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Table of Contents

Table of Contents

Urban Planning (ISSN: 2183–7635)
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Editorial

Car Dependency and Urban Form

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Abstract
In this editorial of the thematic issue on car dependency and urban form, we provide a concise bibliometric overview that examines the prevalence of the concept of car dependency in relation to the built environment. Furthermore, we delve into the prior call for papers and analyse how the various contributions align with the theme. Subsequently, we present an inclusive review of the 11 distinct contributions, employing a classification framework encompassing micro, meso, and macro perspectives. To conclude, we reflect briefly on the utility of the concepts of being car-less versus car-free, and we contemplate the potential ramifications of fleet electrification on the ongoing discourse surrounding car dependency.

Keywords
built environment; car dependency; transport; urban form

Issue
This editorial is part of the issue "Car Dependency and Urban Form" edited by Kobe Boussauw (Vrije Universiteit Brussel), Koos Fransen (Vrije Universiteit Brussel / Ghent University), and Enrica Papa (University of Westminster).

1. Introduction and Call for Papers

In 1989, Newman and Kenworthy made a groundbreaking contribution to the field of car dependency and urban form with their influential book titled *Cities and Automobile Dependence: An International Sourcebook*. Within its pages, they unveiled a renowned graph that depicted the connection between urban density and transport-related fuel consumption (Newman & Kenworthy, 1989a). While earlier literature had touched upon the term "automobile dependence" or its variations, it is undeniably Newman and Kenworthy who bear the responsibility for the wide distribution of the concept, not only in research, but also in professional circles of urban planners and transport planners.

To gain insight into the origins and use of the concept of car dependency, we investigated its occurrence in the titles, keywords, and abstracts of academic publications registered in the Scopus publication database. Our search strategy involved exploring various combinations of words including "automobile" or "car" with "dependency," "dependence," "dependencies," or "dependent." Interestingly, our findings highlight that the earliest frequently referenced publication in this domain dates to 1989. The seminal article titled "Gasoline Consumption and Cities: A Comparison of U.S. Cities With a Global Survey" (Newman & Kenworthy, 1989b) presents the pivotal findings from Newman and Kenworthy's book of the same year. However, in subsequent years there appears to be a relatively sparse number of publications addressing the topic. Significantly, it is only from 1995 onwards that the term gains more prominence, with its usage growing steadily, in line with the global growth of the body of literature in urban planning and transport planning journals that seem to be the natural habitat for papers on the subject. From 2003 onwards the term has also been used in health sciences, in relation to the lack of basic exercise and related syndromes, and in social exclusion studies (see, e.g., Gray, 2004).

In 1995, Goodwin based his editorial of an early issue of the journal *Transport Policy* on a report for the RAC Foundation for Motoring and the Environment and titled it "Car Dependence." In this paper, he draws a strict distinction between "car-dependent people" and "car-dependent trips," and states that car dependency should rather be regarded as a process than as a state. In doing so, Goodwin paves the way for a range of research lines that in their entirety represent and unravel the complexity of the notion of car dependency. Indeed, we observe that since 1995 the number of publications on the topic has systematically increased. However, in the present thematic issue, we adopt a retrospective approach and revisit the original notion proposed by Newman and Kenworthy, positing the existence of varying degrees of car dependency among urban areas or cities.

But this specific subset within the broader body of literature on car dependency has also developed since then, covering an important share of technical analyses that attempt to measure and establish correlations between the built environment and indicators of car use. To gain insight into this body of literature, we expanded our search string in Scopus with the terms "vehicle miles," "vehicle kilometers," "VMT," "VKT" (all referring to the term "vehicle miles/kilometers travelled"), "modal split," and "urban form" or "built environment." One of the earliest, as well as most cited, publications meeting the search criteria mentioned is the article "Travel Demand and the 3Ds: Density, diversity, and design" (Cervero & Kockelman, 1997) and the most cited recent article from the list is "Travel and the Built Environment: A Meta-Analysis" (Ewing & Cervero, 2010).

The call for papers, which preceded the thematic issue, starts from the observation that Newman and Kenworthy's seminal work has been very influential in the field of urban planning, even though it has evoked important criticism on methodological grounds (Mindali et al., 2004; Saeidizand et al., 2022; Van Eenoo et al., 2022) and their notion of car dependency has been found too narrow (Goodwin, 1995). Mattioli et al. (2016) distinguish between three different understandings, or scales, of car dependency: micro (car dependency as an attribute of individuals), meso (as an attribute of trips, activities, or practices), and macro (as an attribute of society). Moreover, there is growing consensus that car dependency is a problem that is intertwined with all facets of society and therefore cannot simply be reduced to a characteristic of urban form (Urry, 2004). Nonetheless, the question of the impact of urban form on car dependency remains a hot topic among urban planners and transport planners.

Therefore, the call for papers invited scholarly contributions that would take a contemporary look at the problem of car dependency and urban form, both in the Global North and in the Global South, based on a genuine concern about how we can shape future urbanisation and urban redevelopment in a less car-oriented manner. Contributions could focus on, but were not limited to, the following topics: determinants of actual, perceived, and subjective car dependency in urban settings such as the importance of design of public space, walkability, bikeability, or transit-oriented development; forced car ownership, forced long-distance commuting, car-dependent passengers; mobility induced social exclusion, transport disadvantage and car dependency; urban form, society, and culture; travel behaviour, residential self-selection, and mode choice; sustainable urban planning and policy in relation to reducing car dependency; spatial and socio-demographic variations of car dependency; and direct and indirect costs of car-dependent built environments.

2. The Contributions

The call for submissions for this thematic issue was initiated in 2021, followed by an online workshop held in June 2022, where all authors could present their proposed contribution. Subsequently, submissions were received in October 2022, initiating the peer-review process. Finally, after peer-review, a total of 11 articles were accepted and published. The contributions are representative of the diversity of research that identifies with issues of car dependency in relation to urban form. Moreover, the contributions are geographically quite diverse. While the epicenter lies in Europe, the inclusion of cases from Asia (China and Mongolia), North America, and Latin America (Suriname) adds a global perspective. Moving forward, we will now provide an overview of the content of the various contributions, along the micro-meso-macro classification proposed by Mattioli et al. (2016).

