimation strategy combines theoretical rigor, empirical performance, and behavioural realism, making maximum likelihood the most suitable approach for our study.

4.4 Descriptive analysis of the empirical survey

This section presents the descriptive statistics of the survey sample and provides an overview of current travel behaviour, distinguishing between private car use, shared mobility experience, and the socio-demographic profile of the opt-out group.

In total, 169 respondents completed the survey. 31 respondents were excluded from the data set due to travelling further than the maximum 20 km distance; the remaining 138 respondents formed the data set in this study. This equals 828 complete choices, higher than the minimum required (i.e. 528).

4.4.1 Descriptive statistics

Regarding the socio-demographic characteristics of the sample, Table 4.2 shows that it contains higher shares of old ≥50 years (64%), university-educated (87%), and high economic level ≥71.000 euro (32%) users who are mostly household with at least two adults (57%), single (30%) and 15% have children up to 17 years old. Regardless of age, they mostly are fully physically mobile (87%), and only 12% have mobility limitations due to their age, concerning cycling and walking, respectively.

Table 4.2: Sample statistics with different socioeconomic variables.

Socio-economic variable	Category	Share sample	Category	Delft population
Age	18-39	22%	15-25	20%
	40-49	12%	25-45	31%
	50-69	43%	45-65	20%
	70≤	21%	65≤	16%
Gender	Male	56%	Male	53%
	Female	42%	Female	47%
Family status	Single	30%	Single	59%
	Households with at least two adults	57%	Multi-person households	41%
	Household with 1≤ children the age 12 years old or younger	10%	Multi-person households without children	21%
	Household with 1≤ children age of 13 up to 17 years old	5%	Multi-person households with children	20%
Hiving children	Yes	55%	-	-
	No	44%	-	-
Number of children	1	23%	-	-
	2-4	77%	-	-
Education level	Less formally educated (under HAVO and VWO)	11%	Practical education level	18%
	Moderately educated (HBO / WO (Bachelor's degree)	30%	Secondary education level	35%

	Highly educated (HBO / WO Master's or doctoral degree)	57%	Theoretical education level	47%
Income (Total family gross annual)	Less than € 42.400	21%	€26.000-€28.000	9%
	Between € 42.400 and € 71.000	19%	€28.000-€32.000	27%
	Between € 71.000 or more	32%	€32.000 or more	64%
Health ability	I am fully mobile (physically able)	87%	-	-
	My mobility is limited (due to age, pregnancy, etc.)	12%	-	-
Health limitation	Walking	53%	-	-
	Cycling	59%	-	-
	Driving	24%	-	-
	Travelling by public transport	12%	-	-
Having driving license	Yes	93%	Yes	74%
	No	5%	No	26%
Having car (private or lease)	Yes	70%	Yes	69%
	No	30%	No	31%
Average Use of car	Daily or weekly	79%	-	-
	Monthly	21%	-	-
Reasons for using car	Rainy/cold weather	34%	-	-
	If I have a heavy, big and a lot of bags (s)	65%	-	-
	When I travel with people who are old and/or children	33%	-	-
	When I have a long trip	76%	-	-
	Always	7%	-	-
	Never	4%	-	-
	Other	14%	-	-
Willing to use shared modes	Yes, for the most trips	8%	-	-
	Yes, occasionally	35%	-	-
	No	57%	-	-

To assess sample representativeness, Table 4.2 compares respondents' socio-demographic characteristics with those of the Delft population. The sample includes a higher proportion of older respondents (64% aged 50 or above) and slightly more males (56%) than the city average (53%). Single-person households are underrepresented (30% vs. 59%), while highly educated individuals are overrepresented (57% vs. about 47%). Car ownership in the sample (70%) is similar to the Delft average (69%), although driving licence possession is considerably higher among respondents (93% vs. 74%). Overall, the sample is somewhat skewed toward older, highly educated, and car-oriented individuals.

Figure 4.3 shows that participants travel most often for social/recreational/visitation purposes (40%) and work/education (35%), with the majority traveling alone (60%). These trips primarily target nearby cities such as Delft, Den Haag, and Rotterdam, with a common travel time of 16-30 minutes.

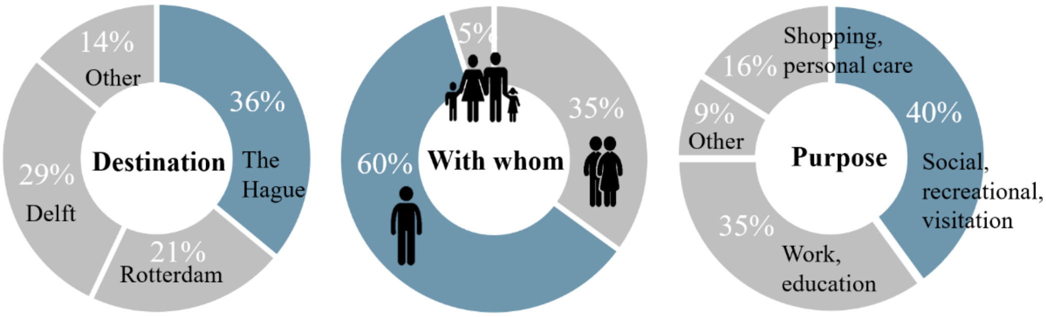

Figure 4.3: Current journey characteristics of Delft inner city residents.

To characterise the trips respondents were asked to reconsider, Table 4.3 reports the original mode of the recalled trip. Car-based trips (driver or passenger) account for 37.7% of recalled trips, with active modes (bicycle, e-bike, walking) making up 48.6% and public transport 10.1%.

Table 4.3. Original mode of the recalled trip (n = 138).

Original mode of recalled trip	Respondents	Share
Car (driver)	43	31.2%
Car (passenger/other car)	9	6.5
Bicycle	21	15.2%
E-bike	14	10.1%
Walk	32	23.2%
Other private	5	3.6%
Public transport	14	10.1%
Total	138	100%

We tested the impacts of socioeconomic indicators on car and shared mode use in Delft City Centre, following age, gender, and family status. Below, we provide an overview of our main findings.

4.4.2 Experience of using private cars and its reasons

As shown is Table 4.2, considering 93% of respondents have a driving license, and 70% have a private or lease car, resulting in significant weekly car use (79%) in Delft city centre, 64% by 1-3 days per week and 15% by four days per week or more. The main reasons are long trips (76%), carrying a heavy, big or numerous bag (65%), and rainy/ cold weather (34%) respectively in all age groups.

The data indicated that 57.7% of individuals over 40 used a car 1-3 days per week. Among all age groups, daily car usage (4 or more days per week) was highest among those aged 50-59 (7.2%). Factors such as adverse weather, heavy or numerous bags, and long trips were significant reasons for car use among individuals aged 40-69. Regarding gender,43% of men drive weekly compared to 34% of women. Both men (57%) and women (41%) primarily drive for long trips and heavy bags. More than half the female population always uses cars, but 33% of the total use is for males. Without a car, 11.5% of women and 13.5% of men use trains or bikes, and 1.9% of men use shared cars. In addition, the findings showed that 85% of singles and families with teenagers use a car weekly. However, families with children under 12 use a car monthly (27.3%).

4.4.3 Experience of using shared modes and its reasons

The survey revealed that most have never used shared modes: shared cargo bike (97%), shared car (79%), shared scooter (77%), and shared bike (66%), respectively. Although 57% are not interested or unsure about using shared modes to travel to a destination outside the city centre, 44% would use them occasionally (35%) or frequently (9%), primarily single men. Families with children (64.3%), especially those under 12 (35.7%), show higher interest, whereas older adults over 50 (46.6%) are the primary opponents. On the other hand, younger users (aged 18-29) are more open to occasional use. They also declared they are willing to walk up to 5 minutes to access these modes (bike 27%; scooter 22%; cargo bike 18%; and car 25%). Figure 4.4 shows the familiarity and experience of Delft's inner-city residents with shared mobility modes.

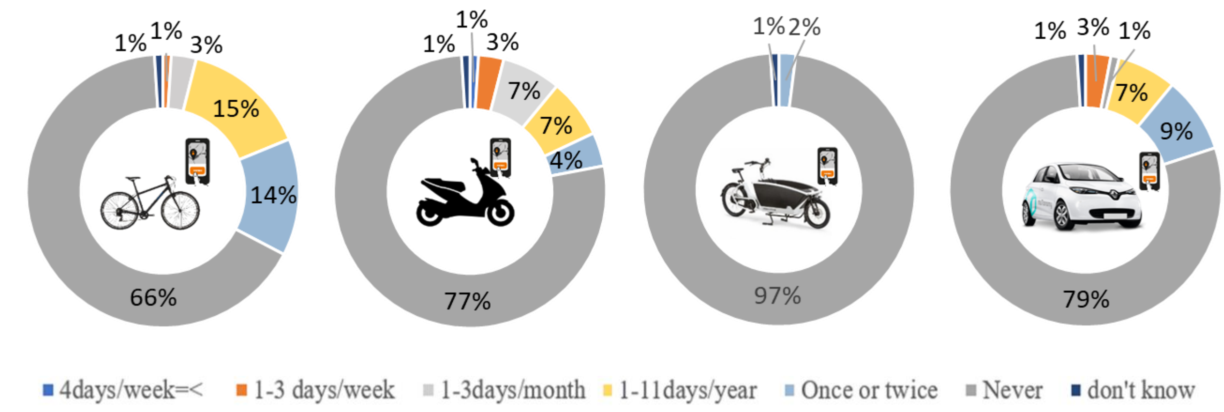

Figure 4.4: Experience of using shared modes of Delft inner city residents.

Shared bike; Despite 66% of residents never using shared bikes, 14% have tried once or twice. The shared bike is mainly used annually (15%), with the highest usage among those aged 25-29. However, those aged 30-39 years often use this mode four days/week or more. Looking at the family status and gender of dominant users shows that single and families with children are the primary users, with men more experienced than women. Regarding the max walking time, users under 40 prefer to walk 5 minutes, while those over 40 prefer a 2-minute walk to reach a shared bike. Moreover, men are willing to walk longer distances than women to reach shared bikes.

Shared scooter: Unlike shared bikes, shared scooters have been mainly used monthly (7.1%). Young individuals aged 18-29 years used it at least once per week. Data shows that shared scooters are more attractive for singles, families with kids under 12 years old, and males, respectively. Female over 40 are more willing to walk 5 minutes to access shared scooters, while younger men users prefer a 2-minute walk.

Shared car: Considering 79% of residents of Delft City Centre have never used a shared car, while 9% have tried it once or twice. Interest decreases among 18-40 years old and increases for those over 40. In addition, families with teenagers and singles use shared cars weekly (28.6%) and yearly (14.6%), respectively. Most users are willing to walk up to 5 minutes (25%), primarily men (13.8%), with some willing to walk 10 minutes (23%), mainly women over 40.

Shared cargo bike: Shared cargo bike has the lowest usage, with 97% of residents having never used them. The few users are mainly single men aged 25-29 (1.4%)—no families with children reported using shared cargo bikes. Interest in accessing shared cargo bikes decreases with age, with most men willing to walk up to 5 minutes.

4.4.4 Observed mode shares from the survey

Table 4.4 presents the observed shares of travel modes based on the stated choice survey responses. The results show that most respondents (64%) selected the opt-out option, indicating a strong tendency to abstain from shared mobility use under the given conditions. Among shared modes, shared e-scooters (12%) and shared bikes (12%) were the most frequently chosen, while shared e-cars (10%) and particularly shared e-cargo bikes (1%) were selected far less often.

These findings suggest that while there is noticeable interest in lightweight shared mobility options, significant barriers remain, particularly related to cost, access, and convenience, that may limit their attractiveness compared to existing transport modes. The high share of opt-out choices indicates that, for many respondents and recalled trip contexts, the presented shared-mode options (given their price and access distance) were not considered acceptable substitutes.

Table 4.4: Observed mode shares form the stated choice survey.

Alternatives	Observations (count)	Average Probability from MXL model
Shared (e) bike	100	0.120 (12%)
Shared (e) scooter sharing	103	0.124 (12%)
Shared (e) cargo bike	10	0.012 (1%)
Shared (e) car sharing	84	0.101 (10%)
Opt-out	531	0.641 (64%)

4.4.5 Socio-demographic profile of optouts

Identifying the socio-demographic characteristics of individuals who opt-out of shared mobility is crucial for understanding resistance to the car-free transitions. Figure 4.5 shows socio-demographic profile of optouts including gender, age, education, income, trip purpose, willingness to use shared modes and interaction of age with income and education.

To support interpretation of the opt-out alternative, we first examine how opt-out selections relate to respondents' mobility context. As the stated choice task asked respondents to substitute a specific recalled trip, a high opt-out share does not necessarily imply opposition to shared mobility in general but may reflect limited substitutability for particular trip–mode combinations.

Descriptively, opt-out choices were more frequent among respondents who reported access to a private car and among trips originally made by car, whereas respondents without car access showed a higher propensity to select at least one shared mode. This pattern suggests that the opt-out often reflects trip-specific feasibility rather than categorical rejection of shared mobility.

Opt-out behaviour is strongly conditioned by the trip being reconsidered and by mobility resources. Table 4.5 shows that respondents recalling a car-based trip opted out of the shared alternatives in 74.7% of their choices, more than double the 32.1% rate among those recalling a public-transport trip; active-mode trips fell in between (62.7%). Car owners opted out far more often than non-owners (72.3% vs. 44.7%) (Table 4.6). These patterns indicate that a high opt-out share does not reflect categorical opposition to shared mobility but rather limited substitutability for specific trip–mode combinations—above all, the substitution of a private-car trip. This trip-conditional reading reframes the opt-out as a diagnostic of where and for whom shared modes are not yet acceptable, rather than as blanket resistance.

Table 4.5: Opt-out rate by the original mode of the recalled trip.

Recalled trip category	Respondents	Opt-out rate
Car-based (driver / passenger)	52	74.7%
Active / other (bike, e-bike, walk)	72	62.7%
Public transport	14	32.1%

Note: "Car-based" combines car driver (43) and car passenger (9); "Active / other" combines bicycle (21), e-bike (14), walking (32), and other private non-car, non-PT trips (5). Categories correspond to those in Table 4.3.

Table 4.6: Opt-out rate by household car ownership.

Recalled trip category	Respondents	Opt-out rate
Owns or leases a car	97	72.3%
No car	41	44.7%

Figure 4.5: Socio-demographic and behavioural patterns of opt-outs

Age is the most decisive factor: 84% of opt-outs are aged 50 or above, strongly highlighting a generational reluctance to embrace shared modes. This age effect is reinforced by the distribution of education and income across age groups. Older cohorts, particularly those between 60–79 years, not only dominate the opt-out group but also hold higher educational qualifications, with many possessing a master's degree or above. At the same time, these age groups are disproportionately represented in the upper income brackets (€72,000–84,000 and above €84,000), underlining that disengagement is primarily concentrated among financially secure and highly educated older individuals.

Furthermore, opting out is concentrated among highly educated and financially secure individuals, suggesting reluctance is not driven by financial constraints or lack of awareness. Specifically, 52% of opt-outs hold a master's degree or above, and over one-third earn above €84,000 annually, with these older cohorts being disproportionately represented in the highest income brackets (€72,000–€84,000 and above €84,000). Regarding trip characteristics, opt-outs are slightly more likely to be male (56%). The opt-out decision is most common for recreational travel (42%), followed by work or education and shopping or personal care (25%).

Attitudinal data reinforce the resistance, as nearly four in five respondents (79%) reject shared mobility outright, while only 2% are willing to adopt it for all trips. Figure 4.6 shows shared modes experience of opt-outs, with most reporting rare use and very few using them often.

Overall, individuals opting out are best described as older, higher income, highly educated, and firmly committed to private mobility. Their higher propensity to opt-out is consistent with several plausible barriers—such as digital access, perceived comfort/safety, physical effort, and established travel routines—which cannot be fully disentangled in the present design and should be investigated further using attitudinal measures or revealed behaviour.

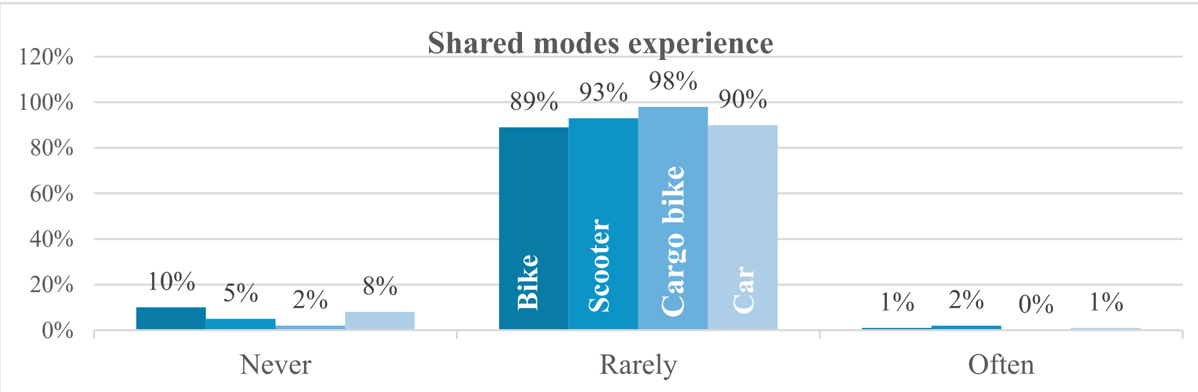

Figure 4.6: Shared modes experience of opt-outs.

4.5 Choice modelling results

This section presents and interprets the results of the discrete choice modelling analysis and explains how the estimated parameters provide insight into residents' preferences for shared mobility in a car-free context. We first report the outcomes of the Mixed Logit (ML) model, which was estimated using the stated choice data described in Section 4.4. The models focus on service attributes (price and access distance), and respondent characteristics, while treating the recalled trip as the behavioural reference point rather than modelling its full set of characteristics. This reflects the study’s exploratory objective: to examine conditional willingness to substitute a recently made trip under shared-mobility scenarios, rather than to predict mode choice for all trip types. As discussed later, trip-specific factors such as original mode and vehicle access are therefore examined descriptively to support interpretation of the opt-out alternative.

As a robustness check, car ownership was included as an additional interaction variable to capture the influence of private vehicle access on substitution behaviour. The results suggest that car ownership slightly increases the likelihood of selecting the opt-out alternative, indicating a lower propensity among car owners to consider shared mobility substitutions. However, the inclusion of this variable did not materially affect the estimated coefficients of the core attributes (travel cost and walking time) or alter the overall behavioural patterns observed in the baseline model. Furthermore, most interaction effects involving car ownership were not statistically significant, and the extended model exhibited a marginally weaker overall fit compared to the more parsimonious specification. For these reasons, the final model specification includes both the main effects, a comprehensive set of socio-demographic interactions, and trip purposes to capture observed and unobserved heterogeneity in mode choice behaviour.

We estimated a further specification adding the prior trip mode (car-based vs. non-car recalled trip) as an interaction on the opt-out alternative, alongside car ownership. The interaction is signed as expected, a car-based recalled trip increases the opt-out propensity, consistent with the descriptive gap in Table 4.5, but it does not significantly improve fit (likelihood-ratio test below the $\chi^2(1) = 3.84$ threshold at 5%) and leaves the travel-cost and walking-time parameters essentially unchanged. Because prior mode is a respondent-level attribute strongly collinear with car ownership and age, it is only weakly identified in a sample of 138 respondents and costs degrees of freedom without altering the substantive findings. We therefore retain the parsimonious specification as the main model and report this as a robustness check. Notably, the reduction in the random-parameter standard deviations when trip- and ownership-related terms are added indicates that part of the unobserved heterogeneity originates in the characteristics of the trips and modes being substituted, not in person-level demographics alone, a point we treat as a substantive finding and a motivation for the trip-enriched designs recommended in the discussion and future-research section.

The model fit indicators (LL = –514.2, Adj. $\rho^2 = 0.593$, AIC = 1084.4) demonstrate that incorporating socio-demographic factors substantially enhances the explanatory power of the model. Moreover, the Mixed Logit (ML) specification significantly outperforms the standard Multinomial Logit (MNL) model (LL = –898.3, Adj. $\rho^2 = 0.452$, AIC = 1461.7), underscoring the importance of accounting for taste heterogeneity. Together, these results confirm that capturing both observed and unobserved heterogeneity yields a more accurate and behaviourally realistic representation of shared-mobility choices. Table 4.7 presents the parameter estimates of the Multinomial Logit (MNL) model, showing the main effects of travel cost, walking time, trip purposes, and socio-demographic factors on shared mobility mode choice.

Table 4.7: The parameter estimates of the MNL model.

Main effects	**MNL Model + Socio-demographic**	
	Estimate	**t-value**
ASC Shared (e) bike	0	(Fixed)
ASC Shared (e) scooter	3.69 **	3.82
ASC Shared (e) cargobike	- 10.8 **	-2.18
ASC Shared (e) car	- 2.81 **	-2.25
ASC “opt-out”	- 4.52 **	-5.14
Travel cost	-0.577	0.91
Walking time	-0.049	0.96
Socio-economic variables	**Estimate**	**t-value**
Age- Shared (e) scooter	- 0.893 **	- 4.76
Age- Shared (e) cargo bike	-0.772 **	- 2.02
Age- Shared (e) car	-0.013	- 0.08
Age “opt-out”	1.01 **	7.05
Male- Shared (e) scooter	0.728 **	4.42
Male- Shared (e) cargo bike	0.765 **	2.06
Male- Shared (e) car	0.425 **	2.75
Male- “opt-out”	0.415 **	3.43
Education - Shared (e) scooter	- 0.214	-1.28
Education - Shared (e) cargo bike	1.47*	1.78
Education - Shared (e) car	0.426 **	2.14
Education - “opt-out”	0.414 **	2.99
Income - Shared (e) scooter	-0.206 **	-2.44
Income - Shared (e) cargo bike	0.292	1.31
Income - Shared (e) car	0.199 **	2.22
Income - “opt-out”	0.223 **	3.28
Trip purpose for work/education- Shared (e) scooter	- 0.146	- 0.81
Trip purpose for work/education- Shared (e) cargo bike	- 1.01 *	- 1.84
Trip purpose for work/education- Shared (e) car	0.165	0.95
Trip purpose for work/education- “opt-out”	0.365 **	2.60
Model fit		
Number of estimated parameters (κ)	26	
Number of observations (n)	828	
Initial log-likelihood	-1332.615	
Final log-likelihood	-898.336	
R2	0.471	
Adjusted R2	0.452	
likelihood-ratio test	1255.561	
AIC	1461.7	
BIC	1584.4	

$^{**}p \leq 0.05$, $^{*}p \leq 0.1$

4.5.1 Mixed logit model results

In this section, we discuss the findings of Mixed Logit model, (Table 4.8). The inclusion of socio-economic variables and trip purposes substantially enriches the explanatory capacity of the model, highlighting systematic differences in mode choice preferences across age, gender, trip purpose, education and income.

Table 4.8: The parameter estimates of the MXL model.

Main effects	**ML Model + Socio-demographic**	
	Estimate	**t-value**
ASC Shared (e) bike	0	(Fixed)
ASC Shared (e) scooter	3.51 **	2.95
ASC Shared (e) cargobike	- 13.41**	- 2.34
ASC Shared (e) car	- 12.30 **	-2.42
ASC "opt-out"	- 6.24 **	-4.63
Random parameters		
Travel cost	- 6.97 **	- 5.45
Walking time	- 1.43 **	-12.10
Random parameter standard deviations		
SD Travel cost	2.18**	-14.54
SD Walking time	0.39 **	7.89
Socio-economic variables	**Estimate**	**t-value**
Age- Shared (e) scooter	- 1.43 **	-6.07
Age- Shared (e) cargo bike	- 1.50 **	-3.39
Age- Shared (e) car	- 1.75 **	-2.87
Age "opt-out"	1.39 **	7.08
Male- Shared (e) scooter	0.783 **	3.96
Male- Shared (e) cargo bike	0.666	1.47
Male- Shared (e) car	0.984	1.69
Male "opt-out"	0.635 **	3.62
Education- Shared (e) scooter	- 0.020	-0.09
Education- Shared (e) cargo bike	2.020 **	2.09
Education- Shared (e) car	1.907 **	2.04
Education - "opt-out"	0.420 *	1.84
Income- Shared (e) scooter	-0.158	-1.57
Income- Shared (e) cargo bike	0.477 *	1.80
Income- Shared (e) car	0.830 **	2.45
Income - "opt-out"	0.180 **	1.97
Trip purpose for work/education- Shared (e) scooter	- 0.088	- 0.40
Trip purpose for work/education- Shared (e) cargo bike	- 1.01	- 1.61
Trip purpose for work/education- Shared (e) car	0.988	1.60
Trip purpose for work/education- "opt-out"	0.477 **	2.43
Model fit		
Number of draws	1500	
Number of estimated parameters (κ)	28	

Number of observations (n)	828
Initial log-likelihood	-1324.6
LL (0) (equal shares)	-1332.61
Final log-likelihood	-514.19
R2	0.6142
Adjusted R2	0.5931
likelihood-ratio test	1636.84
AIC	1084.37
BIC	1216.51

$^{**}p \leq 0.05$, $^{*}p \leq 0.1$

The choice model results reveal several important dynamics shaping residents' preferences for shared mobility in car-free contexts. The alternative-specific constants provide an initial indication of underlying preferences once socio-demographic heterogeneity is accounted for. Scooter sharing shows a positive and statistically significant constant (Estimate = 3.51, t = 2.95) suggesting a general baseline preference for this mode. In contrast, both cargo-bike sharing (Estimate = –13.41, t = –2.34) and car sharing (Estimate = –12.30, t = –2.42) show strongly negative and significant constant, indicating that these options are inherently less attractive to many respondents, even after controlling for observed heterogeneity. The negative constant for the "opt-out" alternative (Estimate = –6.24, t = –4.63) further suggests that socio-demographic factors reduce the baseline inclination to abstain from shared mobility, although specific groups still display strong avoidance tendencies. Mode-specific results for the shared cargo bike should be interpreted with caution, as this alternative was selected in only 10 of the 828 choice observations; the corresponding estimates therefore rest on a small cell and are reported as indicative rather than robust.

The core attributes—travel cost and walking time—play a central role in shaping mode choice. Both variables are negative and highly significant, cost (Estimate = –6.97, t = –5.45) and walking time (Estimate = –1.43, t = –12.10), confirming that monetary and physical access costs are major barriers to adoption. Accessibility is particularly critical: even a one-minute increase in walking time considerably lowers the probability of selecting a shared mode. The estimated Value of Time (VoT), approximately €0.20 per minute of walking (≈ €12/h), indicates that users perceive access distance as a tangible burden, comparable to direct financial costs. Comparable studies report values of short-distance non-business travel time between approximately €6 and €11 per hour (Wardman et al., 2016), which positions our VoT estimate toward the upper, yet still empirically plausible, end of the range. Therefore, although the estimated VoT appears relatively high, it remains consistent with evidence suggesting that users attach a non-trivial disutility to walking time when accessing shared mobility systems. However, the significant standard deviations (SD) associated with both attributes (travel cost; σ = 2.18, t = –14.54 and walking time; σ = 0.39, t = 7.89) demonstrate that sensitivities vary considerably across individuals. This suggests that policy measures such as fare adjustments or improved spatial accessibility will not affect all residents uniformly but are likely to benefit certain user groups more than others.

$$VOT = -\frac{\beta\ walking\ distance}{\beta\ travel\ cost} = -\frac{-1.43}{-6.97} = 0.20\ €/\text{min}$$

4.5.2 Socio-demographic influences on shared mobility preferences

Incorporating socio-demographic variables into the model provides further insight into the sources of behavioural variation. Age emerges as a central determinant: older respondents are consistently less likely to adopt any of the shared mobility alternatives—scooter sharing (–1.43, t = –6.07), cargo bike sharing (–1.50, t = –3.39), and car sharing (–1.75, t = –2.87) — and more likely to choose the opt-out option (1.39, t = 7.08). This pattern reflects a combination of digital, physical, and attitudinal barriers that disproportionately affect older populations. Gender also contributes to differentiated preferences, with men expressing stronger preferences for scooter sharing (0.783, t = 3.96) and a slightly higher likelihood of opting out (0.635, t = 3.62), although effects for cargo bike (0.666, t = 1.47) and car sharing (0.984, t = 1.69) modes are weaker. Education introduces additional complexity: higher educational attainment increases the likelihood of selecting cargo-bike (2.020, t = 2.09), and carsharing (1.907, t = 2.04) services, while also slightly raising the probability of choosing the opt-out (0.420, t = 1.84) alternative. Income shows a similar trend, with higher-income respondents more inclined toward premium or higher-value shared services such as cargo bikes (0.477, t = 1.80) and car sharing (0.830, t = 2.45), and somewhat more prone to abstain from using shared modes altogether (0.180, t = 1.97).

Trip purpose further moderates these patterns. Shared modes appear less attractive for work and education trips, which likely reflects concerns about reliability and time sensitivity. For commuting purposes, respondents exhibit a greater tendency to avoid shared mobility options (0.477, t = 2.43), reinforcing the notion that shared modes are currently perceived as more suitable for discretionary or flexible travel than for daily structured routines.

While vehicle access is not explicitly interacted within the Mixed Logit specification due to sample size constraints, supplementary descriptive checks indicate that substitution willingness varies systematically across these dimensions. Respondents with access to a private car and those recalling car-based trips were more likely to select the opt-out, reinforcing the interpretation that substitution feasibility depends on prior mobility conditions rather than uniform resistance to shared mobility.

Overall, these results highlight that shared mobility adoption is shaped by a complex interplay of cost sensitivities, accessibility constraints, and socio-demographic characteristics. The strong heterogeneity observed across the sample underscores that mobility transitions cannot be understood solely through average effects. Instead, policy design must recognise that user groups differ markedly in their constraints, motivations, and behavioural thresholds. As cities move toward car-free or low-car strategies, understanding these differentiated patterns becomes essential for designing interventions that are both effective and equitable.

4.6 Conclusions, discussion, and policy implications

4.6.1 Main conclusion

This study examined under what conditions inner-city residents in Delft consider shared electric mobility to be an acceptable substitute for a recently made trip, during an ongoing transition toward a private car-free centre. Using a stated choice experiment with an opt-out alternative and Mixed Logit models, we identify how price, access distance, and socio-demographic heterogeneity shape acceptance of shared-mode substitution scenarios.

While core attributes like travel cost and walking time are critical (resulting in a high Value of Time for walking, €0.20 per minute), the model results confirm a strong propensity toward non-participation, particularly among certain demographic groups. Although the descriptive survey data showed that 64% of respondents opted out of shared modes, the Mixed Logit model further reveals that this tendency is statistically associated with age-related and socio-economic factors. Older (50+), affluent, and highly educated residents exhibit a significantly higher likelihood of choosing the opt-out. For these older, more affluent, and more highly educated residents, opting out is not primarily financial; instead, it is closely tied to car access and use. Residents with a car in the household opted out far more often than those without (72.3% versus 44.7%; Table 4.6), and respondents reconsidering a car-based trip opted out in 74.7% of cases (Table 4.5). This suggests that, for these groups, choosing the opt-out reflects established car ownership and habitual car use—and the digital, physical, or attitudinal barriers associated with them—rather than a purely financial constraint. This pattern underscores that car-free zone policies cannot treat all residents uniformly but must address the distinct needs of car-dependent groups showing behavioural resistance. Moreover, the results demonstrate substantial preference heterogeneity across the population. Individuals differ widely in their sensitivity to both cost and walking time, suggesting that interventions such as fare reductions, improved spatial accessibility or service redesign will not have uniform effects. Socio-demographic variables, particularly age, emerge as strong determinants of shared mobility adaption. Younger residents show greater openness, likely due to digital familiarity and flexibility in travel routines, whereas older users remain hesitant. Gender, education, and income also play differentiating roles: men show stronger preferences for scooter sharing, and individuals with higher educational attainment or income are more inclined to adopt premium shared services such as cargo-bike or car sharing. Trip purpose further shapes behaviour: shared modes are notably less favoured for work-business, where time reliability is crucial.

Although this study is grounded in Delft urban context, the behavioural mechanisms it uncovers are broadly relevant to other cities pursuing car-free or low-car strategies. The socio-demographic patterns—particularly the reluctance among older, higher-income, and digitally less-engaged residents—are consistent with international research, suggesting that similar barriers will likely emerge elsewhere. The findings therefore offer a generalisable set of insights: cities should anticipate substantial demand segmentation, recognise that shared mobility is not equally attractive across demographic groups, and ensure that car-free transitions are supported by targeted interventions addressing accessibility and behavioural acceptance. In this sense, while local conditions may vary, the observed behavioural dynamics provide transferable guidance for urban mobility planners aiming to foster equitable and effective car-free environments.

4.6.2 Discussion on study limitation and future research directions

The study has several limitations that should be acknowledged. First, recruitment was primarily conducted through the municipality's Facebook and Instagram channels, which likely over represent digitally connected and civically engaged residents. While these platforms are widely used, they may introduce potential selection bias and reduce external validity, particularly for residents with low digital literacy or limited online presence. Future studies should use stratified sampling or multiple recruitment channels (e.g., local community groups, offline events, random household sampling) to enhance representativeness.

Our design measured revealed recent behaviour (the original mode of the recalled trip and household mobility resources) but did not collect attitudinal constructs (perceived safety, trust, social norms), fine-grained built-environment measures, or the recalled trip's distance and travel time as continuous variables. This was a deliberate trade-off to keep the instrument short for a difficult-to-recruit inner-city resident sample, but it means habitual and attitudinal mechanisms are only partially observed. The systematic association we find between prior car use and opt-out is consistent with a habit or car-dependence interpretation, but disentangling habit from attitude—and quantifying the role of trip length and time—requires hybrid choice / latent-variable models and richer trip data, which we recommend for future revealed-preference work. Relatedly, because trip- and mode-related characteristics were treated as the behavioural reference point rather than modelled explicitly, part of the unobserved heterogeneity captured by the random-parameter standard deviations likely reflects variation in the trips and original modes being substituted, not person-level demography alone.

Second, the stated preference experiment offers controlled causal inference but does not fully reflect the actual market conditions or real-world availability of shared modes. Importantly, the experiment was not calibrated against the actual share of private car trips that could realistically be replaced by shared modes. Future research should incorporate revealed preference data—e.g., through smart-card logs, app-based trip histories, or before-after field trials—to validate the predictive accuracy of stated preferences.

Third, while our model accounts for heterogeneity through random coefficients, psychological constructs such as perceived safety, social influence, and trust in shared systems were not directly measured. These attributes have been shown to influence zero-ownership mobility adoption and could refine behavioural segmentation. Future research should therefore integrate attitudinal latent factors through hybrid choice modelling or structural equation approaches.

Finally, the study focuses on inner-city residents, meaning that the findings do not necessarily generalise to suburban areas or commuters traveling from outside Delft. Future work could compare spatial groups explicitly to understand whether access distance, mode reliability, and sociotechnical acceptance differ between urban neighbourhoods and regional commuters.

Taken together, these limitations do not undermine the validity of the present findings, but they do highlight important avenues for extending the analysis. Incorporating revealed behaviour, psychological dimensions, and spatial heterogeneity could substantially improve the ability to forecast behavioural change under future mobility scenarios.

4.6.3 Policy implications

The findings of the Mixed Logit model on preference heterogeneity and the high rate of avoidance behaviour led to four targeted, scientifically grounded policy implications for cities implementing car-free zones.

1. Engage and familiarise the opt-out group for inclusion

   From a policy perspective, the opt-out alternative should be interpreted cautiously. Rather than solely indicating a rejection of car-free policies or a willingness to forgo activities, it may reflect situations where the offered shared mobility options are not perceived as adequate substitutes for a specific trip, as well as a lack of interest, habitual preferences, or attitudinal resistance toward shared mobility. This distinction is critical: a high opt-out share can signal gaps in service design, coverage, or trip compatibility, but may also indicate deeper behavioural or perceptual barriers to adoption. Accordingly, the opt-out provides diagnostic insight into where shared mobility requires complementary measures, such as improved public transport, enhanced cycling infrastructure, targeted incentives, or awareness and engagement strategies.

2. Prioritize micro-accessibility to reduce access effort

   Our results show that even small increases in access distance significantly reduce adoption; therefore, providing vehicles closer to users—rather than at scattered stand-alone hubs—can lower this access effort. Policy should focus on establishing a sufficiently dense and spatially distributed network of physical pick-up and return locations within short walking time of residences, workplaces, and transit nodes. This does not aim to replace walking as an activity, but rather to ensure that when shared modes are chosen, they can be accessed without long detours or unreliable availability. Improving proximity and availability increases the utility of shared modes, particularly for users who currently avoid them due to low predictability or long access distances.

3. Target engagement using the observed opt-out gradients.

   Our estimates show that older residents (50+), car owners, and those reconsidering a car trip are markedly more likely to opt-out. These gradients identify which groups any engagement or communication effort should prioritise. We note explicitly that our data do not test whether messaging changes behaviour; the content and effectiveness of such engagement (e.g., emphasising reliability and comfort for older residents) is offered as a hypothesis for attitudinal follow-up research rather than a tested finding.

4. Design for access among high-opt-out groups.

   The one design implication our results support directly is reducing access effort: the large, significant walking-time disutility (VoT ≈ €0.20/min) implies that dense, reliable, close-proximity fleet placement—and non-digital access/booking options for groups with low digital engagement and high opt-out—would most plausibly raise acceptance. We refrain from broader inclusive-design prescriptions that the data cannot adjudicate.

By directly addressing the attitudinal and generational barriers identified in this study, cities can move beyond purely infrastructural solutions and foster genuine behavioural inclusion.

Combining improved service reliability, targeted engagement, and visible environmental progress will be essential to converting potential opt-outs into active participants in an evolving, car-free urban mobility system. Future work should explicitly integrate trip characteristics and mobility holdings within larger samples, enabling stronger causal inference regarding substitution across trip types.

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Chapter 5:

User Preferences for Shared Modalities Among Older Adults in Midsized Inner Cities

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Considering the previous chapter's analysis of shared mobility in inner cities, this chapter narrows the focus to a specific demographic group that has received limited attention in shared mobility research—middle-aged and older travellers. While shared mobility solutions are often designed for younger, tech-savvy users, understanding the preferences and barriers faced by older adults is essential for promoting equitable and inclusive urban mobility.

This chapter examines transportation choices among residents aged 50 and above focusing on shared mobility services such as bikes, e-bikes, e-scooters, e-Brommobiels and e-cars in small- to medium-sized Dutch cities, where car dependency remains high. Using a stated preference experiment, the study analyses the acceptance of shared mobility by assessing key factors including travel cost, travel time, walking distance, and socio-economic characteristics. The findings provide valuable insights for policymakers and urban planners, supporting the development of inclusive mobility strategies that enhance accessibility while addressing environmental and congestion challenges.

The chapter is structured as follows: Section 5.1 explores the implications of shared mobility acceptance decisions by senior above 50 and research gaps. Section 5.2 details the research methodology followed by survey design and data collection. Section 5.3 presents data analysis related to the current journey. The choice modelling results and data analyse are detailed in Section 5.4. This chapter concludes in section 5.5.

This chapter is based on the following papers:

Torabi Kachousangi. F., Yashar Araghi, Niels van Oort, & Serge Hoogendoorn. (2024). Exploring Mobility Choices Among Older Adults: A Latent Class Approach to Shared Modalities in Midsized Dutch Inner Cities. *Transportation Research Interdisciplinary Perspectives (TRIP), 33*, 101592. https://doi.org/10.1016/j.trip.2025.101592

5.1 Introduction

Worldwide, motorised traffic is projected to grow from one billion vehicles in 2011 to two billion by 2050, driven by income growth and population increases (OECD/ITF, 2012). While private cars theoretically enable fast travel, they often dominate urban space, causing congestion and reducing urban liveability (Hardt & Bogenberger, 2019). Moreover, as motorized vehicles continue to dominate urban landscapes, space for pedestrians, cyclists, and public transport infrastructure remains limited, exacerbating accessibility challenges. Additionally, private cars dominate public spaces, for instance, in the Netherlands, cars occupy 55% of street space in major cities but remain parked 96% of the time (Jorritsma et al., 2021; van Liere et al., 2017).

This inefficient use of space underlines the urgency for cities to implement space-efficient measures to tackle growing congestion and lack of space while enhancing accessibility (van Marsbergen et al., 2022). The need to discourage car use and transition to sustainable transportation systems has gained recognition among scholars, governments, and health organisations (Green Deal Autodelen II, 2022; van der Linden et al., 2024). While technological advancements like electric vehicles help mitigate environmental concerns, they do not address challenges related to spatial efficiency and congestion (Litman, 2014).

To tackle these issues, many cities are transforming some areas partially or entirely to car-free neighbourhoods, particularly in their inner-city centres or popular commercial and shopping areas (Garling & Loukopoulos, 2007; Nieuwenhuijsen & Khreis, 2016). These car-free developments aim to reduce congestion, enhance transport accessibility, and create safer and more liveable urban spaces by expanding cycling infrastructure, establishing pedestrian zones, and increasing green areas (Nieuwenhuijsen & Khreis, 2016). While reducing car dependency is a key measure to create more space in urban areas, it is crucial to ensure inclusivity and equitable mobility access, particularly for vulnerable populations, particularly older adults, who are more likely to face physical limitations, digital barriers, and greater reliance on private vehicles or public transport.

While much of shared mobility literature focuses on younger, tech-savvy users, a growing body of research highlights the distinctive needs and behaviours of older adults in mobility system. Older people are not a homogeneous group, and their mobility choices are shaped by a variety of factors such as health, lifestyle, car availability, and attitudes toward transport. As Haustein and Siren (2015) demonstrate, segmentation approaches can reveal meaningful subgroups among older adults, ranging from highly mobile individuals to those facing significant transport disadvantage. Understanding these differences is essential to designing inclusive mobility strategies that address both actual and perceived mobility limitations.

The mobility challenges for older adults go beyond physical accessibility and include affordability and digital exclusion. Income disparities and car ownership play a crucial role in determining public transport affordability (Bon et al., 2025), often reinforcing car dependency among specific groups. Additionally, as cities increasingly adopt digital mobility services, new accessibility barriers are emerging. Nearly 75% of public transport and car users report that traveling has become significantly more difficult without a smartphone, highlighting a growing digital divide in mobility access (Durand et al., 2024). While digital tools enhance convenience for many, individuals with lower digital literacy or limited smartphone access—particularly older adults and those unfamiliar with digital platforms—face additional obstacles in navigating transport systems. If left unaddressed, these digital disparities could further marginalize certain populations, restricting their mobility options and deepening transport inequalities (Durand et al., 2024).

Although non-motorized transport modes, such as cycling and walking, have been essential alternatives for ensuring accessibility in car-free city centres (Szarata et al., 2017; Gascon et al., 2015), shared mobility and micro-mobility have emerged as a space-efficient and flexible alternative to private car use that improves urban accessibility and reduce reliance on motorized transportation (Handy et al., 2014). Additionally, shared cars offer a practical solution for occasional car use while reducing overall car dependency (Kolleck et al., 2021; Nijland & van Meerkerk, 2017).

Studies indicate that shared mobility adoption among older adults remains low, faces barriers such as digital illiteracy, unfamiliarity with technology, and physical limitations (Kim et al., 2021; Van Kuijk et al., 2022). Notably, public transport users report higher digital literacy than car users, despite no significant differences in education or age, suggesting that digital skills play an overlooked role in mode choice (Durand et al., 2024). Research on shared mobility services has largely focused on young, urban populations, leaving a gap in understanding how older adults and residents of smaller cities perceive and engage with these services (Dill & McNeil, 2021). Given that older adults constitute a significant portion of inner-city residents, addressing these accessibility barriers is crucial to ensuring that car-free zones remain inclusive and equitable. The segmentation of older adults, as explored by Haustein and Siren (2015), can help uncover specific travel needs and guide the design of targeted mobility policies.

To encourage the adaption of shared mobility solutions, cities are implementing measures such as limiting car ownership and reducing parking availability to alleviate congestion, improve safety, and promote walkability in city centres (Baehler, 2019; Melia et al., 2010; Cathcart-Keays, 2015). However, these initiatives often face strong societal resistance (Pojani et al., 2018), particularly from groups reliant on private vehicles (Cathcart-Keays, 2015; Baehler, 2019; Poudenx, 2008; Jeekel, 2013). A key challenge lies in the digital nature of shared mobility services, which excludes individuals lacking digital literacy or smartphone access (Durand et al., 2021; Durand et al., 2024; Pangbourne et al., 2020). As a result, older adults and non-tech-savvy users are at a disadvantage, further limiting the inclusivity of these transport options.