At the micro-level, the focus is on understanding car dependency on the individual and household scales. Belton Chevallier et al. (2023) delve into the phenomenon of de-motorisation, specifically studying the reduction of car ownership at the household level in four French urban areas. They investigate the factors influencing de-motorisation, such as key life changes, income fluctuations, and the availability of alternative transport options. By interviewing de-motorised households, they reveal the significance of spatial factors and mobility representations and practices in early life stages, of less car-dependent planning policies and providing alternative transport options in lower density areas. Hamiduddin (2023) takes a closer look at the importance of private car access and its impact on mobility and access to opportunities in the ger districts of Ulaanbaatar, the capital city of Mongolia. The ger districts, characterized by informal settlements and limited public transport infrastructure, pose unique challenges for understanding car dependency. Through household questionnaires, Hamiduddin examines the mobility patterns and accessibility levels of car-owning and non-car-owning households in these districts. The study highlights the potential of shared taxis as an alternative mode of transport and underscores the need for improved public transport services to reduce car dependency. Van Eenoo (2023) investigates the characteristics of zero-car households in Flanders, Belgium, and explores their interactions with the residential environment. By analysing data from diverse households, the study reveals that zero-car households are more likely to be single, have lower incomes, and lack children. Contrary to common assumptions, zero-car households are not confined to urban areas alone. The findings emphasize the transport-related challenges faced by these households and advocate for inclusive urban planning and housing policies to address the vulnerabilities of low-income groups.

Moving beyond the individual and household scales, the meso-level perspectives explore car dependency in relation to trips, activities, and practices. Cao et al. (2023) tackle the intricate relationship between the built environment and car dependency in the Puget Sound area. Through the analysis of travel surveys, they identify nonlinear associations between the built environment characteristics and car use. The study suggests that high-density areas and pedestrian-friendly road networks discourage car use, while an optimal level of road density promotes it. These insights provide valuable guidance for urban planners aiming to design interventions that reduce car dependency. Dashtestaninejad et al. (2023) shift the focus to the Noord-Brabant region in the Netherlands, investigating whether car use primarily reflects car dependency or car-oriented preferences. By analysing data from employee questionnaires, the study explores commute travel times for various modes of transport. The findings highlight the importance of factors such as residential densities and proximity to railway stations in influencing car commuting patterns. Additionally, the study emphasises the significance of mode choice preferences in shaping car use. It concludes that a combination of measures, including both infrastructural and behavioural interventions, is necessary to effectively reduce car use and car dependency in commuting trips. Liu et al. (2023) delve into the role of buses in creating a sustainable transport system in Heze, China. Their research identifies the demographic characteristics associated with bus usage, including older individuals, the unemployed, and those travelling within the city centre. By examining travel distances and times, the study suggests that buses have the potential to replace cars for longer trips. To enhance bus travel, the authors propose strategies such as expanding the bus network, improving bus-related facilities, and ensuring punctuality and reliability. These recommendations contribute to the development of more sustainable transport systems.

The macro-level perspective encompasses a broader societal view of car dependency, considering it as an attribute of society and exploring strategies for addressing it. Aumann et al. (2023) present a comprehensive literature review on car-independent neighbourhood planning strategies for urban sustainability. By examining the implications of implemented car-independent policies in Europe, the study highlights the positive impacts of such interventions on sustainable mobility behaviour. However, it also stresses the need for further research to evaluate the psychological implications and attitudinal changes resulting from these interventions. Rymenants et al. (2023) tackle the challenges of transitioning from a car-dependent urban environment to a more balanced modal split in Paramaribo, the capital city of Suriname. Their research emphasises the importance of finding suitable governance strategies to improve mobility in the city. Through a design-driven participatory action research initiative, the authors explore the potential of civic engagement and urban tactics in pressuring the government to provide adequate infrastructure and policies that support a more balanced modal split. The study underscores the significance of stakeholder collaboration and innovative governance approaches in addressing car dependency. Krüger and Altrock (2023) contribute to the discourse by analysing the planning of decentralised mobility hubs in German metropolitan areas. These mobility hubs, integrated into alternative modes of transport and existing parking garages, aim to reduce car dependency, and improve pedestrian flows. The study investigates the emergence of mobility hubs in urban design discourses and evaluates their potential effectiveness compared to traditional parking garages. By examining their impact on car use and promoting alternative modes of transport, the authors shed light on the role of these hubs in reshaping urban mobility patterns. Metz (2023) challenges the prevailing notion of reducing car dependency as the primary goal of sustainable transport policies. The author argues that focussing solely on reducing car dependency might overlook the utility and positive aspects associated with car ownership. Instead, the article advocates for a more nuanced approach that emphasises the availability of alternative modes of transport while mitigating the negative aspects of car use. Ye et al. (2023) explore the relationship between urban polycentricity (UP) and particulate matter emissions from vehicles (PMV) in Chinese cities. Their study investigates the complex interplay between urban structure, economic output, and population density. The findings reveal an inverted U-shaped relationship between UP and PMV, suggesting that increasing polycentricity can initially lead to higher PMV levels, but once a threshold is reached, it results in reduced emissions. The research highlights the influence of economic output and population density on PMV and provides valuable insights for policymakers striving to create more sustainable, polycentric urban environments.

3. Conclusions

This thematic issue of *Urban Planning* encompasses a rich collection of research articles that delve into the multifaceted nature of car dependency. The contributions at the micro, meso, and macro levels provide a comprehensive understanding of car dependency from individual behaviours and household dynamics to trip patterns, practices, and societal attributes. By examining different contexts and perspectives, the studies shed light on the complexities of car dependency and offer valuable insights for urban planners, policymakers, and researchers striving to create sustainable and accessible urban environments.

Apart from the micro-meso-macro classification of Mattioli et al. (2016), there is also a clear difference in perspective between Global Northern regions on the one hand and emerging countries on the other. The conceptualisation of car-less versus car-free (Van Eenoo, 2023) has the potential to extend beyond individual households, and apply to regions, countries, or societies. It is worth noting that in emerging countries, where car dependency is rapidly on the rise, the notion that a car-free lifestyle can be virtuous is not yet widely embraced. In the Global North, there is undoubtedly a presence of the idea of organising cities and urban areas into less car-dependent environments. However, it is important to note that translating this ideal into practice is still more of an exception than the norm. Also, we see that in Global Northern areas the alleged virtues of the electric car thwart the debate on car-independent urban planning, even though an electric car takes up as much urban space as its combustion-based pendant and is therefore perhaps primarily a solution for suburban and rural areas, rather than for urban areas. In this respect, it is somehow surprising that the role of fleet electrification in the debate on car dependency has hardly been addressed by any of the contributions to the current thematic issue.

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Conflict of Interests

The authors declare no conflict of interests.

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Kobe Boussauw is associate professor of spatial planning and mobility, affiliated with the Cosmopolis Centre for Urban Research at the Vrije Universiteit Brussel. He holds degrees in engineering-architecture and urban planning, and a PhD in geography. His policy-oriented research focuses on the mutual interaction between mobility and the built environment. Central themes in his work are proximity as a spatial quality, urban liveability, and sustainability, often with a focus on car dependency in relation to the built environment.

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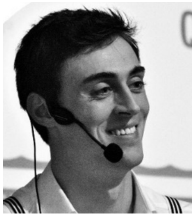

Koos Fransen has a background in industrial engineering and land surveying as well as in urban design and spatial planning. Up until 2022 he was employed as a post-doctoral researcher at the Cosmopolis Centre for Urban Research at the Vrije Universiteit Brussel and at the ISE research group at Ghent University, and is now still affiliated to both universities as a voluntary researcher. His research focuses on accessibility and its link to spatial planning and transport policy, with a primary focus on aspects of social exclusion and transport poverty.

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Article

Demotorization and Space: The Influence of Spatial Factors on Car-Dependency Reduction in France

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Abstract
Although car ownership continues to rise worldwide, temporary or more lasting phases of demotorization (reduction in the number of vehicles owned) are taking place at the household level. Existing studies show that the probability of demotorization increases at certain stages of the life cycle, for example, associated with a reduction in household size or income, or a move to a neighborhood with better transit provision. However, the rationale and temporalities of the decision-making processes involved remain obscure. This knowledge could be useful in informing public action on the measures needed in different categories of territories and populations to encourage a steady and sustainable fall in car ownership. As its contribution to these questions, this article focuses on the influence of spatial factors on household demotorization. The methodology draws on 51 interviews conducted in 2018 with demotorized households in four French urban areas (Paris, Lyon, Bordeaux, and Dijon). The findings highlight the role of the characteristics of the current place of residence, changes in the place of residence or place of work, and the spatial dimensions of travel socialization. If, as things stand, permanent and voluntary relinquishment of the car is only possible in very dense urban areas, our results show firstly that there is a strong case for working on mobility representations and practices from a very early age and, secondly, the importance of implementing planning policies and alternatives to the private car that are credible in areas of lower population density.

Keywords
car dependency; car ownership; demotorization; mobility biographies research; public policies; travel socialization

Issue
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1. Introduction

Given the scale and urgency of the challenges relating to health, energy, and the climate, the prospect of neighborhoods or even entire urban areas without cars or with significantly fewer cars is one that is beginning to be entertained by public authorities (Gao & Newman, 2018; Nieuwenhuijsen, 2020; Njeru & Kinoshita, 2019). These demotorization strategies (Aguiléra & Cacciari, 2020; Dargay et al., 2003), which aim to reduce household car ownership, are a continuation of urban policies that, for decades, have sought to diminish the use—i.e., the modal share—of the automobile (Glazebrook & Newman, 2018). They include the construction of eco-neighborhoods, annual limits on the number of new registration plates (as in Beijing), parking restriction policies, or else the development of carsharing and ridesharing services, which some hope will be facilitated by the large-scale rollout of self-driving vehicles (Le Gallic & Aguiléra, 2022).

The development of less car-dependent lifestyles seems moreover to reflect the aspirations of a growing number of citizens, in particular in industrialized countries and among younger people (Colli, 2020; Drevon et al., 2022; Klein & Smart, 2017). The reasons are not only to do with a growing awareness of the damage cars cause to the environment, the climate, and human health. They are also about the significant—and with the current energy crisis, growing—burden the automobile places on household budgets (Curl et al., 2018), and about the stress, fatigue, and risks generated by day-to-day driving (Hagman, 2006), especially in big cities (Canzler & Knie, 2016).

Nonetheless, although car ownership seemed to level off in the early 2000s in several industrialized countries (a phenomenon termed "peak car"; see Metz, 2013), and although it is falling in some major centers in industrialized countries, globally household car ownership continues to grow in both the industrialized and emerging countries. Rising living standards, combined with profound changes to the spatial organization of populations and activities, notably urban sprawl, feed these dynamics in certain countries, whereas in others they are caused by the rising incomes of people living in urban centers (Guerra, 2015).

The growth in household car ownership is also driven by the persistence of positive representations of the car as a symbol of social distinction, comfort, and freedom. The car also continues to be an instrument of lifestyle individualization and flexibility of opportunities (Luke, 2018), especially in areas of low population density where alternative modes of transportation are in very short supply. While young people in industrialized countries are acquiring driver's licenses and buying their first vehicle later than in the past (Bayart et al., 2020), the main reasons for this are life-cycle changes, the development of urban living, and economic difficulties arising from worldwide crises, rather than a genuine break with the past.

While motorization continues to rise around the world, phases of demotorization, whether temporary or more lasting, may be observed at the household level. However, this phenomenon is not widely documented and in particular, there is a shortage of adequate data such as panel data (Aguiléra & Cacciari, 2020; Clark et al., 2016; Dargay et al., 2003). Moreover, the trends revealed by the available studies are very slight, which also contributes to explaining the low interest of researchers in the topic. In Ireland, only 2.7% of households had demotorized year on year between 1995 and 2001 (Nolan, 2010), 4.5% in Japan between 2005 and 2006 (Yamamoto, 2008), and 9.1% in the UK between 2009 and 2011 (Clark et al., 2016). According to Dargay et al. (2003), 4% of households in Germany, 5.2% in France, and 7% in the UK each year reduced the number of owned cars between the mid-1990s and the early 2000s. Moreover, demotorization is often only temporary: for example, Dargay et al. (2008) showed that in Europe, from 1994 to 2001, between 6% (in Belgium) and 16.9% (in Greece) of households had more than once made a change (either upwards or downwards) to their level of car ownership. However, no figures are available on lasting demotorization (several years), the only kind likely to be associated with real changes in mobility practices. The available literature also shows that partial demotorization, i.e., where the household retains at least one vehicle, is much more common than total demotorization (Aguiléra & Cacciari, 2020). Finally, while studies show that the probability of demotorizing increases at certain stages in the life cycle—particularly those associated with a fall in household size (e.g., divorce or a child leaving home), a loss of income, or a move to a neighborhood with better transit provision—the rationales and temporalities of the decision-making processes occurring within households that demotorize, whether voluntarily or by necessity, remain largely obscure. In particular, there is no clear explanation of why, among households experiencing "similar" conditions, for example moving from the suburbs to downtown, some dispose of a vehicle or even relinquish car ownership entirely, while others do not, or do so much later. Yet knowledge of this kind could be useful in informing public action about what measures to implement in different categories of territory and population in order to encourage a steady and lasting demotorization of our lifestyles.