Younger individuals tend to adopt shared micro-mobility services more readily due to their digital proficiency and flexible mobility habits (Böcker & Anderson, 2020; Chen et al., 2020; Tao & Pender, 2020; Alonso-González et al., 2020; Eren & Uz, 2020; Geržinič, 2022). In contrast, older adults may be hesitant due to unfamiliarity with technology, cognitive decline, and physical limitations (Kim et al., 2021; Van Kuijk et al., 2022). Integrating all socio-economic groups into the urban mobility transition is crucial for broadening acceptance (Geurs & Münzel, 2022). Thus, understanding these barriers, particularly among older adult non-users, is essential for promoting equitable shared mobility solutions. Addressing these gaps is critical for promoting shared mobility in smaller urban areas where car dependency remains high.

This study determines the factors influencing the (un) willingness to use shared mobility among older adult travellers (50+) in small- to medium-sized Dutch cities. We use a discrete-choice latent class model (LCM), which categorises individuals into latent classes based on shared characteristics and similarity in their stated preferences for shared mobility options. This approach captures unobserved heterogeneity and supports the development of inclusive, age-sensitive transport strategies—especially critical as cities move toward car-free zones.

We collect data from a diverse sample of older adults and apply a discrete-choice LCM to segment them based on stated preferences. We then analyse the socio-demographic of each group post-estimation. This segmentation provides valuable insights for designing targeted policies tailored to the specific needs of each segment.

By gathering data from this group, the research aims to provide actionable insights for promoting sustainable transportation options in underexplored demographic groups. Section 2 outlines the study's methodology, detailing the case study across 45 small- to medium-sized Dutch cities, the survey approach (2.1), and the stated choice experiment used to analyse user preferences. Section 3 presents the data analysis related to current journeys, followed by Section 4, which discusses choice modelling results and heterogeneity in transport mode preferences (4.1). Finally, Sections 5 and 6 provide a discussion of key findings, policy recommendations, and concluding remarks.

5.2 Research methodology

To investigate how shared mobility services can effectively reduce private car use in car-free inner cities, this research employs a stated choice experiment to reveal people's preferences for adopting such services. Since car-free zones have not yet been widely implemented in the Netherlands, and shared mobility modes are still emerging, a choice experiment allows us to present hypothetical scenarios.

Additionally, while car-free initiatives have primarily been studied in larger cities, smaller and medium-sized cities—often more car-dependent due to less developed public transport networks—have received less attention. This study addresses this gap by exploring the potential of shared mobility in car-free areas. This approach enables us to examine potential user preferences in a future context where these car-free areas and new mobility options are more prevalent. We selected 45 small to medium-sized cities across the Netherlands to provide a diverse and representative sample, ensuring the findings apply to a range of urban environments. The cities, with populations ranging from 33.880 to 133.133, are in the provinces of South Holland, North Holland, North Barabant, Utrecht, Overijssel, Gelderland, and Limburg, as shown in Figure 5.1. A full list of the 45 cities, along with their corresponding provinces, population, land area, and postal codes, is provided in Appendix 2.6 for reference.

The study examines individuals' attitudes toward different modes of transportation in small and medium-sized Dutch cities. In this section, we describe the research setup.

Figure 5.1: Overview of cities as case studies.

5.2.1 Survey overview

To identify the factors influencing travel behaviour and observe current and future mode choice decisions, we conducted an online survey consisting of two parts: 1) previous experiences, including experiences with shared modes, everyday journeys, and socio-economic characteristics of residents at these inner-cities, and 2) stated choice experiments. This survey was conducted by a survey panel, PanelClix, recognised for its high standards in market research. This panel actively distribute surveys to a diverse range of participants, including some with limited digital access. However, as the survey was conducted online, certain digitally excluded groups may still be underrepresented. The survey was available in both English and Dutch and was initiated between April 2 and April 14, 2024.

Since we are interested in the choice preferences of older adults, defined in this study as individuals aged 50 and above, encompassing the later stages of middle age and beyond— the survey was only accessible to inner-city residents within this age group. The survey began with a brief explanation of the study's purpose and some related information.

Part 1: Past Preferences Survey

This survey aims to capture car dependency, the level of familiarity of residents with shared modes, and their socio-economic characteristics. Firstly, the questionnaire covers aspects such as possession of a driver's license, car ownership, and car dependency. Then, respondents were asked about their experience of shared modes and willingness to opt for them over private cars. The survey delves into respondents' recent trips approximately 10 km distance from the inner city, exploring details like transport mode, trip purposes, distance, and travel companions.

Part 2: Stated Choice Experiment

Choice models based on the random utility maximisation (RUM) theory are widely used to study individual travel behaviour (McFadden, 2000; Ortúzar & Willumsen, 2001; Train, 2003). While some studies have focused on travellers' attitudes toward shared modes (Torabi et al., 2022; Van Dijk et al., 2022), our focus is on understanding behaviour heterogeneity using revealed choice data.

This study adopts the methodological framework originally proposed by McFadden (1986) and further developed by Kamakura & Russell (1989) and Boxall & Adamowicz (2002). By analysing stated preferences, this approach enables a deeper understanding of differences among older adults in their willingness to adopt shared mobility services.

This study employs a discrete-choice Latent Class Model (LCM) to analyse passenger decision-making and segment individuals based on shared preferences. The model consists of two components:

- The choice model, which estimates the probability of selecting a shared mode from a set of alternatives, which assumes that passengers choose the option offering the highest perceived utility.
- The class membership model, which determines the probability of an individual belonging to a specific latent class, where each class is characterised by distinct taste parameters (Swait, 1994; Boxall & Adamowicz, 2002).

Unlike mixed logit models, which assume continuous distributions for taste parameters, LCM assumes a discrete distribution, categorising individuals probabilistically into a fixed number of latent classes (Araghi, 2016).

In our application, class membership is estimated based only on the observed choices from the sated choice experiment to estimate class membership and explain heterogeneity in travel choices. This provides a deeper behavioural understanding of preference variations, making the identified classes more actionable for policymakers and industry stakeholders (Araghi, 2016).

We explored four common shared transportation modes, including 1) shared bike, 2) shared electric bike, 3) shared electric scooter, and 4) shared electric car, and studied the potential impact of the shared e-Brommobiel on the choice of those aged 50 and above. While not yet part of a shared mobility system, this small-size vehicle may promise a comparable option to cars. In addition, three attributes are considered, including 1) Total Travel Cost (return trip, in €), 2) In-Vehicle Travel Time (minutes), and 3) Walking Distance to shared modes (minutes).

The selection of alternatives and attributes are all based on their prevalence and importance in the literature, especially in studies targeting older populations and shared mobility choices. Attribute levels were determined using a combination of Dutch market-based data and behaviour realism, as shown in Table 5.1. Levels were pre-tested in a pilot survey and refined through an efficient design procedure in Ngene, with the aim of balancing realism and statistical variance.

- Total Travel Cost levels were based on public pricing from Dutch operators such as OV-fiets, Felyx, and Greenwheels. For the Brommobiel, we assumed that the price should fall within the average range of shared scooter and car prices.
- In-Vehicle Travel Time was calculated based on average various modal speeds over a 10 km one-way trip.
- Walking Distances to shared modes were set to reflect typical accessibility ranges for shared mobility vehicles in Dutch cities, while remaining feasible for older adults.

Table 5.1: Overview of attributes and attribute levels used in the stated choice experiment.

Attribute	Attributes levels	
Travel cost for a return trip - shared bike	€ 6	€ 8
Travel cost for a return trip - shared E-bike	€ 8	€ 9
Travel cost for a return trip - shared E-scooter	€ 9	€ 10
Travel cost for a return trip - shared E-Brommobiel	€ 10	€ 12
Travel cost for a return trip - shared E-car	€ 12	€ 14
In-vehicle total travel time - shared bike	55 min	65 min
In-vehicle total travel time - shared E-bike	45 min	50 min
In-vehicle total travel time - shared E-scooter	40 min	45 min
In-vehicle total travel time - shared E-Brommobiel	30 min	35 min
In-vehicle total travel time - shared E-car	20 min	25 min
Walking distance to access shared bike	2 min	4 min
Walking distance to access shared E-bike	4 min	6 min
Walking distance to access shared E-scooter	4 min	6 min
Walking distance to access shared E-Brommobiel	8 min	12 min
Walking distance to access shared E-car	8 min	12 min

Considering the age of the participants as well as the complexity of the choice experiment, the participants were visually explained and informed about the car-free area concept and how the choice experiment works by giving an example at the beginning of this part. They were presented as follows:

"*Imagine that the City Centre, where you live, is a car-free area, which means you are not allowed to bring and use your private car in this area. Instead, the below-shared modes are available at stations nearby, while only shared electric cars and shared electric Brommobiels (small cars) are located at the border of the City Centre (Figure5.2). You must walk and take one of these transport modes for your trip, as shown in Figure 5.3.*

You will receive eight different choice sets, each including different shared transport modes. Each vehicle has its own ***total travel cost****, including the staying time,* ***total travel time in that vehicle*** *regardless of the staying time, and the* ***walking distance*** *to access the shared modes.*

For instance, if travelling with a shared (e) scooter takes 40 minutes and 10 euros, it means each way takes 20 minutes and 5 euros.

Suppose you would have a return trip to that destination outside of the City Centre and back home (approx. 10km for one way and in total approx.20km). But you cannot use your private car for this trip, and you must compare different shared modes and choose one, even if it is not your ideal."

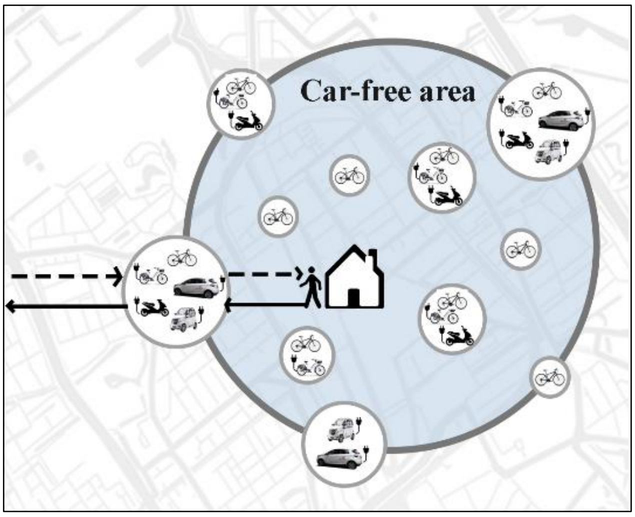

Figure 5.2: Overview of the Car-free area concept

Shared bike 	· Renting for a short-term use · Located in the car-free area · 2-4 minutes walking distance from your house.
Shared electric bike 	· Renting for a short-term use · Faster than a normal bike · Located in the car-free area · 4-6 minutes walking distance from your house
Shared electric scooter 	· Renting for a short-term use · Moves in bike lanes, top speed around 45 km/h · Located in the car-free area · 4-6 minutes walking distance from your house
Shared electric Brommobiel 	· Renting for a short-term use · Microcar with a top speed of around 45 km/h · Moves on roads, not highways · Located on the border of the City Centre · 8-12 minutes walking distance from your house
Shared electric car 	· Renting for a short-term use · Moves on roads and highways · Located on the border of the City Centre · 8-12 minutes walking distance from your house

Figure 5.3: Alternative characteristics.

To determine the appropriate number of choice sets, we first conducted a small-scale test pilot with a limited sample of 25 respondents. This pilot study followed an orthogonal design, which does not require prior knowledge of the parameters but ensures that all attribute levels are evenly represented. The responses from this pilot were analysed to generate preliminary estimates (priors) of the choice model coefficients. These priors were essential for developing an efficient design. An efficient design was subsequently created using Ngene software to improve estimation efficiency compared to a purely orthogonal design. Given the number of attributes (three) and alternatives (five) included in the study, the efficient design process determined that 16 choice sets would be optimal. This number strikes a balance between ensuring robust statistical estimation of preferences while avoiding excessive fatigue among respondents. A larger number of choice sets could lead to disengagement and reduced response quality, whereas fewer choice sets might limit the ability to capture reliable preference estimates.

By leveraging the priors obtained from the pilot study, the final efficient design was structured to maximise the reliability of the collected data in the main survey. This approach ensures that the choice sets are not only statistically sound but also practical for respondents, leading to more accurate insights into shared mobility adoption in car-free urban environments.

Participants were assigned eight choice sets randomly from 16 choice sets to make the survey more practical and manageable while still capturing sufficient data for analysis. They were instructed to recall their recent trips (approx. 10 km distance), compare alternatives, and choose their primary mode for their return trip from home to a destination in/outside the city centre, considering the characteristics of these transport modes, shown in Figure 5.4.

R software was used to perform the maximum likelihood estimation of the discrete choice model. In the next section, the results of the models are presented and discussed.

A2	Shared bike	Shared E-bike	Shared E-scooter	Shared E-Brommobile	Shared E-car
Cost for the return trip	6 euro	8 euro	10 euro	10 euro	14 euro
In vehicle total Travel Time	65 min	45 min	40 min	30 min	25 min
Walking distance to shared modes	2 min	6 min	4 min	12 min	8 min

o Shared bike o Shared E-bike o Shared E-scooter o Shared E- Brommobiel o Shared E-car

Figure 5.4: Example of a choice set demonstrated to respondents in the survey.

5.3 Data analysis related to the current journey

In this section, we present some general descriptive statistics about the past trip and demographic characteristics on using private cars and shared modes, presented in Table 2. In total, 497 respondents participated in the survey. Seventy-nine respondents were excluded from the data set due to not finishing the survey; the remaining 418 respondents formed the data set in this study. This equals to 3344 complete choices.

The data includes demographic factors such as age, gender, family status, education level, and income. It also examines health, private car use, reasons for using cars, shared mobility experiences, and current trip variables. The analysis aims to provide critical insights into the capacity of respondents to use shared modes.

It is worth noting that the sample was designed to be broadly representative of the Dutch older adult's population (50+). Participants were selected from 45 cities across the Netherlands, ensuring geographic diversity and capturing a wide range of socio-economic and urban-rural contexts. This approach enhances the likelihood that the sample reflects the characteristics and behaviours of the target demographic at a national level.

5.3.1 Demographic analysis

Regarding the socio-demographic characteristics of the sample, Table 2 shows that it contains higher shares of 50-69 years (66%), male (58%), less formally educated (53%), and low to medium economic level 71.000 ≥ euro (55%) users who are mostly household with at least two adults (66%), and single (28%). Regardless of age, they mostly are fully physically mobile (75%), and only 19% have mobility limitations due to their age concerning walking (65% people), cycling (42% people), and driving (28% people), respectively.

Table 5.2: Sample statistics with different socio-economic variables (n= 497).

Socio-economic variab	Category	Share sample
Age	50-59	30%
	60-69	36%
	70-79	29%
	80≤	5%
Gender	Male	58%
	Female	42%
Family status	Single	28%
	Households with at least two adults	66%
	Household with 1≤ children the age 12	2%
	Household with 1≤ children with the age of 13 up to 17 years old	4%
Education level	Less formally educated (under HAVO and	53%
	Moderately educated (HBO / WO	24%
	Highly educated (HBO / WO Master's or doctoral degree)	23%
Income (Total family gross annual)	Less than € 42.400	33%
	Between € 42.400 and € 71.000	22%
	Between € 71.000 or more	22%
	Won't say	23%
Health ability	I am fully mobile (physically able)	75%

	My mobility is limited (due to age,	19%
	I am not a mobile	6%
Health limitation	Walking	65%
	Cycling	42%
	Driving	28%
	Travelling by public transport	32%
Private cars use variable		
Having driving license	Yes	86%
Having a car	Yes	81%
Average use of car	4 days per week or more	29%
	1-3 days per week	40%
	1-3 days per month	16%
	1-11 days per year	10%
	Never	5%
Reasons for using a car	Rainy/cold weather	45%
	If I have a heavy, oversized and/or a lot of	1%
	When I travel with people who are old and	34%
	When I have a long trip	61%
	Always	23%
	Never	1%
Shared modes experience variable		
Familiarity with shared mobility concept	Yes	84%
	No	16%
The main reasons for using shared mobility	1) Cost savings compared to private ownership	14%
	2) Environmental consideration: carbon footprint reduction	14%
	3) Comfort: convenient and flexible transport	12%
	4) Sustainability: preference for sustainable options	10%
	5) Skip the parking and traffic troubles	9%
	6) Lack of private vehicles	9%
Main reasons for not/less using shared mobility	1) Comfort: preferred the convenience of a private vehicle	61%
	2) Reliability: issues with services and availability	27%
	3) Cost: shared options are too expensive.	25%

	4) Cleanliness: worries about shared vehicle hygiene	19%
	5) Lack of Awareness: Limited knowledge of shared options	12%
	6) Technology Challenges: Limited familiarity with booking or using shared transport apps/device	9%
Current trip variable		
Main mode	Car as driver	51%
	Car as passenger	17%
	Train/metro/bus/tram	16%
	Two wheels vehicles	12%
	Walking	2%
	Shared modes	0%
Purpose	Social/Recreational/Visit	54%
	To work	19%
	Shopping	14%
	Personal care	6%
With whom	With one or more adults	50%
	Alone	49%

5.3.2 Mobility behaviour and preferences

The data highlights a strong dependence on private car use. Car usage frequency shows that 29% use their cars four or more days per week, while 40% use them one to three days per week, highlighting room for alternatives.

Moreover, weather conditions and the nature of the trip heavily influence car use. Specifically, 45% of respondents use a car in rainy or cold weather, and 61% use it for long trips. Travelling with elderly individuals or children (34%) is also a significant reason for car use. Interestingly, 23% of respondents always use a car, while only 1% never do.

5.3.3 Shared mobility experience

Despite high familiarity (84%), shared mobility adoption remains low, even though it has been identified as a potential alternative to private vehicle ownership in urban transport research. Most respondents reported either never using shared transport or only trying it once or twice, with only a small percentage (1-3 days per month) using it regularly (Figure 5.5). A key barrier is the strong preference for the comfort and convenience of private cars (61%), reinforcing the perception that shared mobility is less convenient. Reliability issues, such as inconsistent service and availability (27%), further deter adoption, highlighting the need for operational improvements to build user trust.

Current transportation patterns further illustrate this trend. When asked about their most recent trip (approximately 10 km) from home to a destination outside the city centre, respondents overwhelmingly reported car use as their primary mode, either as drivers (51%) or passengers (17%). Public transport usage (train/metro/bus/tram) stands at 16%, while two-wheeled vehicles account for 12%. Notably, no respondents reported using shared mobility services, reinforcing the findings that adoption remains minimal despite familiarity. Trip purposes varied, with visit/social/recreational activities (54%) being the most common, followed by commuting to work (19%) and shopping (14%).

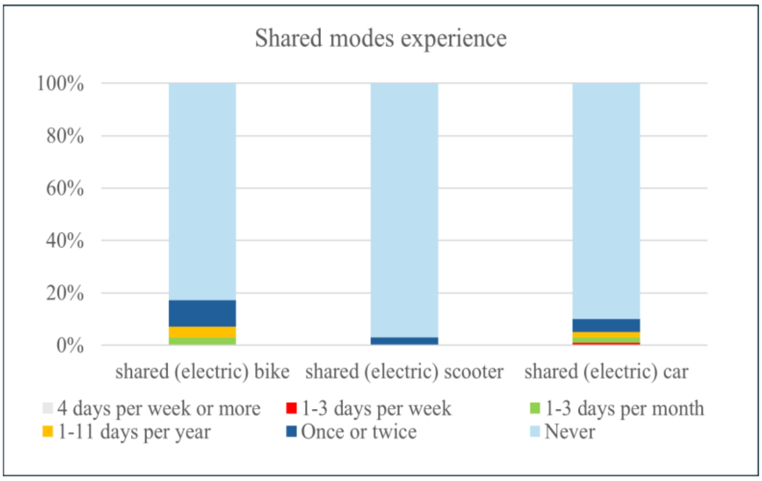

Figure 5.5: Shared mobility experience.

Cost perceptions are divided, with 25% seeing it as a barrier, while others cite cost savings (14%) as a motivator. Hygiene concerns (19%) also impact usage, likely amplified by post-pandemic sensitivities. Additionally, limited awareness (12%) and technological challenges (9%) hinder adoption, suggesting a need for improved user education and more accessible platforms. On the other hand, environmental considerations (14%) and skipping parking or traffic hassles (9%) appeal to some users but remain underemphasised in promotional efforts.

Accessibility also plays a critical role- users prefer shorter walking distances for micro-mobility options (within 2 minutes), while electric cars remain attractive even at longer distances (5-10 minutes), as shown in Figure 5.6. These findings indicate that addressing convenience, reliability, and awareness could enhance shared mobility adoption while also making it a viable alternative for current trip behaviours.

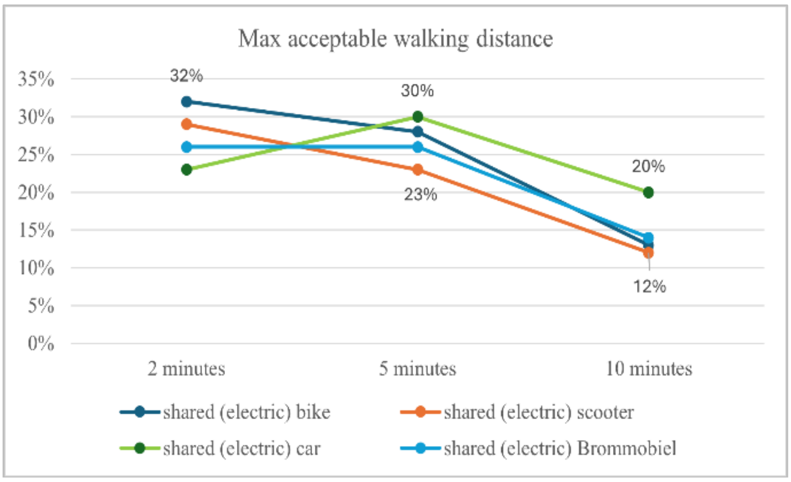

Figure 5.6: Maximum acceptable walking distance to access shared mobility.

The findings indicate a strong dependence on private car use among older adults, despite a high level of familiarity (84%) with shared mobility. While cost savings and environmental considerations motivate some individuals, shared mobility adoption remains minimal, suggesting that perceived barriers outweigh potential benefits. Addressing key concerns could enhance adoption rates and make shared mobility a more viable alternative.

5.4 Choice modelling results and data analysis

In this chapter, we discuss the results of the choice modelling experiments using the data collected.

To provide a benchmark and demonstrate the added value of using a Latent Class Model (LCM), we first estimated a basic Multinomial Logit (MNL) model as a baseline. The MNL assumes homogeneous preferences across all individuals and does not account for unobserved heterogeneity. Table 5.3 presents the parameter estimates and model fit statistics for the MNL model.