For its contribution to this field, this article looks at the rationales of household demotorization (partial or total), taking France as its case study. With regard to methodology, our approach draws on the relatively recent field of mobility biographies research (MBR; Lanzendorf, 2010), which aims to understand changes in mobility practices by situating them in the long-term context of biographical trajectories and successive stages in the life cycle (Müggenburg et al., 2015; Scheiner, 2017), together with travel socialization studies (TSS), which focus specifically on the role of the (primary and secondary) stages of individual travel socialization (Baslington, 2008). These approaches postulate that the experiences, transitions, and disruptions experienced by households prompt them to reconsider and sometimes reorganize their lifestyles, including in certain cases their mobility practices. They show that changes in mobilities occur more frequently during key events in the life of households, events relating to the family sphere (birth of a child, marriage, etc.), work (redundancy, new job, change of workplace, retirement, etc.), or to the social and material environment, for example following a move to a new neighborhood more conducive to walking as a mode of travel (Clark et al., 2016; Oakil et al., 2014). TSS also emphasize the influence of lifelong mobility learning mechanisms, which contribute to shaping attitudes about modes of transportation but also individuals' perception of their capacity to alter their practices (Baslington, 2008; Underwood et al., 2014). The perceptions and meanings that individuals attach to their mobility-related decisions, and where they stand to the dominant social norms, play an important part in changes in practices (Sattlegger & Rau, 2016). Apart from the production of new theoretical and empirical knowledge, the goal of MBR and TSS is to arrive at a better understanding of the factors that influence the transition to more sustainable practices, considering the mechanisms and temporalities that help to shape mobility preferences and habits, and identifying moments in the life cycle that are more conducive than others to the introduction of measures intended to change practices (BouMjahed & Mahmassani, 2018). However, so far this literature has paid little attention to changes in household car ownership (Aguiléra & Cacciari, 2020). Drawing on 51 face-to-face biographical interviews, this article addresses this research gap. More specifically, we address the following research question: What role do spatial factors play in household demotorization processes? Following literature review, spatial factors are investigated both as key events (such as moving home or the arrival of a new mobility service in the neighborhood) and as factors that influence travel socialization.

2. Method and Material

As part of the MODE project financed by the French National Research Agency (2016–2021), we conducted a qualitative survey through semi-structured biographical interviews with 51 people living in a (partially or totally) demotorized household. These households were chosen among the households in the Metaskope Panel (Kantar–TNS Sofres) which were participating in the Parc Auto study. The aim of this annual French study, which has been running since 1983, is to describe the various aspects of household car use, such as car ownership, car characteristics, car use practices, attitudes towards the automobile, use of different mobility services (rental, carpooling, etc.), and so on. We targeted the households in the urban areas of Bordeaux, Dijon, Lyon, and Paris that had declared a reduction in car ownership. As noted in other articles, we met households that had practised various kinds of demotorization: total (no car remaining in household) or partial (household still with a car), recent or less recent, demographic (due to changes in the household itself) or real (with no change in household structure), etc. Most of the households we met were in the totally demotorized category.

The sample contained a slight majority of women (29), people over the age of 60 (21), or people of working-class background (20). We were careful that the sample should be as diverse as possible in terms of gender, age, residential location, and occupation. While certain profiles (urban women of working-class origin in their 50s) were more common than others (few or no interviewees with militant views for or against the car), the diversity of backgrounds (spatial and social) was satisfactory. With the exception of 12 households, the people interviewed mostly lived in dense parts of the urban areas concerned. Nonetheless, an examination of their biographical histories revealed that 32 of them had, at one or more periods in their lives, lived in low-density areas (suburban or rural) characterized by high car dependency.

Face-to-face interviews were conducted in 2018 (i.e., before the Yellow Vests crisis). They lasted 60 to 180 minutes. Inspired by the MBR approach (Müggenburg et al., 2015; Rau & Manton, 2016), more specifically qualitative MBR based on a biographical and reconstructive approach (Sattlegger & Rau, 2016), or on travel socialization surveys (Baslington, 2008), the interviews were built around biographical storytelling by the interviewees about their socialization to everyday mobility and about the construction of a relationship to the car during this process, then about the process of demotorization. In order to reconstruct these narratives, the discussions focused on descriptions of the practices, social relations, and conditions that had shaped and continued to shape the interviewees' relationship to everyday spatial mobility.

The aim was to explore all the trajectories of the interviewees associated with the ownership of and relationship to the car and with their mobility practices, from childhood through to the time of the interview. While the story of their demotorization and their abandonment of the automobile was an important part of the interviews, the aim was also to situate these changes within the context of all aspects of their life experience (family, work, home location, etc.).

All the interviews were transcribed in full and analyzed thematically with respect to several themes such as life stages, key events in motorization and demotorization, or the social, material, and biographical context of everyday mobility. As several articles have already provided an in-depth analysis of our qualitative study (see Cacciari & Belton Chevallier, 2020), the present article mainly focuses on the spatial dimensions of demotorization, a theme that serendipitously appeared during the interviews as more complex than anticipated.

3. Results

3.1. Demotorization: A Heterogeneous and Complex Process

The reasons behind the demotorization of the households interviewed are diverse. The death of a partner, divorce, or a grown child leaving home are common reasons. In this, we see the role of the key events emphasized in MBR. A common occurrence is that the person quitting the household takes a vehicle. For households with multiple vehicles, this does not entail immediate changes in travel practices. On the other hand, in cases where the departing person was the only one able to drive, demotorization has more significant consequences, particularly when the departure is unexpected.

Beyond these events associated with changes in household structure, demotorization is linked with giving up of another kind, this time driving itself. Several people attribute this to the fear of driving. For some, this fear goes back a long way, the outcome of traumatic experiences in childhood (accidents, parental quarrels in the car, etc.) or in adolescence, notably when learning to drive. For others, it is more recent and is triggered, for example, by road traffic accidents. In both cases, the fear of driving often long predates actual demotorization. Other reasons for giving up driving and therefore the car emerged from the interviews, such as physical incapacity (sight problems, backache, etc.), vehicle disrepair, or loss of the driver's license. For these different reasons, the relinquishment of the car is often involuntary, a divergence in the biographical trajectory. In the stories people told, this "forced" demotorization was initially seen as temporary—until their health improved, until they recovered their license, or until they had enough money to buy another vehicle. It could subsequently become permanent, the outcome of positive experiences with other modes of travel.

Whether voluntary or not, seen initially as temporary or lasting, relinquishing driving and car ownership is a process with multiple causes that can take time to emerge and that are often difficult to link unequivocally with a single motive. Other explanations for demotorization lie in the day-to-day experience of mobility. In particular, whether it follows a period of automobile deprivation when other modes of transportation have to be tried, or as a result of periods of excessively intense car use, awareness of the unpleasantness of car travel plays a major role. Congestion, parking difficulties, vehicle maintenance, and damage (especially when the car is parked in a public space) are all reasons that contribute to making the car an unpleasant or tiring mode of travel. Unsurprisingly, this view was particularly marked in households located in very dense urban areas, notably in the center of Paris or Lyon. Over time, the car became a burdensome object that our interviewees preferred to do without. Demotorization is therefore not linked necessarily and directly with a key event. It also arises from the experience of other ways of traveling, which prove more efficient and less unpleasant with practice. In other words, demotorization begins with a reduction in car use before car ownership is ultimately relinquished.

3.2. The Spatial Elements of Mobility Biographies as Factors of Disenchantment and Demotorization

Beyond the experience of other modes of travel, demotorization needs to be placed more broadly within the spatial aspects of the households' biographical trajectories. While the narrative of the growing sensitivity to the downsides of car use is essentially encountered in urban households, it is particularly marked among people aged between 30 and 50, often with children, who have in common the fact of having spent their youth in low-density or car-dependent areas. As a result, these people were socialized very young to the norm of the car, in other words, the view that the "best" way of traveling is at the wheel of an automobile.

More broadly, regardless of the household interviewed, the value attached to the car has not been the same in every place and at every time, reflecting the history of motorization in France in the post-war period. At the beginning of France's so-called Trente Glorieuses, the 30 years of post-war prosperity, and before that, the car was a very rare presence, whether in the city or the countryside. After this, the car occupies a growing space in biographical narratives, wherever people lived. In many cases, therefore, in childhood and then adolescence, the car is an object seen as somehow enchanted. Linked with childhood vacations, in adolescence and early adulthood it becomes tied to the quest for autonomy and social status, especially for men. Passing the driving test is a rite of passage, which over the generations has become increasingly essential and rarely challenged. In consequence, narratives about the car as enchanted or liberating are relatively common among all the people we met. Nonetheless, they are more marked among people who grew up in areas of low population density. Nicolas is a married teacher with two children, that has been living in Montrouge (near Paris) for 10 years, but grew up and lived near Bordeaux' greater suburbs until his 20s. As he explains:

> Nicolas: So, well, I started to learn with a qualified driver in the car when I was 16. I was in Bordeaux, I mean, near…in the countryside. More in the countryside, though, so as a result the car was pretty much essential, otherwise, it was impossible to get around.

Many of the people who were socialized when young to the norm of the automobile because they spent their childhood or adolescence in low-density areas talked about becoming particularly disenchanted with car ownership when they moved to the city. This disenchantment is not only linked with the problems of driving and parking in the city but also with the experience of mandatory travel, especially for work. However, this obligation to travel would probably not have resulted in demotorization in low-density areas, where people report that there is no alternative. It was urban disenchantment with the car that gradually prompted our interviewees to demotorize. The fact that it was gradual is attributable to the persistence of the norm of the automobile, which does not disappear overnight. People had to experience the downsides, abandon deeply embedded preconceptions about the disadvantages of public transit and (above all) the advantages of the car, in particular its reassurance value (to deal with emergencies, especially those associated with children or elderly parents), before deciding to say goodbye to it. Claire, 42 years old, is a good example of this process: after her divorce, she decides to leave her small village in the mountains (Savoie) to come back to Paris. Even though she grew up in Paris until she was 12, she has been used to the car, especially as a mother of four children. Also, it took her several years to get rid of her car, as she explains below:

> And what persuaded you to keep your car when you arrived in Paris?

Claire: Habit I suppose, it's true I don't know…and of course, I have young children, and I admit that then when I got rid of it, I was terrified of not being able to cope. Because yes, for me, a family with children means a car is essential.

And so…saying goodbye to it can't have been easy?

C.: I told myself that it was a trial…To be honest, I thought that probably within 6 months I would have to buy another car. But in the end no!!! Because it's true I eventually realized that not having the stress of finding somewhere to park, worrying about damage…

Not to mention the expense!

C.: Right. But even without the financial aspect, the motivation is not purely financial….Because it's true that somehow owning a car in Paris, it's stressful, and then I know that I would always have to repark because often I couldn't park properly, I had to park badly, late in the evening, and then get up at 7 am to repark….I had to pay pretty much every day. And then, another thing, I remember that coming back from school, we would try to go past the car to make sure that it hadn't been vandalized too much….I thought that it would be a problem not having a car and finally, it was a release.

3.3. From Disenchantment to a More Utilitarian Relationship to the Car: Spatial Components of a New (De)Motorization?

While the downsides of owning a car, and the disenchantment with the car associated with them, are often cited as the natural result of living "in the city" (or, more broadly, in high-density areas), the interviews also reveal the influence of policies designed to reduce car use. The impact of these was particularly strong among people who had always lived in the city, even at times when using a car there was less problematic (in particular people born in the period between the 1950s and the 1980s). Apart from policies designed to discourage private car use and ownership, the interviews show that the availability of efficient alternative travel modes also plays an important role in demotorization processes among urban dwellers. In fact, transport alternatives and disincentives to cars play together in explaining the renunciation of car ownership for most urban people interviewed. This is the case regarding Geraldine, she is a 55-year-old married woman with no children, who has lived in Paris for 15 years, and who previously lived abroad and grew up in the outer suburbs of Paris. As she explains:

Geraldine: And then, after that…I ended up selling it because it wasn't just at home where it took me 90 minutes to park, it was everywhere, you couldn't park anymore because there were Vélib bikes, because there were….Because parking spaces were being removed, Mme Hidalgo was shutting down parking spaces pretty much everywhere. I was forced to give up my car. […]

So you sold your car….Can you give me the date when you sold it?