Table 5.3: Parameter estimates and model fit of the discrete-choice Multinominal Logit model.

Main effects	**MNL**	
	Estimate	**t-value**
ASC_bike	0	(Fixed)
ASC_e_bike	0.15736	1.625
ASC_e_scooter	-0.86665 **	-6.491
ASC_e_Brommobile	-1.48486 **	-6.917
ASC_e_car	0.53124 **	2.013
Total Travel Cost	-0.01445 **	-2.441
Walking Distance to shared modes	-0.02178	-1.842
In-vehicle Travel Time	-0.03792	-1.820
Model fit		
Initial log-likelihood	-5381.96	
Final log-likelihood	-4707.09	
R2	0.1254	
Adjusted R2	0.1241	
likelihood-ratio test	1349.74	

$^{**}p \leq 0.05$, $^{*}p \leq 0.1$

The results show that the MNL captures general trends (e.g., negative preferences for e-Brommobiel and e-scooters, and a significant cost sensitivity), but the overall model fit is limited. The log-likelihood at convergence is -4707.09, with an adjusted rho-squared value of only 0.1241. These values suggest that while the MNL offers a basic explanation of behaviour, it does not capture the variation in preferences observed across different population subgroups.

To capture the heterogeneity in user preferences and move beyond the limitations of the MNL model, we estimated a Latent Class Model (LCM) using the Apollo package (Hess and Palma, 2023). LCM allows for preference variation across latent segments by probabilistically assigning individuals to different classes with distinct utility structures.

To determine the optimal number of latent classes, we considered the ρ^2 values along with the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). These information criteria balance model fit and parsimony (Swait, 1994). In addition to these statistical measures, we also evaluated the interpretability of the results to ensure meaningful segmentation.

To determine the optimal number of latent classes, we estimated multiple models, ranging from a one-class specification (essentially an MNL model) to a five-class model. The model fit indices for these estimations are summarised in Table 5.4.

Table 5.4: Outcomes of Latent Class Model with Increasing Number of Segments.

Number of Classes	No. of parameters	log-likelihood at convergence (LL)	Log-likelihood at 0 (LL(0))	ρ^2	Akaike information criterion (AIC)	Bayesian information criterion (BIC)
1-Class	7	-4707.09	-5381.96	0.1254	9428.18	9470.98
2-Class	15	-3336.99	-5381.96	0.3772	6703.98	6795.7
3-Class	23	-2795.21	-5381.96	0.4806	5644.42	5809.52
4-Class	31	-2223.25	-5381.96	0.5869	4508.51	4698.07
5-Class	39	-2669.3	-5381.96	0.4968	5416.6	5655.08

The 4-class model is the best choice, as indicated by the lowest Bayesian Information Criterion (BIC) and the Akaike Information Criterion (AIC), the highest explanatory power (ρ^2), and the best log-likelihood improvement. The 2-class and 5-class models performed worse, while the 3-class model failed to improve beyond the null model. Given its superior balance of fit, complexity, and interpretability, the 4-class model is the most appropriate selection.

Table 5.5 displays the parameter estimates for the four latent segments, each representing a different pattern of preferences among respondents. To assign different respondents in the dataset to one of the 4 latent segments of the 4-class model, we used the mean probability values. These values indicate the probability of each being part of any of the latent segments. Each respondent gets assigned to a class with the highest probability of being likely to be similar to other respondents in that given class. Hence, we observe that Class 1 contains the highest share (37.14%) and Class 4 the lowest (16.45%). Some classes are more prevalent in the sample than others, implying differences in how groups of respondents make their choices among shared modes. We example the names given to the classes based in the estimated parameter values in detail in section 5.5.

This Latent Class Model shows a significant improvement in model fit. The log-likelihood improves from LL (start) -5381.96 to LL (final) -2223.25, demonstrating a much better explanation of choices than the baseline models. The model's adjusted rho-squared values (0.5811 vs equal shares, 0.5251 vs observed shares) confirm its strong performance. The improvement in fit from the MNL model to the LCM clearly demonstrates the added value of capturing unobserved preference heterogeneity among older adults in shared mobility choices. Detailed class-specific parameters are provided in Section 5.5.

Table 5.5: Parameter estimates and model fit of the discrete-choice latent class model.

Latent Class (4 classes)								
Estimated parameters:	31							
Iterations:	78							
A Number of individuals:	418							
Several modelled outcomes:	3344							
Main effects	**Class 1**		**Class 2**		**Class 3**		**Class 4**	
	Price Sensitive & Private Car Enthusiast **(37%)**		Time-Conscious travellers **(27%)**		Pro-Cycling & Conventional Travelers **(20%)**		Micro-mobility Enthusiasts **(16%)**	
	Estimate	t-value	Estimate	t-value	Estimate	t-value	Estimate	t-value
ASC_bike	fixed to 0	fixed to 0	fixed to 0	fixed to 0	fixed to 0	fixed to 0	fixed to 0	fixed to 0
ASC_e_bike	-0.1363	-0.1983	3.11989	10.3144**	-3.65872	-6.7293**	1.15822	2.4375**
ASC_e_scooter	-1.55536	-1.7564*	0.15552	0.349	-5.48373	-7.1222**	3.13916	6.0307**
ASC_e_Brommobile	-3.05285	-2.2971**	-2.6426	-2.1969**	-5.93053	-4.8499**	2.86716	3.6589**
ASC_e_car	1.66218	1.075	1.27696	1.4682	-4.64114	-3.3917**	2.09814	2.0888**
Total Travel Cost	-0.10016	-2.6442**	-0.02223	-1.2832	-0.06627	-2.4606**	-0.03744	-1.859*
Walking Distance to shared modes	0.02194	0.4025	-0.15202	-3.1875**	-0.0199	-0.2431	-0.08775	-2.739**
In-vehicle Travel Time	-0.0866	-0.846	-0.19612	-2.1986**	-0.23397	-1.9063*	-0.13763	-2.2706**
LL(0,Class)	-5381.96		-5381.96		-5381.96		-5381.96	
LL(final,Class)	-9406.58		-8369.78		-10350.66		-8049.24	
Mean probability	0.3714		0.2679		0.1962		0.1645	
LL (start)	-5381.96							
LL (whole model) at equal shares, LL(0)	-5381.96							
LL (whole model) at observed shares, LL(0)	-4713.38							
LL (final, whole model)	-2223.25							
Rho-squared vs equal shares	0.5869							
Adj.Rho-squared vs equal shares	0.5811							
Rho-squared vs observed shares	0.5283							
Adj.Rho-squared vs observed shares	0.5251							
AIC	4508.51							
BIC	4698.07							

$^{**}p \leq 0.05$, $^{*}p \leq 0.1$

5.5 Observing heterogeneity in transport mode preferences across classes

Each of the four classes defined in the previous section indicates distinct and significant transport mode preferences. Class 1, with the highest assigned portion of respondents (37.14%), serves as the largest segment but lacks strong preferences, as indicated by the statistically insignificant ASCs for most modes. The negative valuation of e-scooters (-1.555, t=-1.756) and e-Brommobiles (-3.052, t=-2.297) suggests a general reluctance toward these modes. However, the negative travel cost coefficient (-0.100, t=-2.644) indicates price sensitivity, making this segment price-conscious but leaner towards private (shared) car use.

Class 2, making up 26.79% of respondents, is highly inclined toward e-bikes, with an ASC of 3.120 (t=10.314), making it the strongest preference for e-bikes among all classes. However, they do not show a strong preference for e-scooters (0.156, t=0.349, insignificant) and display an aversion to e-Brommobiles (-2.643, t=-2.197). The ASC for e-cars (1.277, t=1.468) is positive but not significant, suggesting a mild but uncertain preference. This segment is highly time-sensitive, as seen in the negative coefficients for walking time (-0.152, t=-3.187) and in-vehicle travel time (-0.196, t=-2.199), implying that these travellers favour modes that reduce active and waiting times. Unlike other groups, this class is not cost-sensitive, as reflected in the insignificant travel cost coefficient (-0.022, t=-1.283), suggesting that this segment values convenience and efficiency over price.

Class 3, accounting for 19.62% of individuals, appears to be highly averse to micromobility and small electric modes. A strongly negative ASCs for e-bikes (-3.658, t=-6.729), e-scooters (-5.484, t=-7.122), and e-Brommobiles (-5.930, t=-4.850) indicate a dislike toward these modes. The ASC for e-cars (-4.641, t=-3.392) is also significantly negative, suggesting that this group prefers neither electric cars nor micromobility. This segment is price-sensitive (travel cost: -0.066, t=-2.461) and dislikes additional travel time (in-vehicle time: -0.234, t=-1.906), further reinforcing their preference for conventional transport.

Class 4 represents 16.45% of respondents and shows relatively strong preferences for micromobility and small electric vehicles. Significant and positive ASCs for e-bikes (1.158, t=2.437), e-scooters (3.139, t=6.030), and e-Brommobile (2.867, t=3.659) indicate some inclination toward electrified light vehicles, over conventional options. The ASC for e-cars (2.098, t=2.089) suggests a positive inclination toward electric cars as well. However, this class is time sensitive. The negative impact of walking time (-0.0877, t=-2.739) and in-vehicle travel time (-0.1376, t=-2.270) suggests that this group prioritises speed and convenience. Moreover, the travel cost coefficient (-0.037, t=-1.859) further indicates moderate price sensitivity.

To better define and distinguish the four classes, we analysed class membership and respondents' background characteristics. This was done by weighting demographic attributes based on the posterior probabilities of individuals belonging to each class. The resulting weighted averages are displayed in Table 5.6.

Table 5.6: Cross-tabulation of class membership and background characteristics.

		Class 1	**Class 2**	**Class 3**	**Class 4**
		Price Sensitive & Private Car Enthusiast	Time-Conscious Travellers	Pro-Cycling & Conventional Travellers	Micro-mobility Enthusiast
Variables	**Category**	**(37%)**	**(27%)**	**(20%)**	**(16%)**
Socio-economic					
Age	50-59	28%	31%	23%	43%
	60-69	38%	34%	33%	38%
	70-79	28%	29%	39%	19%
	80≤	6%	6%	5%	0%
Gender	Male	55%	52%	70%	60%
	Female	45%	48%	30%	40%
Education level	Less formally educated	53%	65%	35%	38%
	Moderately educated (Bachelor's degree)	25%	16%	30%	29%
	Highly educated (Master's or doctoral degree)	23%	19%	34%	32%
Income (Total family gross annual)	Less than € 42.400	26%	36%	25%	49%
	Between € 42.400 & € 71.000	21%	23%	29%	17%
	Between € 71.000 or more	25%	19%	26%	16%
	Won't say	28%	21%	20%	18%
Health ability	I am fully physically mobile	70%	78%	80%	71%
	My mobility is limited/ I am not a mobile	30%	22%	20%	29%
Private cars					
License	Yes	93%	88%	73%	85%
	No	7%	12%	27%	15%
Having a car	Yes	93%	79%	67%	72%
	No	7%	21%	33%	28%
Average use of cars	Weekly	82%	66%	48%	72%
	Rarely/never	18%	34%	52%	28%
Shared modes experience variable					
Familiarity with shared mobility concept	Yes	85%	84%	80%	90%
	No	15%	16%	20%	10%
Shared modes Experience	Yes	9%	19%	29%	24%
	No	91%	81%	71%	76%

Current trip variable					
Main mode	Car as driver and passenger	84%	64%	43%	69%
	PT(Train/metro/bus/tram)	10%	15%	30%	16%
	Active modes	6%	21%	27%	15%
Purpose	To work/study	21%	14%	17%	25%
	Shopping/ Personal care	19%	23%	11%	25%
	Social/recreational/visit	59%	63%	72%	50%
Distance	shorter than 15 min	17%	17%	6%	18%
	Between 15-30 min	44%	42%	32%	43%
	longer than 30 min	39%	42%	62%	40%

Table 5.7 summarises and compares the respondents' mobility characteristics based on the Latent Class segmentation.

5.5.1 Price sensitive and private car enthusiast group

The Price Sensitive and Private Enthusiast Group (37%) consists mainly of older individuals (60-79 years), with moderate mobility limitations and mixed income levels. They show no strong preference for emerging mobility options and rely heavily on private cars (93% licensed, 82% weekly usage). Despite high awareness of shared mobility (85%), only 9% have used it. Their trips are mostly social and recreational (59%), with a preference for the car as the mode of transport due to familiarity and convenience.

5.5.2 Time-conscious travellers group

The Time-Conscious Travellers (27%) favour efficiency and affordability. With a balanced age distribution (50-79 years) and moderate education levels, they prefer e-bikes as an alternative to cars. While 88% are licensed and 79% own cars, their weekly car use is lower (66%). Their trips focus on shopping (23%) and leisure (63%), with 21% using active modes, making e-bikes a key part of their mobility strategy.

5.5.3 Pro-cycling & conventional travellers' group

This 20% segment consists of older, well-educated, financially stable individuals (39% aged 70-79). They are the least reliant on cars (73% licensed, 67% ownership, 48% weekly use) and the most multimodal, with 30% using public transport and 27% engaging in active travel. They have the highest experience with shared mobility (29%) and the longest trips (62% over 30 minutes), preferring flexible transport options.

5.5.4 Micromobility enthusiasts' group

Comprising 16%, this relatively young senior group are more educated (43% aged 50-59) and has a progressive approach to transport. Though 85% have a driver's license, they are less car-dependent (72% own a car, 72% weekly use). They show the highest engagement with shared mobility (24%) and familiarity (90%). Their travel is split across private cars (69%), public transport (16%), and active modes (15%), with shorter trips favouring micro-mobility solutions.

Table 5.7: Comparison of respondents' mobility characteristics based on latent class segmentation.

	Class 1	**Class 2**	**Class 3**	**Class 4**
Summary	Price Sensitive & Private Car Enthusiast **(37%)**	Time-Conscious Travellers **(27%)**	Pro-Cycling & Conventional Travellers **(20%)**	Micro-mobility Enthusiasts **(16%)**
Age	Mostly 60-79	Evenly spread 50-69	Mostly 60-79	Mostly 50-69
Gender	Balanced (55%M, 45%F)	Balanced (52% M, 48% F)	More males (60%)	More male (60%)
Education	Mostly less formally educated (53%)	At least formally educated (65%)	Most educated, 34% highly educated	More educated, 32% highly educated
Income	Mixed, many undisclosed	Mixed, 36% below € 42,000	Balanced, 26% above € 71,000	Lower-income, 49% below € 42,400
Health ability	70% fully mobile	78% fully mobile	80% fully mobile	71% fully mobile
Car dependency	Highly car-dependent, 93% licensed and own a car, 82% weekly car users	Moderate car use, 88% licensed, 79% own a car, 66% weekly users	Lowest car dependency, 73% licensed, 67% own a car, only 48% weekly users	Less car-dependent, 85% licensed, 72% own a car, 72% weekly car users
Familiarity with shared modes	Low experience (9%), 85% aware but not engaged	Moderately aware (84%), low engagement (19%)	Highest engagement (29%), 80% familiar with shared mobility.	Most aware (90%), moderate engagement (24%)

Main mode	Most car-dependent (84%), least use of alternative modes	Highest active mode use (21%), driven by e-bike adoption.	Least car-dependent (43%), most public transport use (30%)	Still car-dominant (69%), but highest openness to active transport (15%)
Purpose	Most social /recreational trips (59%), least work-related (21%)	Most shopping trips (23%), least work related trips (14%)	Most social trips (72%), least shopping trips (11%)	A most balanced mix of work, shopping, and social trips
Distance	Most long trips (39% >30 min), least short trips (17%)	Most balanced mix of short, medium, and long trips.	Most long trips (62% >30 min), least short trips (6%).	Most evenly distributed trip durations

5.6 Discussion and recommendations

This study offers important insights into the diverse travel preferences of 50+ age and contributes to research on sustainable mobility in aging populations. Using a latent class approach, we identified four distinct traveller profiles with varying degrees of openness to shared mobility options.

Our findings confirm that preferences of older adults for shared mobility are heterogeneous. Some groups are willing to experiment with new, flexible transport modes, while others remain car-dependent due to physical, digital, or psychological barriers. These differences reflect broader challenges in shared mobility adoption among older populations.

By highlighting heterogeneity within the 50+ age group, this study moves beyond simplistic categorizations of "older adults" and supports the development of more inclusive and age-sensitive mobility strategies. Our findings suggest that shared mobility systems—often designed for younger, digitally savvy users—must adapt to accommodate older adults with varying needs and abilities. This has implications not only for service design but also for public engagement, pricing models, and infrastructure planning.

5.6.1 Policy implications

From a policy perspective, segment-specific interventions are key to promoting shared mobility among ageing populations. Tailoring transport policies to the needs of different traveller groups will support more inclusive urban mobility while reducing private car dependency. Based on the mobility characteristics and preferences of each segment, as identified through the latent class analysis, the following interventions are proposed. Table 5.8 summarizes practical interventions aligned with each group, including example strategies and implementation notes.

Table 5.8: Targeted interventions by segment with strategy examples.

Segment	Main Barriers	Suggested Actions	Example Measures
Price Sensitive and Private Car Enthusiast Group	High car reliance, cost sensitivity, habit, low trust in new modes	– Lower entry barriers – Intoroduce subsidies for mobility options – Improve accessibility – Promote shared services through trials	– Monttly mobility credits (e.g., €10 -15/month for 65+ users) – Workshops via senior centres on using mobility apps
Time-Conscious Travelers	Concerned with efficiency, strong preference for quick transport	– Expand fast alternatives like e-bikes – Invest in e-bike infrastructure – Integrate with public transport	– Promote e-bike sharing schemes via pension fonds/pension unions/ communities/local governments (€20/month) – e-bike parking at supermarkets and stations
Pro-Cycling & Conventional Travelers Group	Preference for familiar public or active modes	– Strengthen walking and cycling networks – Enhance integration – Support multimodal connections	– Upgrade bike lanes and lighting
Micro-mobility Enthusiasts Group	Openness to change and interest in innovation, but cost-sensitive	– Introduce low-cost micromobility subscriptions – Improve access to shared micro-mobility	– Low tariffs (e.g. €1 per scooter ride) during off-peak hours – Microbility passes bundled with transit subscroptions – Expand micromobility options near transit hubs – Increase public awareness campaigns

In general, expanding micro-mobility infrastructure, integrating e-bikes with public transport, and introducing financial incentives for shared mobility adoption could significantly influence behaviour. Additionally, increasing public awareness and trial opportunities could help hesitant groups familiarize themselves with new mobility options. Implementing these targeted policy interventions can help cities transition toward more inclusive, sustainable, and multimodal transport systems.

These recommendations aim to move beyond one-size-fits-all transport policy. Understanding which groups are more receptive to shared mobility can help policymakers better target investments and communications.

These interventions could be supported through municipal mobility budgets or co-funded by public-private partnerships with shared mobility providers.

5.6.2 Study limitations

Despite these insights, few limitations should be acknowledged. The study focuses on small to medium-sized cities in the Netherlands, which may limit the generalizability of the findings to larger metropolitan areas or rural regions with different mobility contexts. The online survey format may have also restricted participation among older adults with limited digital literacy. Although efforts were made to ensure demographic diversity through the panel provider, some voices may remain underrepresented. While including demographic characteristics in the latent class model could have enriched the interpretation of class profiles, our attempts to do so led to model instability and non-convergence—likely due to limited variability in the sample, which consisted exclusively of individuals over 50 years old living in relatively homogeneous urban contexts. Lastly, the use of a stated preference method, although valuable for exploring hypothetical behaviour, may not fully capture actual decision-making processes. Future research could complement this work using revealed preference data or experimental interventions.

5.6.3 Future research

To expand on these findings and address current limitations, future research could diversify the sample to include participants from a broader range of geographic contexts, including both larger urban centres and rural areas. This would enhance the generalizability of the results and may allow for greater demographic diversity in latent class membership estimations. In addition, employing longitudinal methods could provide insight into how travel behaviour evolves over time, particularly in response to aging, policy interventions, or shifts in mobility options. Lastly, evaluating the effectiveness of specific incentive models—such as fare reductions or mobility credits—through real-world pilot programs would provide valuable evidence for designing targeted interventions.

5.7 Conclusion

This study explores the challenges and opportunities of promoting shared mobility in car-free city centres, with a particular focus on medium-sized Dutch cities and the often-overlooked demographic of middle-aged and older residents. Through the Latent Class Model (LCM), this study captures the diversity of preferences among respondents and provides a nuanced understanding of the factors influencing shared mobility adoption. It identifies latent passenger segments, offering valuable insights for sustainable mobility policies and passenger behaviour analysis.

Findings clearly indicate that older adult travellers (50+) do not form a very homogeneous group and exhibit some diverse mobility preferences. This underscores the importance of developing targeted, segment-specific transport policies rather than relying on one-size-fits-all approaches. While shared mobility options—such as e-bikes, e-scooters, e-Brommobiel, and e-cars—offer sustainable alternatives, their adoption is hindered by barriers such as perceived inconvenience, lack of reliability, high cost, cleanliness concerns, and limited awareness compared to private cars. For older adults, specific challenges such as unfamiliarity with technology, cognitive decline, and physical limitations further contribute to their hesitancy to engage with shared mobility services.

Segment analysis reveals key behavioural patterns: The Price Sensitive and Undecided Group (37%) remains highly car-dependent, with little interest in new mobility trends perhaps due to age-related limitations, digital unfamiliarity, and mobility constraints. Time-Conscious travellers (27%) balance car use with a strong preference for e-bikes, particularly for leisure and shopping trips. Pro-Cycling and Conventional Travelers (20%) are the least reliant on private cars, embracing a multimodal approach with high public transport and shared mobility engagement. Micromobility Enthusiasts (16%), though younger and relatively more educated than the rest of the classes, face financial constraints that limit their ability to adopt shared services despite their openness to alternative mobility.

Our findings suggest that policies promoting shared mobility must move beyond age-based assumptions and instead reflect the nuanced travel behaviours, preferences, and constraints of different groups. By doing so, cities can build more inclusive and adaptable transport systems that serve both younger and older generations.

Chapter 6:

Conclusion and Recommendations

In this final chapter, we reflect on the core findings and contributions of this dissertation. We investigated the role of emerging shared mobility services and mobility hubs in influencing individual travel behaviour and contributing to sustainable urban mobility. departing from a conceptual analysis of system-level impacts (Chapter 2) to empirical findings of user preferences across different urban contexts and demographics (Chapters 3, 4, and 5), the research sought to bridge the gap between technological innovation and behavioural adoption in transport planning. It delivers behaviourally informed knowledge to support a sustainable and inclusive urban mobility transition, and informed policy making.