G.: Well, I sold it…3 to 5 years after [her return]. I mean, I still tried. I'm stubborn. But now, I use rental cars when I'm on holiday….Public transportation and rental cars when I need a car. Or taxis, a taxi when I need to travel in Paris, I mean a taxi when there is no transit.

However, the links between spatial context and demotorization are not only about the characteristics of different areas and the mobility conditions they create. They also reflect the sociability of individuals and the social links that they form in these areas in the course of their lives. Several people explained how, in changing their spatial context, they also, above all, changed their social context. For example, living in more urban areas and spending time with people who are activists or more involved in the ecological transition favors a weakening of the norm of the car, and sometimes a rejection of the object itself. Thus, our interviews show that the political, social, and economic context of urban territories can also contribute to a form of disenchantment with the car that can result in demotorization. Agathe (age 33, engineer, in a relationship, one child) has lived in Lyon since she finished studying and is active in an environmental group outside her work. She grew up in a small, highly car-dependent village in the Haute-Loire, where her parents and some friends still live. Her narrative of demotorization led to a debate with her parents:

Agathe: In the end, it was precisely that, to some extent, the difference with my parents, it was that they didn't understand why I wanted to sell my car, they wondered how I was going to live without a car, and for me, I wasn't worried about it at all!…I mean, no, I knew that I no longer wanted one, and of course, I knew perfectly well they were going to say that, but I was convinced that for me it was more a burden than anything else, and I knew that, well, there was the train, and they didn't have any idea about ridesharing either, and I must say that since I ditched the car I've never had any problem traveling, in order to…yes, it's true, I had to explain to them that it was possible to live without a car, in Lyon at any rate…where they live, no, but in Lyon in any case…. I have a lot of friends who have stayed, in fact, in Haute-Loire. I don't hassle them about it, because they don't have any other choice. But in Lyon, well, my mates, they're all like us in fact, they don't have cars, they have a bike and that's it.

However, the interviewees still communicate the persistence of one spatialized norm of the car. Whether they lived in the city or the country, all the people we interviewed stressed the importance, even the necessity, of having a driver's license, especially for their children or grandchildren. It is essential to be able to drive, whether for work, for vacations, or to be able to live in the countryside one day. No need to own a car, simply to be able to drive, just in case. In other words, the development of a utilitarian rather than an enthusiastic attitude to the car does not undermine people's spatialized representation of it. On the contrary, it reinforces that representation. It prompts them to relinquish the car when they live in the city or have access to efficient local mobility services. But it also prompts households to go back to the car when they choose to move to the countryside. In other words, people who have demotorized have not necessarily permanently ditched the car in favor of other transport modes in their life plans, particularly their residential plans. To return to the case of Agathe, a new mother, the interview reveals that she is considering moving to a more rural environment, which she sees as "a privileged environment, I find, for children, the countryside, less stress." She argues that "a healthy environment, a long way from the city, is ultimately a bit better" for her son. In consequence, she acknowledges that she will eventually have to think about getting a car, though now the goal is an electric or hybrid vehicle that will reconcile the need for mobility with the commitment to ecological transition.

4. Conclusion and Recommendations

This research shows that, as things stand, permanent and voluntary relinquishment of the car is more likely or feasible in very dense urban areas. While the proximity of stores and jobs or the existence of alternative transportation options facilitate travel by other means than the car, most urban areas are primarily associated with negative externalities that ultimately encourage people to relinquish car ownership: expensive parking, congestion, fatigue, etc. In this case, and as noted in previous research on decreasing car use (Beirão & Cabral, 2007; King, 2022), we can see the outcome of urban policies introduced several years ago, especially in France's most heavily populated urban areas.

Nonetheless, while car dependency is intimately linked with urban life, that is not the only factor. In fact, the perceptions and representations associated with the car evolve over the life cycle and, in our household survey, reveal a gradual disenchantment with car ownership which builds up gradually and cumulatively during the life cycle and therefore may not necessarily be linked with a significant key event, as is often seen in quantitative MBR. Previously a symbol of freedom and autonomy, or linked with childhood vacations, the car has become associated with frequent work trips, lift giving (children, elderly parents, etc.), and more generally with constraints that occur with varying intensity in different residential contexts and vary from one person to another. The disparate nature of this disenchantment explains why not all the people in our sample have demotorized in the same way, and why some urbanites kept their vehicles for a long time before relinquishing them. It also explains why car use continues, especially for vacations, for example by renting. Finally, the shift to a more utilitarian relationship to the car over the years does not fundamentally challenge the spatial representation of travel practices amongst people who have demotorized, who never rule out reverting to the car if they move home. In fact, it could be that the utilitarian position tends to reinforce that representation, especially as electric or hybrid cars can provide an ecological alibi.

Obviously, our results are based on a very particular category of households, those that have already to some extent given up on car use. In some areas such as Bordeaux or Dijon and the less dense parts of the four urban areas, it is a kind of household that is less likely to be encountered. Despite this rarity, our sample illustrates in its narrative and also its socio-spatial structures how demotorized households may appear in different kinds of places and how they do not necessarily differ from motorized households in any respect other than car ownership. This may help us to understand the drivers of lasting demotorization and how to foster demotorization by still-motorized households, one of several prerequisites to achieving car-free cities (Nieuwenhuijsen et al., 2019).

In terms of political recommendations, the consequences of these findings are twofold. Apart from very specific cases (physical incapacity, poverty, withdrawal of license, etc.), the process of relinquishing car ownership is gradual, which demonstrates the normative influence of the car, an object that individuals are socialized to from childhood. In order to reduce car dependency, therefore, there is a strong case for working on mobility representations and practices from a very early age. Finally, the spatially situated vision of car ownership and use raises questions about the scope and relevance of public policies. While car use restriction policies are acceptable and accepted in the core of metropolitan areas, there are no plans to introduce them in less dense areas where the car is seen, both by users and by the authorities, as essential. These facts show the importance of implementing planning policies and alternatives to the private car that is credible in areas of lower population density. In this regard, it is important to take into account the rich literature that highlights the huge differences in travel behavior, transport infrastructures and services, and willingness to adopt more sustainable modes between, on the one hand, metropolitan areas, medium-sized and small towns, and rural areas (Flipo et al., 2021), and, on the other hand, between the core and periurban parts of urban areas (whatever their size; Hasiak & Richer, 2021; Obregón-Biosca, 2022). The increase in homeworking that has followed the pandemic, which seems simultaneously to have led to more (but shorter) trips in the vicinity of home (for purposes other than work) and to an increase in the distances between home and the workplace (Wöhner, 2022), notably in less densely populated areas, makes this shift in approach all the more urgent.

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Conflict of Interests

The authors declare no conflict of interests.

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Article

Why the Car Is Not Always King in Global South Cities: Evidence From Ulaanbaatar

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Abstract
Access to a private car has established itself as a critical control on mobility and access to opportunities for residents living in a diverse range of settings, globally. Across cities of the Global South, the benefits of private car access are often intensified by the absence of viable alternative modes of travel. This article explores the influence of private car access and mobility in relation to residents living in "ger district" areas of Ulaanbaatar, Mongolia's capital city. These peri-urban areas are informally created when rural migrants set up home on the edge of the city, initially using mobile felt dwellings called "ger" that become augmented or replaced by permanent structures over time. An absence of forward planning as well as unmade roads and hilly topography mean that the ger districts are often poorly served by public transport, while the low density of the built environment also means that informal transport services can be limited in coverage and relatively expensive. This article utilises a database of household questionnaires collected in 2020 to compare mobility patterns and accessibility between car-owning and non-car-owning households in three case study ger districts, capturing seasonal differences between the extreme cold of the wintertime and warmer summer conditions. The findings not only reveal stark mobility and access differences in relation to car ownership but also discrepancies between car ownership and actual car use for important and routine journeys. This indicates that despite a lack of public transport available, many households opt to use what public transport they can. This pattern provides a potentially important basis for future policies that aim to limit car use in order to reduce traffic congestion and broaden access to the city for non-car-owning households by providing more accessible public transport.

Keywords
car ownership; car use; Global South; informal settlements; mobility; Mongolia; private car; public transport

Issue
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1. Introduction

Across many cities of the so-called Global South, rapid inward migration and urbanisation continue to overwhelm the capacity of urban governments to provide basic access to services and opportunities, as well as access to mobility services that allow citizens the ability full participation across the different facets of urban life (Castañeda, 2020). Such a situation appears to be evident in Ulaanbaatar, Mongolia's capital, where the largely unplanned ger districts have ballooned in the decades following the country's embrace of economic liberalisation in 1991 and the allowing of free movement to move to the capital after the end of socialism. This shift triggered an influx of migration from the countryside, giving rise to rapid population growth within the ger districts and movement within the city as people sought areas to set up land plots on the city's outer limits. Today, the ger districts house over half of Ulaanbaatar's residents or almost one-third of Mongolia's entire population.

In contrast to the high-density informal settlements found in other Global South cities, a 2002 law entitling each Mongolian household to a 0.07 ha plot of land has allowed the ger districts to grow in a low-density, sprawling, peri-urban fashion (Terbish et al., 2022), an urban pattern that lengthens travel distances and makes public transport services inefficient to operate. New residents arriving from the countryside typically establish home by setting up a "ger," or collapsible felt dwelling used by Mongolia's mobile pastoralists, on vacant land and establish boundaries by enclosing their plot with a high fence to form "hashaa." Over time, depending on the economic opportunities of different households, hashaa can become built out with new buildings that augment or replace the ger as living accommodation or for micro-enterprises such as retail outlets or car repair garages. This means that the older ger district areas closer to main roads and formally planned areas of the city typically have the greatest building density and the most diverse land uses. Additionally, earlier research undertaken by Hamiduddin et al. (2021) showed that being located closer to the main roads brought superior access to public transport services. By definition, therefore, newer households tend to live in areas of the ger districts situated away from both public transport services and the mixed land uses associated with the more established ger district areas.

By global standards, permanent settlement is a relatively recent concept in Mongolia, where livelihoods were traditionally based on nomadic pastoralism. Permanent settlement began to emerge from the 1920s, after the adoption of communism, leading to the successive expansion of formally planned urban development through waves of Soviet-style urban planning through to the 1970s and, since the collapse of communism in 1989, to market-oriented speculative schemes (Boldbaatar et al., 2014). Today, Ulaanbaatar features a relatively dense core of formally planned city development that has become shrouded by the much lower-density peri-urbanism of the ger areas. The city's estimated 1.5 million inhabitants are served by a transport system that is dominated by buses and cars. The bus system forms the backbone of the city's public transport system, consisting of a total of 138 bus lines, divided into main, express, feeder, and seasonal summer house routes operated by approximately 800 vehicles (Mott MacDonald, 2019). In addition, a number of shorter and dedicated electric trolley bus lines operate within the inner city. Private minibuses or "mickrobus" form a patchwork of local services in different areas of the city (Plueckhahn & Bayartsetseg, 2018), plugging the gaps in the bus network or providing local services between the neighbourhood and main bus line, although restrictions applied by the municipal authority has attempted to reduce congestion at bus stops caused by mickrobuses. Lastly, taxis provide the foundational plank of the transport system with eleven licensed taxi companies operating approximately 600 vehicles across the city (Mott MacDonald, 2019), a markedly insufficient fleet for a city of 1.5 million residents (My Mongolia Travel, 2023). Car-owning residents make up the shortfall by providing informal taxi services in their own private cars—hailing a ride in a private car is a common aspect of life in the city. Across the ger areas, share-taxis can be found operating along fixed routes within some neighbourhoods, typically bringing residents from peripheral areas to central areas close to main bus routes.