This final chapter is structured as follows: Section 6.1 summarises the main findings, providing systematic answers to the four guiding research questions. Section 6.2 provides an integrated synthesis on the broader context of the research, focusing on sustainability, inclusion, and contextual transferability. Section 6.3 translates the research insights into policy and planning implications and identifies directions for future research on sustainable and inclusive urban mobility. Section 6.4 concludes with a critical discussion of the study's limitations and their implications for interpretation and generalisation.

6.1 Main Findings and conclusions: synthesis of behavioural and systemic impacts

In this thesis, we investigated how shared mobility and mobility hubs affect individual travel behaviour and contribute to low-carbon, socially inclusive urban transport systems. Through an integrated methodological framework, combining a systematic literature review, life-cycle thinking, stated preference experiments, and advanced discrete choice modelling, it addressed four interconnected research questions related to environmental performance, behavioural determinants, adoption heterogeneity, and context sensitivity. The findings provide a multi-level understanding of how shared mobility functions within broader mobility transitions.

Which roles do shared mobility and mobility hubs play in reducing CO_2 emissions by facilitating modal shifts in urban transportation systems? (Chapter 2)

Shared mobility and mobility hubs each contribute to CO_2 reduction but operate through different mechanisms. Shared mobility reduces operational emissions by encouraging a shift away from private car ownership. Mobility hubs, in turn, strengthen the sustainability of shared mobility by mitigating life-cycle inefficiencies and improving system logistics, offering multimodality and reducing travel time by public transport t and by shared modes for first and last mile trips.

A systematic literature review informed of a life-cycle conceptual framework linking behavioral change, technological innovation, and system operations. The review showed that shared mobility, particularly car-sharing and micro-mobility, lowers emissions when it replaces private car trips or when it strengthens public transport by improving first–last-mile accessibility. Electrified car-sharing exhibits especially large reductions, while micro-mobility extends public transport catchment areas and encourages multimodal, low-carbon travel. Poorly integrated services, however, may merely substitute for already low-carbon modes such as walking or cycling.

Despite these operational benefits, the long-term sustainability of shared services is constrained by life-cycle impacts, including embodied energy in manufacturing and emissions from maintenance and rebalancing. For micro-mobility, short asset lifespans and intensive redistribution operations can significantly erode environmental gains.

Mobility hubs address these inefficiencies by functioning as strategic infrastructure that allows increased use of shared mobility. By concentrating supply and demand at accessible locations, hubs reduce fossil-fuel-based rebalancing, promote safer operating environments that extend vehicle lifetimes, and improve fleet utilisation—key determinants of life-cycle carbon intensity. In doing so, hubs transform from simple interchange points into structural components of sustainable mobility systems, and boost the use of public transport

Although shared modes currently contribute modestly to overall emission reductions due to limited adoption, their integration into mobility hubs strengthens multimodal connectivity and supports gradual, long-term modal shift. As technology, policy, and system integration mature, shared mobility and hubs can increasingly function as central enablers of durable low-carbon transport transitions.

Which factors influence passenger's preferences and acceptance of shared access/egress modes at multimodal railway stations? (Chapter 3)

Passenger preferences for shared access/egress modes at multimodal stations are shaped by travel attributes, contextual conditions, and socio-demographic factors. Using a stated preference experiment and a Nested Logit model for users of a small multimodal station, Chapter 3 identified cost, travel time, and availability as the core determinants of shared-mode acceptance. Cost was the strongest predictor, indicating substantial price sensitivity. Travel time also negatively influenced choice, while availability alone was not statistically significant, likely because participants implicitly considered availability in their evaluation of time and cost.

Mode-specific acceptance differed significantly. Shared bicycles showed the most robust acceptance; small increases in time or cost had limited effect. Autonomous vehicles (individual and collective) were positively perceived but highly elastic, losing attractiveness with small increases in inconvenience. Shared e-steps and e-scooters had the lowest utility, reflecting perceived discomfort or risk.

Contextual conditions strongly shaped preferences. Adverse weather substantially reduced acceptance of non-motorised modes, while carrying luggage increased preference for faster shared or automated options. Socio-demographic characteristics moderate acceptance. Travellers aged 26–45 were the most receptive to innovative modes, while younger and older groups showed lower acceptance due to affordability constraints or preference for conventional modes. Higher-income and highly educated travellers were more willing to adopt advanced shared services. Gender effects were evident, with women showing higher acceptance of e-scooters.

Overall, the findings show that acceptance of shared access/egress modes is concentrated among middle-aged, higher-income, and more educated travellers, while younger, older, and lower-income groups remain reliant on conventional modes. This highlights a need for inclusive pricing, careful design, and supportive station area infrastructure to ensure equitable access.

Which determinants shape mode choices and avoidance behaviour among residents in car-free inner-city areas considering shared modes as their primary travel options? (Chapter 4)

Chapter 4 analysed mode choices and avoidance behaviour among residents in a neighbourhood transitioning toward a car-free environment. A key methodological innovation was the inclusion of an "opt out" (activity substitution) alternative, which allowed the study to capture of modal substitution and complete trip avoidance.

Travel cost and accessibility (i.e. walking distance to shared stations) were the strongest drivers of mode choice. Both had consistently strong effects across modes, highlighting the importance of affordability and spatial proximity for shared-mode adoption. Significant unobserved preference heterogeneity suggests that pricing or infrastructure improvements will affect individuals unevenly. The high sensitivity for walking time reflects strong responsiveness to perceived effort and convenience.

Socio-demographic characteristics also shaped adoption. Younger, digitally competent individuals showed strong preferences for shared micromobility, while men exhibited higher willingness to use e-scooters. Higher-income and higher-educated residents were more inclined toward premium shared services such as carsharing and cargo-bike sharing. In contrast, shared modes were less attractive for commuting, suggesting limited suitability for time-sensitive trips.

Avoidance behaviour was a notable result: the "opt-out" option had the highest average utility, with more than half of respondents. Avoidance was prevalent among residents aged 50 and above and among affluent or highly educated individuals, indicating that non-adoption may stem from digital, physical, or psychological barriers—not only from cost. Despite high avoidance rates, meaningful substitution potential exists. Shared e-scooters and e-bikes emerged as the most viable alternatives to car travel, particularly for short urban trips. Shared e-cars and cargo bikes were less attractive, indicating the need for better integration and targeted incentives to increase uptake.

Which behavioural and socio-economic factors affect the adoption of shared mobility among adults aged 50 and above in small and mid-sized cities? (Chapter 5)

In this chapter, we investigated shared mobility adoption among adults aged 50 and above in small and mid-sized cities using a Latent Class Model. Four distinct segments emerged, namely: Price-Sensitive and Private Car Enthusiasts (37%), Time-Conscious Travellers (27%), Pro-Cycling and Conventional Travellers (20%), and Micromobility Enthusiasts (16%). These segments reveal substantial heterogeneity in attitudes toward shared mobility within older populations.

Across the sample, travel time, cost, and accessibility were central determinants of choice. Time-Conscious Travellers strongly penalised slow or indirect shared modes, while Price-Sensitive and Private Car Enthusiasts displayed pronounced cost aversion. Accessibility barriers deterred adoption among several segments, reinforcing the need for well connected, and easy entry networks

Mode-specific preferences were also segment-dependent. Price-Sensitive and Private Car Enthusiasts were least willing to adopt shared e-scooters, e-Brommobiels, or shared e-cars, reflecting reliance on private vehicles. Micromobility Enthusiasts showed the highest acceptance of shared e-scooters and e-Brommobiels, indicating openness to flexible, innovative modes. Pro-Cycling and Conventional Travellers preferred familiar active or conventional public transport modes.

Socio-economic factors also helped with predicting class membership. Car availability had the strongest influence, decreasing the likelihood of belonging to any shared-friendly segment. Higher income and male gender were associated with Micromobility Enthusiasts, while higher education associated with the Time-Conscious segment. Women and lower-income individuals were more likely to belong to the Price-Sensitive segment.

Overall, adoption among older adults is shaped by diverse behavioural profiles and socio-economic conditions. Cost, time, accessibility, and car availability form key barriers, while a smaller but important subgroup demonstrates strong micromobility potential. These heterogeneities underline the need for tailored and inclusive interventions in smaller urban areas (the typical study area of this chapter).

6.1.1 Cross-chapter comparison and synthesis of behavioural findings

Here, we briefly discuss the synthesis of key behavioural findings from the discrete choice models developed in Chapters 3, 4, and 5. This subsection does not introduce new empirical analysis or modelling; instead, it brings together and interprets the main results reported in the individual chapters to facilitate cross-context understanding within the thesis. The focus is on identifying recurring behavioural mechanisms and context-specific differences in mode utility, cost sensitivity, and behavioural acceptance across the three empirical settings.

The synthesis indicates that several behavioural determinants are consistent across modelling contexts, most notably the dominant role of travel cost. Across all three studies, cost exerts a strong influence on the utility of shared mobility options, with particularly high sensitivity observed among older adults and lower-income users. Time, accessibility, and walking distance also consistently affect mode choice, although their relative importance varies by context and population group. Table 6.1 summarises these patterns across the three empirical chapters.

Across the different urban contexts examined, shared bicycles emerge as a comparatively robust option, displaying relatively high utility both in multimodal hub settings and in inner-city environments. In contrast, micromobility modes such as e-scooters tend to appeal more strongly to younger and digitally confident users, while shared cars and cargo bikes exhibit more limited utility across most population segments. These patterns suggest that the effectiveness of specific shared modes is highly contingent on both user characteristics and spatial context.

A consistent pattern across the empirical chapters is the prominence of avoidance behaviour in restrictive urban environments. In the car-free zone context examined in Chapter 4, the high probability associated with the “no-trip” alternative—reaching up to 64% in certain scenarios—indicates substantial behavioural resistance to mandatory modal change. This resistance is particularly pronounced among older and more affluent residents, underscoring the importance of addressing physical, digital, and perceptual barriers alongside infrastructural or pricing interventions.

The synthesis further highlights socio-demographic differentiation in behavioural responses. Older adults exhibit the highest overall cost sensitivity and are more likely to reject shared mobility options under unfavourable conditions. Conversely, higher-income and highly educated individuals show greater acceptance of technologically advanced modes, such as automated vehicles, pointing to potential socio-economic and digital equity concerns in the deployment of emerging mobility solutions.

Table 6.2 consolidates the core cross-cutting insights derived from this synthesis, summarising how universal economic drivers, context-dependent utilities, and socio-demographic characteristics jointly shaped shared mobility adoption. Overall, the cross-chapter synthesis suggests that while cost sensitivity represents a fundamental constraint across all contexts, spatial accessibility, walking distance, and contextual factors acquire heightened importance in dense urban settings and among ageing populations. These findings reinforce the need for differentiated and context-aware policy approaches that recognise behavioural diversity and equity considerations. The implications of these insights for transport policy and planning are discussed further in Section 6.3.

Table 6.1: Cross-Chapter Summary of Key Behavioural Findings from Discrete Choice Models (Chapters 3–5).

Dimension	**Chapter 3 (Access/Egress at multimodal hub) Nested Logit**	**Chapter 4 (Car-Free Zone) Mixed Logit**	**Chapter 5 (Older Adults in Small/Mid Citis) Latent Class Model**
User/Trip Context	Travellers accessing/egressing a small railway station (multimodal hub).	Residents living in an inner-city area transitioning to a car-free zone.	Adults aged 50+ living in small to mid-sized cities.
Most Important Attributes	1. Cost (dominant) 2. Travel time 3. Availability (not significant independently)	1. Cost (strong negative) 2. Walking distance (strong negative) High VoT for walking (€0.20/min)	Attribute importance varies by class: • Price-Sensitive: Cost • Time-Conscious: Time • Several classes penalise walking distance strongly
Impact of Age	Younger age (20–39): higher Shared e-step; lower Shared e-scooter	Adults 50+ strongly associated with choosing *no-trip*	Older adults cluster into segments rejecting shared modes (Price-Sensitive; Conventional)
Impact of Gender	Male → higher Shared e-step	Men → higher scooter sharing	Male → Higher probability of being Micromobility Enthusiast
Impact of Income	Low income → lower Collective AV adoption	High income → higher Cargo-bike sharing & car-sharing	Higher income → higher Micromobility Enthusiast membership
Impact of Education	High education → higher Shared e-step	Higher education → higher premium shared modes (cargo-bike, car-sharing)	Higher education → higher Time-Conscious segment (strong time sensitivity)
Key Behavioural Pattern	Shared bikes are the most resilient access/egress mode.	"No-trip" dominates → strong resistance to mandatory modal shift.	Older adults show strong heterogeneity; resistance and openness coexist.

Drawing these insights together, Table 6.2 summarises the core cross-cutting findings derived from the three empirical chapters.

Table 6.2: Synthesis of Core Cross-Cutting Behavioural Insights across Empirical Chapters.

Theme	Core finding
System sustainability	Mobility hubs reduce life-cycle emissions by lowering rebalancing needs, reducing vandalism, improving vehicle durability, and increasing fleet utilisation.
Cost sensitivity	Direct travel cost is the strongest determinant of adoption; older adults and low-income groups display the highest price sensitivity.
Spatial utility	Shared modes are most effective for short trips and first–last mile connections; limited suitability for long or inter-city trips.
Foundational mode at hubs	In cycling-oriented cities, shared bikes/e-bikes should represent ≥50% of hub supply to maximise sustainable multimodal access.
Resistance/avoidance	Trip avoidance (“opt-out”) achieves the highest utility in car-free transitions, especially among older, affluent, or highly educated residents.
Tech equity	High-cost, technologically advanced modes (e.g., AVs) attract affluent, highly educated users, reinforcing digital and economic divides.
Ageing populations	Older adults display heterogeneous behavioural profiles; prior shared mobility experience strongly predicts adoption, while digital literacy remains a major barrier.
Gender	Male users show consistently higher acceptance of shared micromobility and are more likely to belong to pro-shared behavioural segments.
High Preferred Modes	Shared (e-)bikes and shared e-scooters consistently demonstrate high utility across diverse contexts.
Least Preferred Modes	Shared cargo bikes and shared Brommobiels remain the least attractive in most demographic groups.
Walking Distance/Spatial Barriers	Walking distance is a major deterrent, especially for older adults and residents in car-free zones; penalties can reach €0.20/min.
Time Sensitivity	Highly educated individuals and work-related trips correlate with strong time sensitivity, reducing acceptance of slower shared modes.
Weather and luggage	Rain/cold increase demand for fast, sheltered modes; carrying heavy luggage increases willingness to pay for convenient, motorised shared options.

Overall, the comparative analysis demonstrates that shared mobility adoption is shaped by cost accessibility, availability, and socio-demographic characteristics. Cost sensitivity is a dominant constraint across all contexts, while spatial accessibility and travel time acquire particular significance among older adults and residents in dense urban areas. Emerging mobility solutions such as AVs exhibit substantial socio-economic bias, whereas micromobility and shared bicycles show the broadest appeal under favourable conditions.

The findings collectively underscore the need for targeted policies that account for behavioural diversity, equity considerations, and spatial conditions. These insights form the empirical foundation for the policy recommendations presented in Section 6.3.

6.2 Integrated synthesis: sustainability, inclusion, and contextual transferability

This section provides an integrated synthesis of the findings across all chapters, focusing on their broader implications for sustainable, inclusive, and transferable urban mobility transitions. This section interprets how behavioural evidence on shared mobility adoption, avoidance, and heterogeneity informs key sustainability and equity challenges faced by contemporary transport systems. By linking system-level environmental considerations with individual-level travel behaviour, the section positions the thesis contributions within ongoing academic and policy debates on low-carbon urban mobility.

6.2.1 Sustainability: from operational efficiency to life-cycle integrity

This thesis broadens the understanding of transport sustainability by moving beyond the narrow focus on increasing the use of public transport and creating mode shift. While shared mobility can contribute to reducing operational emissions through modal shift away from private car use, the empirical findings show that shared mobility, on its own, is insufficient to achieve meaningful decarbonisation.

Chapter 2 demonstrated that the environmental performance of shared and micromobility services depends critically on life-cycle factors such as manufacturing, maintenance, vehicle durability, and rebalancing logistics. Life-Cycle Assessment (LCA) therefore represents an essential analytical lens: operational savings can be offset by indirect emissions if systems are poorly designed or inefficiently managed.

The empirical findings offer a consistent message: significant CO_2 reduction occurs only when shared modes operate within well-designed mobility hub systems. Hubs help to mitigate some inefficiencies that undermine sustainability by:

- increasing vehicle lifetimes through supervised environments, and
- enhancing fleet utilisation by concentrating demand.

This shifts the policy emphasis from simply deploying shared mobility to integrating shared, active, and automated modes within infrastructure, where behavioural efficiencies reinforce one another in urban environment.

Although current CO_2 reductions from shared and micromobility services remain modest due to limited market share and short planning horizons, their long-term potential is substantial. When embedded within multimodal hubs, these services enhance first–last-mile connectivity, support gradual modal shift, and can evolve into core components of high-utilisation, low-carbon mobility systems. Consequently, sustainable mobility policy should priorities system integration, life-cycle efficiency, and equitable scaling over isolated technological rollouts.

6.2.2 Mobility inclusion: addressing the dual challenge of technological and behavioural exclusion

The transition toward shared, digital, and low-carbon mobility is not purely technological; it is fundamentally behavioural. The empirical findings across Chapters 3, 4, and 5 reveal that new mobility solutions are adopted unevenly across populations and travel context. In this thesis, these differences are empirically linked to socio-economic characteristics, digital literacy, prior experience with shared systems, and trip related attributes such as purpose and situational constraints.

Technological exclusion and divide innovation

Preferences for emerging transport technologies, particularly automated vehicles, vary strongly across socio-economic lines. As shown in Chapter 3, stated choice modelling results indicate that higher-income and highly educated individuals exhibit significantly higher acceptance of automated vehicles for access and egress trips, while lower-income and less-educated travellers display stronger cost sensitivity and lower willingness to adopt these options. This pattern reflects unequal access to innovation driven by affordability and familiarity rather than by travel needs alone. This evidence indicates a form of technological exclusion in which innovation mobility services primarily benefit early adopters and digitally confident users. Without targeted affordability measures, accessible interfaces, and non-digital access options, technology-driven mobility reforms may reinforce existing socio-economic inequalities rather than reduce them.

Behavioural and digital exclusion in shared systems

Chapters 4 and 5 reveal deeper mechanisms of behavioural and digital exclusion beyond access to technology. In the car-free inner-city case analysed in Chapter 4, the inclusion of an “opt-out” alternative in the choice model shows that a substantial share of residents, particularly older and higher-income individuals, prefer non-participation over adopting available shared mobility options. This finding indicates that restrictive or unfamiliar shared mobility environments can lead to travel avoidance rather than modal substitution.

Similarly, the latent class analysis in Chapter 5 demonstrates that among adults aged 50 and above, large behavioural segments remain dependent on private or conventional modes. These segmentations are characterised by strong cost sensitivity, low digital confidence, and concerns about accessibility. Only a small share of older adults expressed consistent willingness to adopt new shared services. These results indicate that digital, ergonomic, and cognitive barriers often constrain adoption more than attitudes or environmental values.

The intersection of age, digital literacy, and policy design

Across the empirical studies, the adoption of shared and automated mobility unfolds unevenly along demographic lines. Younger, higher-income, and digitally literate groups tend to act as early adopters, whereas older, lower-income, and digitally limited travellers face greater risks of being excluded from emerging mobility systems. This dual divide, technological (innovation access) and behavioural (participation readiness), emphasises the need for inclusive mobility design. Beyond spatial accessibility, mobility systems must also address digital usability, perceived reliability, and psychological comfort.

Practical measures include the development of age-friendly interfaces, simplified or hybrid booking mechanisms, assisted onboarding processes, and the implementation of micro-hubs designed with low physical and cognitive thresholds. Age-friendly interfaces should priorities intuitive navigation, clear visual hierarchies, and accessible language, ensuring usability for individuals with varying levels of digital literacy and potential sensory limitations. Similarly, simplified or hybrid booking mechanisms—such as combination of app-based, telephone-based, and in-person reservation options—can mitigate barriers associated with exclusive reliance on digital platforms, thereby accommodating users who may be less confident or less able to engage with fully digital systems.

Assisted onboarding also plays a critical role in bridging initial adoption gaps. This may involve targeted training sessions, community-based support programmes, or real-time assistance at key points of interaction, enabling users to gradually build confidence and familiarity with shared mobility services. In parallel, the design of micro-hubs should account not only for physical accessibility—such as proximity, seating, shelter, and step-free access—but also for cognitive ease, including clear signage, predictable layouts, and minimal decision complexity. Such features are particularly important for older adults and other vulnerable groups who may experience higher cognitive or physical burdens when navigating unfamiliar systems.

Collectively, these strategies reflect a shift from a technology-centric approach to a user-centric paradigm, in which service design is actively aligned with the capabilities and needs of diverse user groups. By addressing both technological and behavioural dimensions of exclusion, these measures can reduce participation barriers, foster trust in emerging mobility systems, and support more equitable adoption patterns. In doing so, they contribute not only to social inclusion but also to the broader effectiveness and sustainability of shared mobility systems, as a wider user base enhances system efficiency, utilisation, and long-term viability.

Toward more inclusive mobility transitions

Drawing directly on the empirical findings in Chapters 3, 4, and 5, this thesis indicates that inclusive mobility transitions require coordinated interventions at multiple, interrelated levels. These levels, the system level, the design level, and the behaviour level, reflect where adoption barriers were empirically observed to arise in the analysed cases.

At the system level, Chapter 4 shows that even when shared mobility services are available, unequal spatial distribution and limited alternatives can lead to avoidance behaviour, particularly among older and vulnerable populations. This highlights the need to ensure that shared and automated services are equitably distributed across neighbourhoods.

At the design level, findings from Chapters 3 and 5 demonstrate that cost sensitivity, interface complexity, and physical accessibility significantly influence adoption decisions, especially for older adults and first/last-mile users. This underscores the importance of human-centred design in digital interfaces, vehicle ergonomics, and micro-hub layouts.

At the behavioural level, Chapters 4 and 5 reveal that lack of familiarity, confidence, and prior experience with shared mobility often leads to non-adoption or opt-out behaviour, even when services are technically available. This points to the need for behavioural interventions such as outreach, training, and co-creation to support gradual engagement

Across the analysed contexts, non-adoption is shown to result not from refusal but from mismatches between system design and user capabilities. As mobility transitions accelerate, addressing these mismatches becomes essential for achieving both sustainability and social adoption.

The question of how far the behavioural mechanisms and policy recommendations derived from this thesis can be applied to other cities. Section 6.2.3 addresses this by examining contextual transferability.

6.2.3 Generalisability and contextual sensitivity

The empirical findings show that shared mobility transitions are sometimes context dependent. Adoption behaviour, mode preferences, and equity outcomes respond to local socio-economic structures, spatial forms, cultural norms, and governance capacities. As such, the behavioural insights developed in this thesis provide general principles but must be calibrated to local conditions.

The case studies illustrate how behavioural determinants vary across environments. For example:

- In smaller multimodal hubs, cost dominated decision-making.
- In dense inner-city areas, beside cost, spatial convenience and walking distance were the strongest determinants.
- Among older adults in smaller cities, perceived inconvenience, lack of reliability, high cost highly affected the choices.

The behavioural patterns observed in small to mid-sized cities cannot be directly extrapolated to metropolitan areas, where service density, digital infrastructure, and public awareness are substantially higher. These variations underscore that behavioural elasticities are spatially bounded. Policies must therefore be sensitive to population structure, service density, digital infrastructure, and daily mobility patterns.

6.3 Discussion: study limitations

This section critically discusses the main methodological, empirical, and conceptual limitations of this dissertation and reflects on their implications for interpreting the findings. While these limitations do not undermine the core contributions of the thesis, they define the scope within which the results should be understood and transferred to other contexts.

Reliance on stated-preference data

A primary limitation of this dissertation is the reliance on cross-sectional stated-preference (SP) data across all empirical chapters. Stated choice experiments are well suited for analysing emerging mobility options—such as shared micromobility, automated services, and car-free urban scenarios—that are not yet fully observable in real-world travel data. They allow systematic control over attributes such as cost, access distance, availability, and contextual conditions, which is essential for isolating behavioural mechanisms.

However, SP data cannot fully replicate real-world decision-making. Respondents evaluate hypothetical scenarios without experiencing actual service reliability, operational frictions, learning effects, or long-term adaptation. As a result, estimated sensitivities, particularly for novel modes, may differ from revealed behaviour once services mature. This limitation is especially relevant for findings related to automated vehicles, mobility hubs, and car-free policy contexts, where user experience and trust may evolve substantially over time.

Moreover, the cross-sectional nature of the data prevents observation of behavioural dynamics such as habit formation, inertia, or gradual acceptance. The results therefore represent stated intentions and short-term preferences rather than long-term behavioural trajectories.

Context-specific empirical setting

The empirical studies were conducted within the Dutch mobility system, which is characterised by high cycling rates, relatively dense urban form, strong public transport provision, and progressive transport governance. These favourable conditions shape baseline travel behaviour and influence how shared mobility is perceived relative to private cars, walking, and cycling.

Consequently, behavioural parameters estimated in this thesis—such as cost sensitivity, substitution patterns, and acceptance thresholds—should be interpreted as context-dependent rather than universally transferable. In more car-dependent, low-density, or institutionally constrained regions, shared mobility may face stronger barriers related to spatial coverage, service reliability, and cultural norms. Conversely, some findings—such as the dominance of direct travel cost and the importance of behavioural heterogeneity—are likely robust across contexts, even if their quantitative magnitudes vary.

The contribution of the thesis therefore lies less in providing universally applicable numerical estimates and more in identifying behavioural mechanisms and design principles that can inform locally adapted policy and planning decisions.

Sampling constraints

Another limitation relates to sample composition. Data collection relied primarily on online surveys, which tend to over-represent younger, higher-educated, and digitally proficient individuals. Although targeted efforts were made to include older adults, particularly in Chapter 5, certain groups—such as digitally excluded users, lower-income households, and individuals with limited mobility—remain under-represented.

As a result, barriers related to digital access, affordability, and physical capability may be underestimated in the modelling results. This limitation is particularly relevant for conclusions regarding inclusivity and equity in shared mobility adoption. While latent class and mixed logit models capture observed and unobserved heterogeneity within the sample, they cannot compensate fully for the absence of structurally excluded populations.

The findings on behavioural resistance and avoidance should therefore be interpreted as conservative estimates, especially in relation to vulnerable or marginalised groups.

Partial integration of environmental and behavioural models

Although this dissertation conceptually integrates behavioural choice modelling with life-cycle environmental perspectives, the empirical chapters focus primarily on individual-level travel behaviour. The behavioural models estimate preferences, substitution patterns, and avoidance behaviour, but they do not directly quantify aggregate system-level outcomes such as total emission reductions, network performance, or operational efficiency.

The link between behavioural change and environmental impact is therefore established conceptually and analytically, rather than through fully coupled demand–emission models. While this approach strengthens behavioural realism and avoids speculative system-level assumptions, it limits the ability to produce precise estimates of total CO_2 reductions under specific policy scenarios.

Accordingly, conclusions regarding sustainability impacts should be understood as indicative of potential mechanisms and directions of change, rather than as precise forecasts of emission outcomes.

Taken together, these limitations highlight the trade-offs inherent in studying emerging mobility systems at an early stage of development. The methodological choices made in this thesis priorities behavioural insight, inclusivity, and exploratory relevance over predictive precision. Within this scope, the findings provide robust evidence on how individuals respond to shared mobility options, mobility hubs, and car-restrictive policies, while also delineating clear boundaries for interpretation and transferability.

These limitations directly motivate the future research directions outlined in the next section and point toward the value of longitudinal data, revealed-preference validation, and integrated behavioural–system modelling in advancing sustainable and inclusive urban mobility research.

6.4 Reflection: policy implications and future research

This dissertation contributes a conceptual, methodological, and contextual understanding of how shared mobility and mobility hubs can support sustainable and inclusive mobility transitions. Across the empirical chapters, the findings demonstrate that technological innovation alone cannot deliver environmental or social benefits unless it is embedded within behaviourally informed, accessible, and context-sensitive mobility systems.

Methodologically, the thesis advances behavioural transport analysis through the use of discrete choice models, latent class segmentation, and innovative stated-preference designs. The introduction of a “no-trip” option and age-specific segmentation captures dimensions of equity, accessibility, and behavioural resistance often overlooked in conventional modelling. This approach allows exploration of future scenarios—such as automated services, car-free districts, and multimodal hubs—that are not yet fully observable in practice.

Across the analysed contexts, the findings show that behavioural mechanisms such as cost sensitivity, digital readiness, and age-related limitations are widely relevant but strongly shaped by local governance capacity, spatial form, and cultural norms. These insights affirm that equitable decarbonisation depends on policies that combine technological deployment with inclusive design, behavioural relevance, and local adaptability.

The following subsections translate these reflections into policy guidance, identify the study's methodological and contextual constraints, and outline future research avenues for advancing sustainable and inclusive mobility transitions.

6.4.1 Policy and planning implications

The evidence from this dissertation indicates that sustainable and inclusive mobility transitions require coordinated strategies that integrate environmental performance, behavioural insights, and institutional capacity. The policy implications are organised across four domains.

Designing low-carbon and system-efficient infrastructure

Infrastructure planning should explicitly integrate life-cycle environmental performance and behavioural feasibility. Key actions include:

- applying life-cycle criteria when assessing shared fleets to prevent upstream emissions from offsetting operational savings;
- strengthening small and medium-sized rail stations as multimodal hubs to reduce car dependency and improve regional accessibility;
- increasing hub density and optimising spatial placement to minimise walking distances and expand catchment areas;
- using data-driven logistics to reduce rebalancing, idle time, and other operational inefficiencies.

These measures ensure that system-level sustainability aligns with user experience and modal attractiveness.

Behaviourally informed and inclusive mobility design

The behavioural models reveal that shared mobility adoption is governed by strong heterogeneity and is sensitive to situational conditions. Effective mobility design should:

- tailor service configurations to key behavioural segments (e.g., Time-Conscious Travellers, Price-Sensitive users, Micromobility Enthusiasts);
- address non-use and resistance through hands-on trials, onboarding support, and familiarisation initiatives;
- prioritise physical and digital accessibility, especially for older adults, lower-income households, and digitally limited users;
- adapt operations to weather conditions, luggage needs, and trip purposes to accommodate real-world variability.

Inclusive design is therefore a prerequisite for enabling and sustaining modal shifts.

Pricing and accessibility policy

Cost was the most influential behavioural determinant across all empirical contexts. Policies should therefore:

- introduce integrated or MaaS-based pricing structures that encourage multimodal travel and simplify cost comparisons;
- implement affordability measures for price-sensitive users, including older adults and low-income households;
- combining parking reforms with low-cost shared mobility bundles to reduce private car entrenchment;
- support early adopters by ensuring reliable, accessible, and well-maintained shared services that foster cultural uptake.

Affordability is thus central not only to individual adoption but also to system-wide sustainability.

Governance and strategic integration for inclusive transitions

Effective governance is essential to translate behavioural and environmental evidence into practice. Recommended actions include:

- aligning national sustainability targets with local operational capacities through shared indicators and performance metrics;
- implementing privacy-secure data governance frameworks that enable monitoring of adoption, avoidance, and user diversity;
- establishing adaptive policy cycles wherein services are regularly refined based on real-time behavioural data;
- using pilots and living labs to test innovations before large-scale deployment.

These measures position governance as a core enabler of inclusive and effective mobility transitions.

6.4.2 Future research directions

Building on the identified limitations, several research avenues can be considered to deepen and extend understanding of sustainable and inclusive mobility transitions.

1. Longitudinal and Real-World Behavioural Dynamics

   Future studies should integrate SP and revealed-preference data in longitudinal or hybrid panel designs to examine how behaviour evolves with exposure to real-world mobility hubs, car-free measures, and automated services shapes behavioural stability, habit formation, and long-terms adaption.

2. Integrated Behavioural–Environmental Modelling

   There is a need for models that explicitly connect behavioural choice with operational data such as rebalancing, charging, and maintenance. Such models would produce more accurate estimates of system-level environmental outcomes and allow assessment of trade-offs between design choices and life-cycle impacts.

3. Mobility Hubs and Spatial Design as Systemic Enablers

   Further research should explore how macro- and micro-scale hub design—including layout, ergonomics, signage, and cognitive load—affects user comfort and adoption. Agent-based modelling, virtual reality simulations, and immersive experiments could reveal how design interacts with behavioural mechanisms.

4. Integrated Mobility-Hub Test Beds

   A natural next step would be to bring the separate behavioural findings of this thesis together in a single integrated test bed. Each empirical chapter examined acceptance and avoidance for particular modes and contexts in isolation; a logical extension would be to design — either as a real-world pilot or as a simulation — an experimental mobility hub in which automated, shared, electric, and conventional bike-like vehicles physically co-exist and are offered together. Such an environment would allow the acceptance and avoidance patterns identified here to be confirmed or revised under realistic, integrated conditions, and would be especially valuable for testing whether the reluctance observed among older adults persists when a fully formed, co-located mobility system is actually experienced rather than hypothetically stated. This would also help bridge stated preferences and revealed behaviour, addressing a limitation common to the survey-based methods used throughout this work.

5. Digital Inclusion and Human–Technology Interaction

   Given substantial heterogeneity among older adults and digitally limited users, participatory and inclusive design methodologies should inform the development of accessible digital interfaces, non-digital access pathways, and ergonomic vehicle features. Embedding these insights in behavioural models would support measurable standards for inclusive shared mobility.

6. Contextual Transferability and Spatial Diversity

   Comparative research across diverse urban settings is needed to evaluate which behavioural mechanisms generalise and which remain context bound. Studying regions with different densities, governance structures, and levels of car dependency would strengthen understanding of the spatial robustness of shared mobility adoption patterns.

Collectively, these research avenues outline a multidisciplinary trajectory for advancing shared mobility and mobility-hub planning. They underscore the need for empirically grounded, inclusively designed, and contextually adaptive mobility systems. By situating behavioural insights within broader environmental and governance frameworks, future work can further support the development of low-carbon, equitable, and resilient urban mobility transitions.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT O4 in order to improve language and readability, with caution, but not for the technical model estimation and discrete choice analysis. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publications.

Appendices

Appendix 2.1. Wrap up table for modal shift towards shared micro-mobility*.

Modal Shift	Description of mobility impacts	Impact on CO_2 reduction	Country	References
Modal shift to Shared Micro-Mobility (bike and scooter)				
Towards micro-mobility	- Replaces short-distance cars trips (0-3 miles) with observed reductions of 50% in the US, 60% in Germany, and 70% in the UK.	The amount of CO_2 reduction was not analysed for any entries.	General	Abduljabbar et al. (2021); Smith & Schwieterman, (2018); INRIX (2019)
Modal shift to shared conventional bike	- Shared bikes; Mobike (14%) and OV fiets (17%) increased train use. Conversely, Mobike (16%) and OV fiets (45%) users reported decreased bus and tram use.	The amount of CO_2 reduction was not analysed for any entries.	Delft, The Netherlands	Ma et al., 2020
Towards shared mobility	- Promote multimodal trips with greater flexibility at the first/last mile - As first/last mile modes, can replace cars trips - Enables bike and scooter sharing for different trip purposes in multimodal trips	The amount of CO_2 reduction was not analysed for any entries.	General	Liao & Correia (2022)
Modal shift to shared conventional bike	- Replace 47% of bus trips - Replace 17% of car trips - Replace 36% of walking trips - Shared bike can be used as main and last mile with PT, specifically London buses.	- Over five years, the BSS produced around 200 tonnes of CO_2—small, but not negligible. At the functional unit level: 9.6g CO_2/km, which is: 50× less than petrol car (259g CO_2/km), and between private bike (4.7g CO_2/km) and e-bike (31.2 g CO_2/km) - Assuming typical travel distances: 4,300 tonnes CO_2 saved over 5 years. it is equivalent to 100 Edinburgh–London plane trips with 200 passengers. - Assuming constant use and replacement: Over 12,000 tonnes CO_2 saved in 10 years. - Policy-wise, it cut Edinburgh's transport emissions by just 0.5%, a modest yet positive shift.	Edinburgh, UK	D'Almeida et al. (2021)
Modal shift to bike-sharing	- 46% of trips shifted from Public Transport (PT). - 27% of trips shifted from walking. - 18% of trips shifted from private bike use. - 9% of trips introduced new mobility options that wouldn't have occurred without shared bicycles.	The amount of CO_2 reduction was not analysed for any entries.	Würzburg, Germany	Pfertner (2017) Master thesis
Versatility of bike-sharing	- Serves as a complement to public transport and an alternative to private car use, displacing other modes of transportation.			
Reduce CKT	Bike sharing significant decreases private and total car kilometres travelled.			

From bike to bike-sharing	- Shared bikes have a lifetime mileage of 12,500 km, extendable to 20,000 km with improvements, with significant impacts from manufacturing.	- Manufacturing accounts for 79% of their Global Warming Potential (GWP), with impacts of 58-80g CO_2/km depending on servicing distance.	Paris, France	de Bortoli (2021)
Modal shift to smart bike-sharing **Smart station bike-sharing**	- High environmental impact due to extensive electronics. - Requires a 71% vehicle substitution rate. - Lower environmental impact due to its centralized electronic system. - Requires a 38% vehicle substitution rate.	- Emits 1,460 kg CO_2 per bike (148 Pts) and has a lifecycle emission rate of 0.13 kg CO_2 per kilometre. - Both systems show significant GHG emissions from rebalancing. Smart Bike: 0.036 kg CO_2 /km - Emits 479 kg CO_2 per bike (55 Pts) and has a lifecycle emission rate of 0.069 kg CO_2 per kilometre. - Lower environmental impact per private bike and per kilometre (89.63 kg CO_2) compared to both smart bike and smart station systems.	General	Bonilla-Alicea et al. (2020)
Shared bikes (HTM-Fiets)	- Substitutes 46% of urban transit (bus/tram) trips, alleviates crowding, and improves accessibility when well-integrated.	The amount of CO_2 reduction was not analysed for any entries.	The Hague, The Netherlands	van Marsbergen et al. (2022)
First/Last Mile shared bike	- Shared micromobility (bikes and e-mopeds) complements public transport, reduces travel time, and improves accessibility.	The amount of CO_2 reduction was not analysed for any entries.	Rotterdam, The Netherlands	Montes et al. (2023)
Shared bikes	- Travelers prefer private over shared vehicles, but shared vehicles gain preference in flexible, on-demand scenarios.	The amount of CO_2 reduction was not analysed for any entries.	Almere, The Netherlands	Stam et al. (2021)

* CO_2 reduction percentages in the table refer to every person attending the shared mobility system.

Appendix 2.2. Wrap up table for modal shift towards shared car*.

Modal Shift	Description of mobility impacts	Impact on CO_2 reduction	Country	References
Modal shift to shared car				
Private car to shared car use	- Elderly and low-educated individuals are reluctant to use carsharing services. - Travel distance may increase if car sharing is more convenient than public transport. - The probability of choosing not to own a vehicle is estimated to be 16%.	Car sharing; - reduces CO_2 because of shift from private to shared car - reduces CO_2 by using fuel-efficient vehicles and fewer vehicles. - increases CO_2 if it replaces public transit. - Road transport sector emissions: 85,440,000 t CO_2 per year - Car sharing on the basis of conventional cars changes daily CO2 emissions as follows: - from private to shared car: -5929 t CO_2 from bus to shared car: +7069 t CO_2 - from subway to shared car: +4764 t CO_2 - from private car disposal to carsharing disposal: -3094 t CO_2 - In total: +2810. - On an annual basis this change is 1,1025,589 t, representing 1.2% of total road CO_2 in 2014.	Urban areas - South Korea	Jung & Koo (2018)
Private car to shared car use and hence decrease in total car use	- Carsharing users annually drive 7,000km instead of 9,100km (- 18%; percentage derived by authors). - 1,500 km of the 7,500km are driven with the shared car. - 39% of the shared car kilometres were before travelled by private car (driver and passenger).	- Shift from private car to shared car caused -250kg CO_2/year (-12%; percentage derived by authors).	Netherlands	Nijland et al. (2015)
PT to shared car use	- 39% of the shared car kilometres were before travelled by PT (train: 35% and bus, tram & rapid transit: 4%).	- Shift from active travel and public transport to shared car caused +160kg CO_2/year (+8%; percentage derived by authors).		
Cycling to shared car use	- 6% of the shared car kilometres were before travelled by cycling and "others" (2 % bicycle users & 4% others) shifts to carsharing system.			
Untravelled to shared car	- 16% of the shared car kilometres would not been taken without this service. This is included in the change of car-kms mentioned above.			
Decrease of private car ownership	- Shifting from private to shared cars decreased car ownership from 0.85 to 0.72 cars per household in 2014. - 37% of car owners and 8% of non-car owners would have bought a new car if not for car sharing.	- Changes in car ownership from private to shared car caused -85 to -175 kg CO_2/year (= -4% to -8%; percentages derived by authors). - Total: Net change of CO_2 is -175 to -265kg (-8% to -13%; percentages provided by Nijland et al.).		
Private car to shared car	- 1 shared car replaces or prevents to purchase 16 private cars. - carsharing results in a reduction of approximately 5,000 vehicles, including 2,300 privately owned cars and 2,700 unpurchased vehicles on Bremen's streets. - No longer car owners among carsharing members, now make 3/4 of their trips by using shared mode which	The amount of CO_2 reduction was not analysed for any entries.	Bremen, Germany	Schreier et al. (2018)

Reduce VKT	previously made by private cars, leading to a reduction in parking demand. - More than 50% less travelled kilometres than as a household in Bremen using a private car only			
Private car to shared car. Reduce CKT **Decrease ownership of private car**	- 60% of shared car users drove, on average 5,000 kilometres less, resulting in 3.6 million less car-kilometres. - 46% of all carsharing trips at mobility stations replaced a public transport trip, 23% a private car trip as driver. 29% of car sharing trips represent new mobility (trip would not have taken place if there was no shared car). 83% of users stated mobility stations make private car unnecessary. - 15% of the car sharers abolished a car in the last year before the survey, while 4% added one to the household. Of the 15% a small half stated that car sharing was of (large) influence for that decision, while also a small half stated that car sharing prevented them from buying an additional car.	- Shift to shared cars changes CO_2 by about -650 tons/year CO_2; - -629 tons/year CO_2 (-97%; percentage derived by authors) because of the reduction of (fossil) car-kms, about -10 ton/year CO_2 (-1,5%, percentage derived by authors) due to the fact that shared cars are smaller and more efficient, and about 31 tons/year CO_2 (+5%, percentage derived by authors) because of modal shift from public transport and other low-emission modes to the shared car. - The total reduction represents about 1% (percentage provided by Pfertner) of total local transportation emissions. - Interpretation of reviewer: 1% less CO_2 is a small reduction, indicating that the shared cars still represents a niche market. - The CO_2 lifecycle emissions (production and recycling of cars) were not included.	Würzburg-Germany	Pfertner (2017) Master thesis
Private car to shared car **Reduction in private car ownership** **Car shedding Rate DriveNow** **Reduced planned car purchases (DriveNow)** **Flinkster** **Reduced planned car purchases (Flinkster)**	- Combining station-based and free-floating carsharing systems has the most significant impact on reducing car ownership. Mobility changes were not analysed. - Frequent use of carsharing and membership in station-based providers significantly reduce the importance of private cars. - DriveNow users have shed existing cars at a rate of 6.5%. - 7.1% of DriveNow users reported that planned car purchases did not take place. - Flinkster users have shed existing cars at a rate of 15.3%. - 8.3% of Flinkster users reported that planned car purchases did not take place.	The amount of CO_2 reduction was not analysed for any entries.	Berlin & München, Germany	Giesel & Nobis (2016)
Private car to shared car (Car2go) **PT to shared car**	- Car2go; suppresses car ownership (5-9 private cars per car2go) more than it causes people to sell their cars (2-3 private cars per car2go) in Calgary, Seattle, Vancouver, and Washington. - A shared conventional car (CV) replaces 7-11 private cars and 10-16% CMT per household - Car2go increased 34.75% average of driving distance and decreased it by 12.75%. - Car2go increased 5% average frequency of bus usage and decreased it by 32%	- GHG reduction directly correlates with CMT reduction in Car2go. - Each Car2go vehicle results in a 6% GHG reduction per household, linked to lower car miles travelled (CMT). - Each Car2go vehicle displaces between -4 to -14 ton GHG per Car2go vehicle per year in all citie (12% in San Diego). - With 80% mileage suppression, GHG emissions per household decrease by carg2go household are expected to decrease by 4%-18%, averaging 12% .	Calgary & Vancouver, Canada and Seattle, Washington, D.C., & San Diego, USA	Martin & Shaheen (2016)

	- Car2go increased 5% average frequency of bus usage for first/last-mile; a 32% decrease in bus usage when replacing public transport as main mode.			
Cycling to shared car	- Car2go increased 4% average frequency of cycling and decreased it by 5%.			
Walking to shared car	- Car2go increased 18% average of walking frequency and decreased it by 11%.			
Decrease car ownership of private car	- In five cities, 2%-5% (average 3%) of car sharing users sell their privately owned cars. 7% to 10% (average 8,75%) of the car sharing users forgoes a vehicle purchase.	- The CO_2 lifecycle emissions (production and recycling of cars) were not included.		
Reduce CMT	- CMT reduction is predicted range from 6% to 16% of car2go household CMT. 12% in average			
Private car to shared car	- Carsharing saves costs, reduces travelled distance, increases sustainable transport modes - Average distance travelled by shared cars is lower than car owners pre-sharing system - For non-car users number of car trips increased slightly due to vehicle access - Because of limited use, the carsharing (electric and conventional) has a minimal impact on CO_2 of all travellers. This can change if more (car-dependent) people switch to carsharing system. - Joining carsharing saves travel costs, including the cost of owning a car, an average of €2935 per year for previous active mode users and PT travellers. - The figure of €2,785 represents the average annual travel cost savings specifically for former car users who were previously car owners and decided to sell their cars to join a car sharing service.	- Car owners who frequently use active and PT reduce CO_2 (86 kt) by joining carsharing, less driving, and selling their cars. This reduction could potentially increase to 895 kt with the implementation of supportive policies and financial incentives. - Non-car owners who previously used active and PT modes and switched to carsharing imposed additional travel costs, an average of €179 per year (calculated by reviewer) and slightly increased CO_2 (no explanation of % mentioned) - Car dependency and individual CO_2 increased slightly for no-car households after joining a carsharing system, but significantly less than when purchasing a car. - Equipping carsharing platform with electric cars will significantly decrease CO_2. - Carsharing users have a lower car dependency and have lower CO_2 compared to non-users of carsharing. - Because of limited use, the carsharing (electric and conventional) has a minimal impact on CO_2 of all travellers. This can change if more (car-dependent) people switch to carsharing system.	Dublin, Ireland	Rabbitt & Ghosh (2013)
Reduce CKT	- Car owners who joined to car sharing system travelled 9% less kilometres than before joining.			
Decrease car ownership of private car	- 13.5% (2295 cars) of 17,000 car2go members will dispense cars, leading to a net reduction of 1995 cars by 2014 - Car2go is expected to reduce users' annual CKT by promoting sustainable mobility.	- Due to a reduction in car ownership, carsharing users reduced their carbon footprint from 2786 kg per year to 2474 kg per year by an average of -146 to -312 kg (5%-11%) CO_2 per year	Ulm, Germany	Firnkorn & Müller (2011)
Car to Station-Based Car Sharing	- Replaces private car ownership (up to 11 private cars per shared vehicle); complements public transport and reduces car dependency.	- Average net CO_2 reduction of 30% per user due to reduced car ownership and usage.	The Netherlands	van der Linden et al. (2025)
Reduce CKT	- Encourages shared car use as a complement to insufficient public transport services.	- Indirect impact by reducing car ownership and enabling reduced car kilometre travelled (CKT).		

* CO_2 reduction percentages in the table refer to every person attending the shared mobility system.

Appendix 2.3. Wrap up table for modal shift towards electric (shared) bike*.

Modal Shift	Description of mobility impacts	Impact on CO_2 reduction	Country	References
Modal shift to electric (shared) bike				
Private car to private e-bike	- 15% e-bike PMT mode share (in base year this is 0%) leads to 9.9% fewer car trips and 12% (3.4 million; percentages calculated by reviewer) fewer total car MPT per day. - Replacement of modes: authors adopt results from other studies using this as input of own study. - 72% of e-bike miles come from the car. - 12% of e-bike miles come from the bicycle. - 13% of e-bike miles come from public transport - 2% of e-bike miles come from walking	- Cars at the 15% e-bike mode share case contribute to 98.9% of emissions from the sum of CO_2 emitted by mobility - CO_2 at the 15% e-bike share case decline by 12%, averagely by 225 kg CO_2/ person/ year Sum of emissions from all vehicle types, cars, and e-bike charging is 991 metric tons per day relate to the 15% share of e-bike share (in PMT).	Portland, USA	McQueen et al. (2020)
Private car to private e-bike **PT to private e-bike** **Private conventional bike to private e-bike**	- 80% of car trips in urban areas in Sweden have a distance of 3-4 km, which is suitable for e-bike replacement. - For 42%-60% of the e-bike users cars were the main mode used before (range = dependent on the travel purpose). - The average kilometrage per week and person previously travelled by car and now by e-bike is ca. 55 km/person (urban) and 62 km/person (rural). - For 11%-24% of the e-bike users public transport was the main mode used before. - For 19%-37% of the e-bike users conventional bikes were the main mode used before.	- Average CO_2 reduction per person per week (car to e-bike) is 7.7 kg CO_2 (urban) and 8.6 kg CO_2 (rural), or in general 8.2 kg CO_2/week due to modal changes, frequency, and distance travelled in urban and rural areas - Equals 272 kg CO_2/person/year (33.2 typical e-bike use weeks) or 394 kg CO_2 /person/year (48 travel weeks); 14%-20% respectively	Sweden, Urban areas and rural areas	Hiselius & Svensson (2017)
Car to e-bike **Walking to e-bike** **Public transport to e-bike** **Conventional bicycle to e-bike**	- Significant reduction in car use, with up to 20% reduction in car mileage observed in trials. - Partial shift from walking to e-bikes for longer trips or in hilly areas. - Moderate shift from public transport to e-bikes, depending on distance and convenience. - Increased trip length for some users compared to conventional bikes.	The amount of CO_2 reduction was not analysed for any entries.	Brighton, UK	Cairns et al. (2017)
Private car to e-bike **Conventional bike to e-bike**	- Substantial reduction in car commuting due to the incentive program, particularly for distances under 15 km. - Shift from conventional cycling to e-bikes for some users, increasing the range and speed of cycling.	The amount of CO_2 reduction was not analysed for any entries.	The Netherlands	Kruijf et al. (2018)
Private car to shared e-bike **Conventional bicycle to e-bike** **Public transport to e-bike** **Walking to e-bike**	- Encouraging people to use e-bikesharing can have a significant impact on private car trips, even more so than traditional bike - Reduction in car trips, particularly for short distances.	The amount of CO_2 reduction was not analysed for any entries.	General	Bourne et al. (2020)

Motorized transport to e-bike		- E-bikes reduce CO_2 emissions by at least 25% per p/km compared to cars and public transport, except for bicycles and walking.	Germany	Kämper et al. (2016)
Petrol Car to e-bike		- Shifting from a patrol car to an e-bike cuts CO_2 emissions by up to 90%, saving about 150 g CO_2 per p/km.		
Conventional Bicycle to e-bike		- E-bikes add 7.4 g of CO_2 per p/km compared to conventional bicycles due to manufacturing and electricity use. - E-bikes can save up to 2,400 kg CO_2 per week, but also add 50 kg CO_2 from less efficient mode shifts.		
Less CTM		- Replacing car trips with e-bikes can save more CO_2 than it generates, potentially replacing 80 million pkm of car trips.		
Private car to shared e-bike	- Regarding potential share e-bike users, 17% originate from the car (including carpooling and taxi). For conventional bike this was only 8%. - e-bikes contribute to heightened congestion at intersections, safety concerns, and potential environmental impacts.	The amount of CO_2 reduction was not analysed for any entries.	Beijing, China	Campbell et al. (2016)
PT to shared e-bike	- 30% of shared e-bike users are from bus and subway users while, 20% of them are from shared bike.			
Conventional bike to shared e-bike	- 11% of shared e-bike users were bike users while 17% of them were shared bike users. - 6%of bikesharing users were private e-bike users while 15% of them were bikesharing users.			
Walking to shared e-bike	- 27% of shared e-bike users were pedestrians - 49% of of shared bike users were pedestrians - 28% of shared bike users were users of sheltered modes (including bus, subway, drive alone, and taxi) while 47% of e-bike sharing users used sheltered modes. - 72% of bike sharing users were users of unsheltered modes, while 53% of e-bike sharing users used were users of unsheltered modes.			
Distance	- The average distance of bikesharing is 2.9 km while it is 4.5 km for e-bikesharing. - 80% of trips are shorter than 10km, where the average commuter bus trips is 9.6 km - shared e-bike can be used for longer trip distances compared to shared bike			
PT to e-bike (base scenario)	- In the base scenario, where e-bikes are introduced, there was a greater reduction in public transport usage, boosting other active modes like biking	- Reduces CO_2 by lowering car usage.	The Netherlands, Denmark,	Astegiano et al. (2019)

Private car to e-bike	- Policy vs. Baseline Scenarios; The scenario with toll policies for cars entering the city center led to the highest decrease in car use. - Influence of Cycling Culture: Advanced cycling infrastructure in Northern Europe (e.g. The Netherlands) leads to a higher e-bike modal share. In the Netherlands, the base scenario shift is less significant.	- Greater CO_2 reduction in policy scenario due to lower car use. - Significant CO_2 reduction in cycling-friendly countries.	Germany, Norway, Sweden, & Finland	
Private/shared car, truck, motorcycle, or moped to shared e-bike	- 20-23% of shared e-bike trips originate from private/shared car, truck, motorcycle, or moped	- -80 to -90g CO_2/pkm 1	Berlin, Düsseldorf, Paris, Stockholm, Melbourne, & Seattle	Krauss et al. (2022)
Walking to shared e-bike	- 49% (Seattle) and otherwise 25-30% of shared e-bike trips originate from walking	- +60 to +72g CO_2/pkm		
Public Transport to shared e-bike	- 13% (Seattle) and otherwise 30-39% of shared e-bike trips originate from public transport	- Bus/shuttle: -12 to -18g CO_2/pkm - Metro/urban rail: +21 to +57g CO_2/pkm		
Taxi/ride-hailing to shared e-bike	- 6% (Berlin) and otherwise 11-14% of shared e-bike trips originate from taxi use or ride-hailing	- -157 to -164g CO_2/pkm		
Shared/private bicycles, e-bikes, pedelecs, or e-scooters to shared e-bike	- 9-19% of trips substituted	- Private e-bicycle: +47 to +48g CO_2/pkm - Private bicycle: +53 to 64g CO_2/pkm - Shared e-scooter: -30 to -34g CO_2/pkm		
Walking to shared e-bike	- 24% of shared e-bike trips replace walking trips and 9% of walking distance	- Gross emissions are 83g CO_2/pkm, which is highe than the average emissions of replaced modes (58 CO_2/pkm), resulting in a net increase of 25g CO_2/pkm.	Zurich, Switzerland	Reck et al. (2022)
PT to shared e-bike	- 27% of shared e-bike trips replace public transport trips and 43% of public transport distance.			
Private car to shared e-bike	- 11% of shared e-bike trips replace car trips and 15% of car distance.			
Private bike to shared e-bike	- 33% of shared e-bike trips replace bike trips and 29% of bike distance.			
Private e- bike to shared e-bike	- 3% of shared e-bike trips replace e-bike trips and 5% of e-bike distance.			
Walking to e-bike	- 26% of shared e-bike trips replace walking trips and 9% of walking distance	- Gross emissions are 34g CO_2/pkm, which is less than the average emissions of replaced modes (88g CO_2/pkm) resulting in a net decrease of -54g CO_2/pkm		
PT to e-bike	- 20% of shared e-bike trips replace public transport trips and 29% of public transport distance.			
Private car to e-bike	- 37% of shared e-bike trips replace car trips and 48% of car distance.			
Private bike to e-bike	- Replace 17% of bike trips and 14% of bike distance.			

CO_2 reduction percentages in the table refer to every person attending the shared mobility system.

Appendix 2.4. Wrap up table for modal shift towards electric shared scooter*.

Modal Shift	Description of mobility impacts	Impact on CO_2 reduction	Country	References
Modal shift to electric shared scooter				
- Private car to shared e-scooter	- 34% of station-less shared scooters would have otherwise used the private car or shared rides	- Shared e-scooters and bicycles have high CO_2 emissions due t lifecycle and collection/relocation process. - Only when all shared e-scooters can last at least two years (lifecycle) can the system achieve a universal net reduction of CO_2 in all - Station-less shared e-scooters produce 202g life cycle CO_2per passenger-mile; of this, 50% is driven by materials and manufacturing, 43% by daily colletion for charging, and 7% by usage. In comparison, shared station-ess bicycles produce 190g CO_2 per passenger-mile. - They produce higher life cycle GHG emissions compared to buses with high ridership (82g) private e-bikes (40g) and private bicycle (8g) because of the rebalancing trips conducted by cars and other lifecycle emissions. - Ways to reduce CO_2 impacts of shared e-scooters: - 50% reduction; collect with fuel-efficient vehicles (177g CO_2-eq/passenger-mile) - 40% reduction; collect only scooters with battery deplation below 50% to charge (164g CO_2-eq/passenger-mile) - 35% reduction; drive shorter distance per scooter to collect or distribution (147g CO_2 -eq/passenger-mile). - 4% reduction; increase scooter lifetime, assuming at least 2 years lifetime (141g CO_2 -eq/passenger-mile).	Raleigh, US	Hollingsworth et al. (2019)
PT to shared e-scooter	11% of station-less shared scooters would have otherwise used the bus			
Cycling to shared e-scooter	- 8% of station-less shared scooters would have otherwise used the bicycle			
Walking to shared e-scooter	- 41% of station-less shared scooters would have otherwise walked			
Passenger miles travelled	- Each passenger-mile of an e-scooter displaces 0.34 (private car), 0.11(bus), and 0.08 (bicycle) miles of trips.	- Increased collection (repositioning) distance of 2.5 miles per scooter leads to 27% increase in life cycle CO_2 emissions - Reduced collection (repositioning) distance of 0.6 miles per scooter leads to 27% decrease in life cycle CO_2 emissions.		
Private car to shared e-scooter	Shared e-scooter: - suitable for short distance trips (0.5-2 miles) and not for long distance trips (over3 mile) except to access bus or train stops. - allows access to 16% more jobs in loop business district within 30 minutes compared to PT and walking.	The amount of CO_2 reduction was not analysed for any entries.	Chicago, USA	Smith & Schwieterman (2018)

	- increases non-auto trips in parking-constrained areas from 47% to 75% - offer greater accessibility to locations that may not be easily accessible by walking or public transport.			
Private car to shared e-scooter			Berlin, Dusseldorf, Paris, Stockholm, Melbourne and Seattle	Krauss et al. (2022)
Walking to shared e-scooter	- 40-64% of e-scooter respondents	- +94 to +101 g CO_2/pkm		
Public transport to shared e-scooter	- 22-39% of e-scooter respondents	- Bus/shuttle: +16 to +18 g CO_2/pkm - Metro/urban rail: +51 to +92 g CO_2/pkm		
Taxis or ride-hailing to shared e-scooter	- 4-12% of e-scooter respondents substitute for taxis or ride-hailing	- -128 to -129 g CO_2/pkm		
From cars, trucks, motorcycles, or mopeds to shared e-scooter	- 3-9% of shared e-scooter respondents	- ICE fossil fuel: -48 to -55 g CO_2/pkm - Battery electric: -5 to +53 g CO_2/pkm		
From private or shared bicycles or e-bicycles or private e-scooters to shared e-scooters	- 3-8% of shared e-scooter	- Private bicycle: +87 to +94 g CO_2/pkm - Private e-bicycle: +78 to +82 g CO_2/pkm - Shared bicycle: +48 to +54 g CO_2/pkm - Shared e-bicycle: +30 to +34 g CO_2/pkm		
E-scooter to shared e-scooter	- No modal shift analysed. Focus on emissions per person-km. - private e-scooters have lower environmental impacts due to longer lifespans (4,000-10,000 km) and lighter weight. - Shared e-scooter, with a 7,300 km lifespan and 22 kg weight, show high environmental impacts primarily from manufacturing.	- Manufacturing accounts for 78-83% of GWP, with aluminum alloy as a major factor; use and infrastructure have a smaller share - Manufacturing contributes 79% to GWP; overall impact includes 58-80 g CO_2/km, with minimal electricity consumption (2%).	Paris, France	de Bortoli (2021)
E-moped to shared e-moped	- No modal shift analysed. Focus on emissions per person-km. - Shared e-mopeds last 48,000 km and weigh 126 kg, with major environmental impacts from manufacturing and batteries.	- Use stage contributes 80% of GWP, manufacturing 16%, and pavement just 4% to GHG emissions. - Manufacturing accounts for 68% of GWP, with batteries contributing 36% and moped production 55%. Energy consumption during use is 39%.		
Walking to shared e-scooter	- Replace 51% of walking trips and 25% of walking distance/ km	- Gross emissions are 106 g CO_2/pkm, which is higher than the average emissions of replaced modes (55 g CO_2/pkm), resulting in a net increase of 51 g CO_2/pkm.	Zurich, Switzerland	Reck et al. (2022)
PT to shared e-scooter	- Replace 19% of public transport trips and 38% of public transport distance/ km			
Private car to shared e-scooter	- Replace 12% of car trips and 15% of car distance/ km			
Private bike to shared e-scooter	- Replace 13% of bike trips and 13% of bike distance/ km			
Private e- bike to shared e-scooter	- Replace 1% of e-bike trips and 2% of e-bike distance/ km			
Shared e- bike to shared e-scooter	- Replace 4% of shared e-bike trips and 5% of shared e-bikes distance/ km			

Walking to e-scooter	- Replace 35% of walking trips and 19% of walking distance/ km	- Gross emissions are 42 g CO_2/pkm, which is less than the average emissions of replaced modes (58 g CO_2/pkm), resulting in a net decrease of -16 g CO_2/pkm.		
PT to e-scooter	- Replace 23% of public transport trips and 27% of public transport distance/ km			
Private car to e-scooter	- Replace 17% of car trips and 25% of car distance/ km			
Private bike to e-scooter	- Replace 24% of bike trips and 27% of bike distance/ km			
Private e-bike to e-scooter	- Replace 2% of e-bike trips and 1% of e-bike distance/ km			
Walking to shared e-scooter	- 42% of trips replace walking	- Gross emission are 106 g CO_2/pkm, which is higher than the average emissions of replaced modes (55 g CO_2/pkm), resulting in a net increase of 51 g CO_2/pkm. - Emissions could vary by ±40% based on travel distance. - Emissions could vary by ±40% based on travel distance	Germany	Weschke et al., (2022)
Cycling to shared e-scooter	- 11.5% of trips replace bike			
PT to shared e-scooter	- 20% of trips replace PT			
Increase multimodal trips	- 23% of trips connect to public transport, as first or last mile feeders. only 26% of these trips might have been made entirely using public transport, net substitution is 6.5%			
Private car to shared e-scooter	- 11.5% of trips replace car			
Other shared modes to shared e-scooter	- 2.9% of trips replace bike sharing trips, and less than 1% replace car sharing trips.			
Taxi and ridesourcing	- 3% of trips replace taxi and ridesourcing			
Increase trips	- 7% of trips are induced demand			

* CO_2 reduction percentages in the table refer to every person attending the shared mobility system.

Appendix 2.5. Wrap up table for modal shift towards shared electric car *.

Modal Shift	Description of mobility impacts	Impact on CO_2 reduction	Country	References
Modal shift to shared electric car				
Private car to shared electric car	- Electric vehicles use for delivery and one-way trips increase car sharing adoption	- More e-car charging stations lead to increased usage and emission reduction - Replacing 50% of gasoline stations with EV charging stations and corresponding replacement of vehicles reduces CO_2 by 64% per year, given the Dutch energy mix for electricity production - Increasing recharging station for EV and reaching 71.1% of gasoline/diesel stations results in zero emissions associated with modal shift to car sharing. - CO_2 arise not only from car use but also from the transport modes that carsharing replaces, such as public transit, walking, or cycling. - Shifting from car and public transit to car sharing may not compensate for forgoing car purchases - If 50% of the shared cars are electric ones, the increase of daily CO_2 is less: +1013 t. - If 100% of shared cars are electric ones, daily CO_2 decline by 1579 t.	Urban areas South Korea	Jung & Koo (2018)
Private car to shared e-car	- Car2go; - suppresses car ownership more than it causes people to sell their cars - increases driving distance by 11% for some users but decreased it by 27% for others. - Shared electric vehicles replace fewer cars (7 cars per shared car) and decrease fewer CMT (7% per household). - Shuttles are needed to collect and deposit EVs for recharging, which limits the potential benefits.	- GHG reduction aligns with CMT reduction in car2go. - Each Car2go vehicle (electric) results in a -6% reduction in GHG emissions per Car2go household. - Each Car2go vehicle displaces between -6 to -13 metric ton GHG per Car2go (electric) Vehicle per year in San Diego.	San Diego-USA	Martin & Shaheen (2016)
PT to shared e-car	Car2go increased frequency of bus usage by 8% and decreased it by 26%.			
Cycling to shared e-car	Car2go increased frequency of cycling by 7% and decreased it by 6%.			
Walking to shared e-car	Car2go increased walking frequency by 34% and decreased it by 9%.			
Decrease car ownership	- 1 shared electric car2go vehicle can replace 1 owned car and decrease car ownership. - 1 shared electric car2go vehicle (2%) can stop future purchase of 6 cars, (10%).			
Reduce CMT	- Car2go caused an 11% increase and a 27% decrease in driving distance. - Car2go reduces CMT per car2go household per year by -7%.			

Shared cars to hybrid or shared electric car	- Lower number of vehicles per capita among members. - Reduced vehicle ownership in a 1 to 6 ratio. - Decreased demand for parking space. - Lower fixed costs. - Acts as a complement to public transport.	- The shift led to a 35% and 47% cut in energy usage, translating to around 35% and 65% less CO_2.	Lisbon, Portugal	Baptista et al. (2014)
Private car to shared e-car **PT to shared e-car** **Reduce CMT**	- E-bike sharing may be a more appropriate alternative for such short trips. Decreases public transport use - Increases walking and supports active, sustainable travel modes. - Reduces overall driving distances The average trip distance for electric carsharing is short (2.7–3 km).	- Electric carsharing produces lower emissions per passenger-kilometer than conventional carsharing partly due to the limited range of battery electric vehicles. The amount of CO_2 reduction was not analysed for any entries.	General	Liao & Correia (2022)

* CO_2 reduction percentages in the table refer to every person attending the shared mobility system.

Appendix 5.1. A full list of the 45 cities, along with their corresponding provinces, population, land area, and postal codes.

Province	No.	Cities	Population (January 2024)	Land (km2)	Postcode
South Holland	1.	Leiden	130.181	21.91	2311-2312
	2.	Zoetermeer	128,424	34.45	2711
	3.	Dordrecht	122.089	79.01	3311
	4.	Alphen aan den Rijn	114,968	126.23	2405
	5.	Delft	109,573	22.65	2611
	6.	Schiedam	81,855	17.82	3111
	7.	Vlaardingen	76,472	23.57	3131
	8.	Gouda	75,763	16.50	2801
	9.	Spijkenisse	72,500 (year 2021)	30.27	3201
	10.	Capelle aan den Ijssel	67,948	14.14	2901
	11.	Katwijk	66,960	24.75	2221
	12.	Rijswijk	59,640	13.96	2282
	13.	Hellevoetsluis	40,312 (year 2022)	41.10	3221
	14.	Barendrecht (town)	48,689	19.75	2991
	15.	Ridderkerk (town)	47,713	23.72	2981
	16.	Noordwijk (town)	45,732	58.37	2201
	17.	Gorinchem	38,682	18.83	4201
	18.	Voorburg	42.255 (year 2021)	6.24	2271
North Holland	19.	Hilversum	94,426	45.61	1211
	20.	Alkmaar	91.035 (year 2021)	110.46	1811
	21.	Purmerend	95.177	93.73	1441
	22.	Zaandam	78,7045	23	1501
	23.	Hoofddorp (town)	77,885 (year 2021)	37.85	2131
	24.	Beverwijk	42,893	18.40	1941
	25.	Hoorn	75.621	20.38	1621
North Brabant	26.	Helmond	95,884	53.18	5701
	27.	Roosendaal	67,060 (year 2021)	106.50	4701
	28.	Bergen op Zoom	53,245 (year 2021)	53.23	4611
	29.	s-Hertogenbosch (Den Bosch)	111.025	36.38	5211
	30.	Oss	58.550 (the year 2021)	-	5341
	31.	Uden	36.805	-	5401
	32.	Waalwijk	33.880 (year 2021)	19.88	5141
Utrecht	33.	Veenendaal	69.437	19.46	3901
	34.	Nieuwegein	65.974	23.51	3431
	35.	Woerden	53.730	88.57	3441
Overijssel	36.	Zwolle	133.133	111.10	8011
	37.	Hengelo	83.051	60.84	7551
	38.	Deventer	81.545 (year 2021)	-	7411
	39.	Almelo	74.355	67.27	7601
	40.	Kampen	37.595 (year 2021)	-	8261
Gelderland	41.	Ede	76.750 (year 2021)	318.18	6711
	42.	Tiel	42.372	32.88	4001
Limburg	43.	Sittard-Geleen	92.624	79.01	6131
	44.	Heerlen	87.498	44.94	6411
	45.	Weert	44.875 (year 2021)	-	6001

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Summary

Urban mobility systems, particularly within the highly developed and intensely urbanised context, face increasing pressure from rising travel demand, limited urban space, and the need to reduce carbon emissions associated with private car use. Despite substantial national investment and ambitious objectives to establish a sustainable and reliable transport system by 2040 in The Netherlands, conventional policy efforts to encourage commuters to shift from private cars to public transport have achieved limited success. The continued preference for the private car is explained by its perceived advantages in convenience, immediate accessibility, and overall service quality, allowing it to retain a substantial competitive position and comfort relative to public transport.

The integration of emerging transport options, such as shared, electric vehicles, and automated mobility, through mobility hubs offers an alternative approach to urban mobility challenges. By combining multiple services at a single access point, mobility hubs can improve door-to-door travel and increase the competitiveness of shared mobility relative to the private car in terms of cost, flexibility, and reliability. However, the effectiveness of such systems depends not only on technological availability but also on user acceptance and adoption. Therefore, empirical analyses of travellers' preferences and decision-making are required to assess the potential impacts of shared mobility integration and to inform policy development across strategic, tactical, and operational levels.

The central aim of this thesis is to analysis the behavioural impacts of introducing and integrating shared transport options and the mobility hubs that support them. The research examines shared mobility behaviour across three empirical contexts: access and egress trips at multimodal hubs, mobility choices in car-free inner-city areas, and travel behaviour among older adults aged 50 and above. Specifically, the thesis investigates how shared (micro-) mobility solutions, when integrated through mobility hubs, may influence individual modal choice and the potential to reduce reliance on private car use, thereby contributing to low-carbon, accessible, and socially inclusive urban transport systems. This objective is addressed through the central research question: How does shared mobility influence individual travel behaviour and modal choice across different urban contexts?

Empirically, the research draws on Stated Choice (SC) experiments and survey data analysed using discrete choice models, including Nested Logit, Mixed Logit, and Latent Class Models. This methodological approach enables the examination of user preferences, behavioural heterogeneity, and adoption and avoidance patterns across contexts.

The thesis begins with an assessment of the systemic and environmental implications of shared mobility before progressively focusing on specific user groups, trip purposes, policy environments, and demographic characteristics. This structure supports a transition from system-level sustainability considerations to individual-level behavioural responses and distributional effects.

Chapter 2 establishes the environmental and system-level foundation for the subsequent behavioural analyses by examining the contribution of shared mobility and mobility hubs to CO_2 emission reduction from a life-cycle perspective. The methodology involved a systematic synthesis and critical review of existing literature, explicitly linking the component parts—shared, electric, and micro-mobility—with the concept of mobility hubs, specifically applying Life Cycle Assessment (LCA) principles to the integration concept.

The synthesis shows that while shared mobility can reduce direct operational emissions, these benefits may be partly offset by emissions associated with vehicle production and by behavioural substitution effects, such as travellers shifting from active modes (walking or cycling) to shared motorised options. The results indicate that mobility hubs play a critical role in minimising life-cycle emissions by improving vehicle utilisation, maintenance, and energy management. The chapter concludes that sustainable transport planning requires coordination between life-cycle assessment and behavioural modelling, as technological change alone is insufficient without integrated system design.

Chapter 3 focuses on individual travel behaviour at multimodal hubs, addressing the first- and last-mile problem for rail trips. The aim of this study was to identify the specific trade-offs and factors influencing passenger preferences and acceptance of shared access/egress modes (including shared bicycles, e-steps, e-scooters, and Automated Vehicles (AVs)) when offered as convenient alternatives at multimodal railway stations functioning as potential mobility hubs. The methodology employed a SC experiment focused on a functional railway station (e.g., Delft Campus), which allowed for the analysis of interdependent decisions between the main trip (rail) and the access/egress leg.

The results show that in high-cycling contexts such as the Netherlands, shared bicycles must reach a sufficient scale within mobility hubs to effectively support sustainable access and egress. Automated vehicles exhibit higher potential for first- and last-mile connections than motorised micromobility, although this potential is concentrated among higher-income and highly educated users. Across all access and egress options, direct travel cost emerges as the dominant determinant of adoption, highlighting strong economic sensitivity.

Chapter 4 examines mode choice and avoidance behaviour in car-free inner-city environments. Methodologically, this chapter used the explicit modelling and inclusion of a “optout” meaning not to choose any of the given alternatives in the SC design. The analysis demonstrates that restrictive policies, such as car-free zones, reduced parking availability, and access restrictions for private vehicles, can lead to measurable demand suppression when shared mobility options are perceived as inadequate.

This chapter addressed the social consequences of policy changes. The results indicate that older residents face greater barriers to adaptation, reflecting digital and physical constraints. The relative importance of non-cost attributes varies by context, but travel cost remains a key factor across all user segments.

Chapter 5 investigates shared mobility adoption among older adults. The aim of this chapter was to investigate the behavioural, attitudinal, and socio-economic factors affecting the adoption and acceptance of shared mobility among adults aged 50 and above in small and mid-sized cities. The methodology employed a Latent Class Model to identify distinct, behaviourally consistent segments within this older adult population.

The findings reveal substantial behavioural heterogeneity, with distinct segments differentiated by digital literacy, physical capability, and openness to new technologies. Prior experience with shared mobility is a strong predictor of future adoption, while a car-dependent senior segment shows persistent resistance. These results indicate that digital and physical barriers embedded in system design can limit participation and reinforce transport disadvantage.

Overall, this dissertation provides a behaviourally informed analysis of shared mobility and mobility hubs across multiple urban contexts. The central conclusion is that while technological innovation is a necessary condition for urban mobility transformation, behavioural adaptation and the extent to which mobility systems accommodate user heterogeneity and participation barriers ultimately determine their effectiveness. The findings show that technological progress alone does not lead to adoption when users face cost constraints, digital exclusion, or physical accessibility limitations.

The key cross-cutting general conclusions, derived from the synthesis of all empirical chapters, offer comprehensive guidance for future policy and academic discussion:

1. System Integration of Mobility Hubs: The thesis conclusively demonstrates that achieving the highest level of environmental effectiveness requires treating shared mobility as part of an integrated transport system. The results show that while shared fleets offer operational benefits, they must be integrated through mobility hubs, which are essential for minimizing life cycle emissions and ensuring that system efficiency is fully aligned with user adoption patterns. This elevates the role of hubs from simple transfer points to essential elements of a sustainable transport strategy.
2. Dominance of Economic Factors: Across every empirical context, whether access/egress trips at hubs, local trips in car-free zones, or general mode choice among diverse demographics, the most noticeable and consistent factor influencing shared mobility adoption is the direct travel cost perceived by the user at the moment of decision-making. Despite the high long-term costs of private car ownership, it is the immediate, transactional cost of shared services that primarily drives adoption or rejection. This finding is critical for designing competitive pricing strategies.
3. Heterogeneity and the Behavioural Adaption: The research contributed to the social dimension of transport policy by highlighting behavioural differences within the population. In particular, the analyses of older adults and inner-city residents emphasized that successful mobility transitions depend on users' ability to adapt to new mobility systems. The presence of a car-dependent seniors segment and the high avoidance in car-free zones indicate that when shared mobility systems do not account for differences in digital literacy, physical capability, and prior experience, some users may withdraw from travel altogether. This can reduce accessibility and increase the risk of transport disadvantages.
4. Influence of Context and Experience: The thesis confirmed that traveler preferences and behavioural flexibility are spatially and functionally specific. The relative weighting of non-cost attributes (e.g., convenience versus time) varies significantly based on the urban area's density, scale, and policy setting. Furthermore, the finding

that prior experience with shared mobility is a superior predictive variable for future adoption suggests that effective policy should prioritize incentives for first-time use and focus on consistently high service quality to build positive behavioural momentum.

In conclusion, this dissertation connects transport engineering innovation with behavioural analysis by combining shared mobility and mobility hubs with empirical modelling of user preferences and adoption behaviour. The results demonstrate that sustainable urban mobility depends not on isolated technologies, but on integrated mobility system that align technological design with behavioural realities, providing an empirical basis for policies aimed at increased shared and socially inclusive transport systems.

Samenvatting

Stedelijke mobiliteitssystemen, met name binnen een hoogontwikkelde en intensief verstedelijkte context, staan onder toenemende druk door de groeiende vervoersvraag, beperkte openbare ruimte en de noodzaak om de CO_2-uitstoot van het particuliere autogebruik te reduceren. Ondanks aanzienlijke nationale investeringen en ambitieuze doelstellingen om tegen 2040 een duurzaam en betrouwbaar vervoerssysteem in Nederland te realiseren, hebben conventionele beleidsinspanningen om forenzen te stimuleren de overstap te maken van de auto naar het openbaar vervoer (OV) slechts beperkt succes opgeleverd. De aanhoudende voorkeur voor de auto wordt verklaard door de ervaren voordelen op het gebied van gemak, directe beschikbaarheid en algehele servicekwaliteit, waardoor de auto een sterke concurrentiepositie en een hoog comfortniveau behoudt ten opzichte van het openbaar vervoer.

Als antwoord op deze uitdagingen biedt de integratie van opkomende vervoersopties — zoals deelmobiliteit, elektrische voertuigen en geautomatiseerde mobiliteit — via mobiliteitshubs een alternatieve benadering voor stedelijke mobiliteitsvraagstukken. Door meerdere diensten op één toegangspunt te combineren, kunnen mobiliteitshubs de deur-tot-deurreis verbeteren en het concurrentievermogen van deelmobiliteit ten opzichte van de auto vergroten in termen van kosten, flexibiliteit en betrouwbaarheid. De effectiviteit van dergelijke systemen hangt echter niet alleen af van technologische beschikbaarheid, maar ook van gebruikersacceptatie en -adoptie. Daarom zijn (empirische) analyses van de voorkeuren en besluitvorming van reizigers noodzakelijk om de potentiële impact van de integratie van deelmobiliteit te beoordelen en om beleidsontwikkeling op strategisch, tactisch en operationeel niveau te onderbouwen, met name wanneer deze hubs in stedelijke gebieden worden geïntroduceerd.

Het hoofddoel van dit proefschrift is het analyseren van de gedragseffecten van de introductie en integratie van deelvervoer en de ondersteunende mobiliteitshubs. Het onderzoek onderzoekt het gedrag met betrekking tot deelmobiliteit binnen drie empirische contexten: de voor- en natransport bij multimodale hubs, mobiliteitskeuzes in autoluwe binnensteden, en het reisgedrag van ouderen (50-plussers). Concreet onderzoekt het proefschrift hoe deelsystemen voor (micro-)mobiliteit, geïntegreerd via mobiliteitshubs, de individuele modaliteitskeuze kunnen beïnvloeden en de afhankelijkheid van de auto kunnen verminderen. Hiermee wordt bijgedragen aan CO_2, toegankelijke en sociaal inclusieve stedelijke vervoerssystemen. Deze doelstelling wordt behandeld via de centrale onderzoeksvraag: *Hoe beïnvloedt deelmobiliteit het individuele reisgedrag en de modaliteitskeuze binnen verschillende stedelijke contexten?*

Empirisch steunt het onderzoek op Stated Choice (SC)-experimenten en enquêtegegevens, geanalyseerd met discrete keuzemodellen zoals Nested Logit, Mixed Logit en Latent Class-modellen. Deze methodologische aanpak maakt het mogelijk om gebruikersvoorkeuren, gedragsheterogeniteit en patronen van adoptie en vermijding in verschillende contexten te onderzoeken.

Het proefschrift begint met een beoordeling van de systemische en milieu-effecten van deelmobiliteit, waarna de focus verschuift naar specifieke gebruikersgroepen, reismotieven, beleidskaders en demografische kenmerken. Deze structuur ondersteunt een overgang van duurzaamheidsoverwegingen op systeemniveau naar gedragsreacties en verdelingseffecten op individueel niveau.

Hoofdstuk 2 legt de basis op milieu- en systeemniveau voor de daaropvolgende gedragsanalyses door de bijdrage van deelmobiliteit en mobiliteitshubs aan CO_2-reductie te onderzoeken vanuit een levenscyclusperspectief (Life Cycle Assessment, LCA). De methodologie bestaat uit een systematische synthese en kritische review van bestaande literatuur, waarbij de componenten — deelvervoer, elektrisch vervoer en micromobiliteit — expliciet worden gekoppeld aan het concept van mobiliteitshubs.

De synthese laat zien dat, hoewel deelmobiliteit de directe operationele emissies kan verlagen, deze voordelen deels tenietgedaan kunnen worden door emissies die gepaard gaan met voertuigproductie en door gedragsmatige substitutie-effecten (zoals reizigers die overstappen van actieve modi zoals lopen of fietsen naar gemotoriseerde deelopties). De resultaten duiden erop dat mobiliteitshubs een cruciale rol spelen bij het minimaliseren van levenscyclusemissies door de voertuigbezetting, het onderhoud en het energiebeheer te verbeteren. Het hoofdstuk concludeert dat duurzame transportplanning coördinatie vereist tussen LCA en gedragsmodellering, aangezien technologische verandering alleen onvoldoende is zonder een geïntegreerd systeemontwerp.

Hoofdstuk 3 richt zich op individueel reisgedrag bij multimodale hubs en behandelt het first- and last-mile vraagstuk voor treinreizen. Het doel van deze studie is het identificeren van de specifieke afwegingen en factoren die de voorkeuren en acceptatie van reizigers beïnvloeden ten aanzien van deelsystemen voor voor- en natransport (waaronder deelfietsen, e-steps, e-scooters en geautomatiseerde voertuigen (AV's)) wanneer deze worden aangeboden als alternatief op multimodale treinstations. Via een SC-experiment op een treinstation (zoals Delft Campus) zijn de onderlinge beslissingen tussen de hoofdreis (trein) en het voor- en natransport geanalyseerd.

De resultaten tonen aan dat in een land met een sterke fietscultuur zoals Nederland, deelfietsen een voldoende schaalgrootte moeten bereiken binnen mobiliteitshubs om een effectieve bijdrage te leveren. Geautomatiseerde voertuigen vertonen een hoger potentieel voor first- en last-mile verbindingen dan gemotoriseerde micromobiliteit, hoewel dit potentieel geconcentreerd is bij gebruikers met hogere inkomens en een hoog opleidingsniveau. Over alle opties voor voor- en natransport heen blijken de directe reiskosten de dominante factor voor adoptie, wat wijst op een sterke prijsgevoeligheid.

Hoofdstuk 4 onderzoekt de modaliteitskeuze en het vermijdingsgedrag in autoluwe binnensteden. Methodologisch hanteert dit hoofdstuk de expliciete modellering van een "opt-out" optie in het SC-ontwerp. De analyse toont aan dat restrictief beleid, zoals autovrije zones en beperkte parkeermogelijkheden, kan leiden tot een meetbare afname van de vervoersvraag wanneer deelmobiliteitsopties als ontoereikend worden ervaren.

Dit hoofdstuk behandelt ook de sociale gevolgen van beleidswijzigingen. De resultaten wijzen uit dat oudere bewoners grotere barrières ervaren bij de aanpassing, wat digitale en fysieke beperkingen weerspiegelt. Hoewel het relatieve belang van niet-kostengerelateerde kenmerken varieert per context, blijven reiskosten een sleutelfactor voor alle gebruikerssegmenten.

Hoofdstuk 5 onderzoekt de adoptie van deelmobiliteit onder ouderen (50-plussers) in kleine en middelgrote steden. Met behulp van een Latent Class Model warden verschillende gedragssegmenten binnen deze populatie geïdentificeerd.

De bevindingen onthullen een aanzienlijke gedragsheterogeniteit; segmenten onderscheiden zich door digitale vaardigheden, fysieke capaciteiten en openheid voor nieuwe technologieën. Eerdere ervaring met deelmobiliteit is een sterke voorspeller voor toekomstige adoptie, terwijl een auto-afhankelijk segment van senioren weerstand blijft tonen. Deze resultaten geven aan dat digitale en fysieke barrières in het systeemontwerp de participatie kunnen beperken en vervoersarmoede kunnen versterken.

Dit proefschrift biedt een gedragswetenschappelijke analyse van deelmobiliteit en mobiliteitshubs in diverse stedelijke contexten. De centrale conclusie is dat, hoewel technologische innovatie een noodzakelijke voorwaarde is voor de transformatie van stedelijke mobiliteit, de uiteindelijke effectiviteit wordt bepaald door gedragsaanpassing en de mate waarin systemen rekening houden met de heterogeniteit van gebruikers en barrières voor deelname.

De belangrijkste overkoepelende conclusies zijn:

1. Systeemintegratie van mobiliteitshubs: Voor maximale milieueffectiviteit moet deelmobiliteit worden behandeld als onderdeel van een geïntegreerd vervoerssysteem. Hubs zijn essentieel om de efficiëntie van het systeem af te stemmen op gebruikerspatronen en om levenscyclusemissies te minimaliseren.

2. Dominantie van economische factoren: De meest consistente factor die de adoptie van deelmobiliteit beïnvloedt, zijn de directe reiskosten op het moment van de beslissing. Ondanks de hoge langetermijnkosten van autobezit, bepalen de onmiddellijke, transactionele kosten van deeldiensten of reizigers de overstap maken.

3. Heterogeniteit en gedragsaanpassing: Succesvolle mobiliteitstransities hangen af van het vermogen van gebruikers om zich aan te passen. Wanneer systemen geen rekening houden met verschillen in digitale geletterdheid en fysieke vermogens, lopen bepaalde groepen het risico volledig af te zien van reizen, wat de sociale inclusiviteit schaadt.

4. Invloed van context en ervaring: Voorkeuren zijn locatie- en functiegebonden. Aangezien eerdere ervaring een sterke voorspeller is voor adoptie, moet beleid zich richten op het stimuleren van het eerste gebruik en het waarborgen van een constant hoge servicekwaliteit.

Concluderend verbindt dit proefschrift innovaties in de verkeerskunde met gedragsanalyse. De resultaten tonen aan dat duurzame stedelijke mobiliteit niet afhankelijk is van geïsoleerde technologieën, maar van een geïntegreerd systeem dat technologisch ontwerp afstemt op de gedragsrealiteit.

About the author

Fatemeh Torabi Kachousangi was born in Iran in 1987. She earned her Bachelor’s degree in Architectural Engineering from Tehran University, where she developed a strong interest in design and urban environments. She continued her studies at Delft University of Technology, where she obtained a Master’s degree in Urbanism within the Spatial Planning & Strategy– Complex Cities program. Her master's thesis focused on Transit-Oriented Development and explored strategies for revitalising neglected historic districts, aiming to strengthen local identity and improve urban cohesion. Her work was recognised as one of the top theses of 2012–2014 and was featured in *Delta* magazine, TU Delft.

In 2019, Fatemeh began her part-time PhD at Delft University of Technology, joining the Smart Public Transport Lab (SPTL) within the Transport & Planning Department at the Faculty of Civil Engineering & Geosciences. Her doctoral research investigated the impact of emerging transport modes on modal shift and travel behaviour in different urban contexts. During her PhD, she co-supervised international summer schools and sharing her expertise in sustainable mobility. In 2019, she received the best poster award in the UIC Conference for her research on intermodal hubs.

Outside academia, Fatemeh enjoys cycling, traveling, and photography. She is passionate about sketching, painting, and calligraphy, which serve as creative outlets that bring her joy and allow her to explore visual details.

Author’s Publications

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Summary

Shared mobility is a key component of sustainable urban transport, providing integrated alternatives to private car use. Travel behaviour determines the effectiveness of these systems across urban contexts and user groups. This thesis examines how shared mobility, supported by mobility hubs, influences travel behaviour and modal choice using stated choice experiments and discrete choice modelling.

About the Author

Fatemeh Torabi Kachousangi conducted her PhD research at Delft University. She holds a Master's degree in Urbanism from Delft University of Technology and a Bachelor's degree in Architectural Engineering from Tehran University. Her research interests include shared mobility, mobility hubs, and travel behaviour.

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