At the present time, the existing literature on mobility and access across Ulaanbaatar is extremely sparse and largely confined to consultancy or NGO studies on travel patterns across the overall population or in reference to specific aspects of life, such as access to healthcare (e.g., Kim et al., 2023) or addressing air pollution (Ariunsaikhan et al., 2020; Aschmann, 2019) or transport management (e.g., Gantulga et al., 2022). However, the existing literature reveals a fine balance between the overall use of the car and the use of public transport for journeys across the city. According to Khurelbaatar (2018), 51% of all journeys made in Ulaanbaatar are undertaken using public transport, compared to 42% by private car and 5% by taxi. However, this analysis of modal share does not provide a breakdown of route type and no specific data on mickrobus ridership or comment on whether private car transport included travel on a paid-passenger basis. *The Economist* reports that approximately 60% of automobiles in Ulaanbaatar are hybrid vehicles that can better cope with the extreme cold of the winter ("Everyone in Mongolia drives a Prius," 2018). Second-hand vehicles imported from Japan can be purchased for as little as $2,000 owing to stringent and expensive vehicle testing the Japanese government requires on vehicles more than three years old. However, although the cost threshold for vehicle ownership is low by any standards, average fuel costs of approximately $1.5/L (Global Petrol Prices, 2023) add a considerable cost burden for households on modest incomes. Since 2016, the municipal government has attempted to limit the use of private cars on weekdays from 8 am to 8 pm through a number plate rationing system ("Average salary in Mongolia is 394 USD," 2017) similar to schemes introduced across cities of Latin America and Asia (Han et al., 2010). In principle, private vehicles are excluded from using the city's roads on one weekday per week.

This article builds on the previous work of the author by, firstly, presenting a more detailed analysis of car ownership and use among ger district residents, secondly, by examining access and mobility patterns between car owners and non-owners, and, thirdly, reflecting on how existing disparities between car owners and non-owners might be addressed with respect to Ulaanbaatar's specific context and challenges. The research questions guiding this article are:

- RQ1: Who are the car users of Ulaanbaatar's ger districts?
- RQ2: What access and mobility advantages do car users have over non-car users?
- RQ3: How might access and mobility disadvantages experienced by households without access to a private car be reduced?

1.1. Car Use and Development

Although there is a broad and consistent association between household income and car ownership across international data sets, the relationship is rarely linear. Research by Dargay and Hanly (2007) depicts an uneven S-shaped curve, with slow growth in vehicle ownership among low-income households, accelerating through middle earners and slowing again as saturation in vehicle ownership is achieved among higher-income households. For example, in the UK, Stokes (2015) observes that 56% of households in the lowest quintile have cars compared to 94% in the highest two quintiles, whereas 89% in the middle quintile are car owners. The pattern can be readily observed across countries of the Global South (Dargay & Hanly, 2007) and indicates the importance of the private car as a household spending priority globally. In Mongolia, a detailed analysis of vehicle ownership in relation to income is not yet available, but aggregate data from the Asian Development Bank (2009) shows that motorisation has generally increased with national economic growth, with a surge in the first decade of this century that accompanied an economic boom and more available credit. In line with many emerging cities (Gakenheimer & Dimitriou, 2011), motorisation and urban growth in Ulaanbaatar have out-paced the development of the city's transport infrastructure, leading to chronic levels of traffic congestion and the absence of viable alternatives to road-based transport and lengthy commutes relative to the comparatively small scale of the city (Hamiduddin & Plueckhahn, 2021). Indeed, the authors found that the car drivers experienced very slow driving speeds as low as 8 km/h on their route from an outer ger district to the inner city—only double the average walking pace and slower than typical cycling speeds. Yet, as Haustein (2021) notes, the full utility value of the private car for a household can be difficult to capture. In Ulaanbaatar's ger districts, many carless households face the prospect of lengthy walks on unlit dirt tracks to access public transport services that are confined to the major roads (Terbish & Rawsthorne, 2016). During Mongolia's long and harsh winter, travel by foot or bicycle is both arduous and potentially treacherous—a greater consideration for many car users against the disbenefit of being stuck in traffic congestion.

Precise car ownership data is not publicly available for Ulaanbaatar's ger districts, but recent research by Hamiduddin et al. (2021) in three ger districts found that between one-third and a half of households owned a car. Furthermore, earlier research conducted on one of the ger districts by the author (Hamiduddin & Plueckhahn, 2021) found that residents who commuted by bus had an average overall journey time of 56 minutes in each direction, compared to 35 minutes by car. This particular ger district had no bus services into the city. Instead, residents living close to neighbourhood fixed share-taxi routes had the option of taking this informal transport service to a drop-off point close to a bus stop, while those living away from the route typically faced a walk of up to 1.5 km from their home to a bus stop. The research highlighted the specific issue of first/last journey stage access to the strategic urban transport network faced by many ger district residents.

1.2. Improving Non-Car Accessibility

Many Global South cities have embarked on programmes to improve city-wide access for non-car users. Most interventions focus on cost-effective improvements to public transport, through new bus rapid transit (BRT) schemes, other light rapid transit systems, or the deployment of innovative approaches such as cable car systems to overcome physical constraints. Such interventions may be accompanied by land-use strategies such as transit-oriented development or "smart growth" corridors that aim to support ridership by densifying populations within a walkable catchment area (Cervero, 1998; Papa & Bertolini, 2015). Whilst BRT schemes have become particularly popular because of their relatively low cost and technological simplicity, they are notably more complex and expensive to retrofit into mature urban areas, where the need to avoid extensive clearance and reconstruction may restrict a scheme to established arterial routes. This is the case with Ulaanbaatar's now long-proposed BRT system (Figure 1), which would aim to create dedicated busway routes and metro-style stations on key arterial roads. Some preparatory aspects ahead of the technical implementation of the BRT system have now been completed. These have included the introduction of smartcard ticketing accompanied by the introduction of a new public-private partnership service agreement, a development that led to some disruption to bus services and a temporary loss of ridership during roll-out (Gerilla-Teknomo, 2017). Despite delays to the full introduction of the BRT system, the Mongolian government recently reaffirmed its commitment to beginning the technical implementation of the project (The UB Post, 2023).

In theory, the strategic BRT system would be augmented by non-BRT feeder services of smaller, local buses on existing and improved roads. In their practical application, these schemes face significant and myriad challenges. Perhaps the greatest of these is the scale of interventions required to integrate all areas of the city into the system, and the resources, expertise and institutional capacity required to achieve this. The existing, much-delayed plan would leave significant areas of the existing ger districts outside of the standard 400 m walking catchment and does not appear to make provision for the growth of the ger districts, which has continued over the decade since the Ulaanbaatar BRT plan was initially published.

A striking feature of the Ulaanbaatar transport system, compared to other low-middle income cities of Asia, is that it is very heavily focused on more formal transport modes and larger vehicles. Share-taxi and

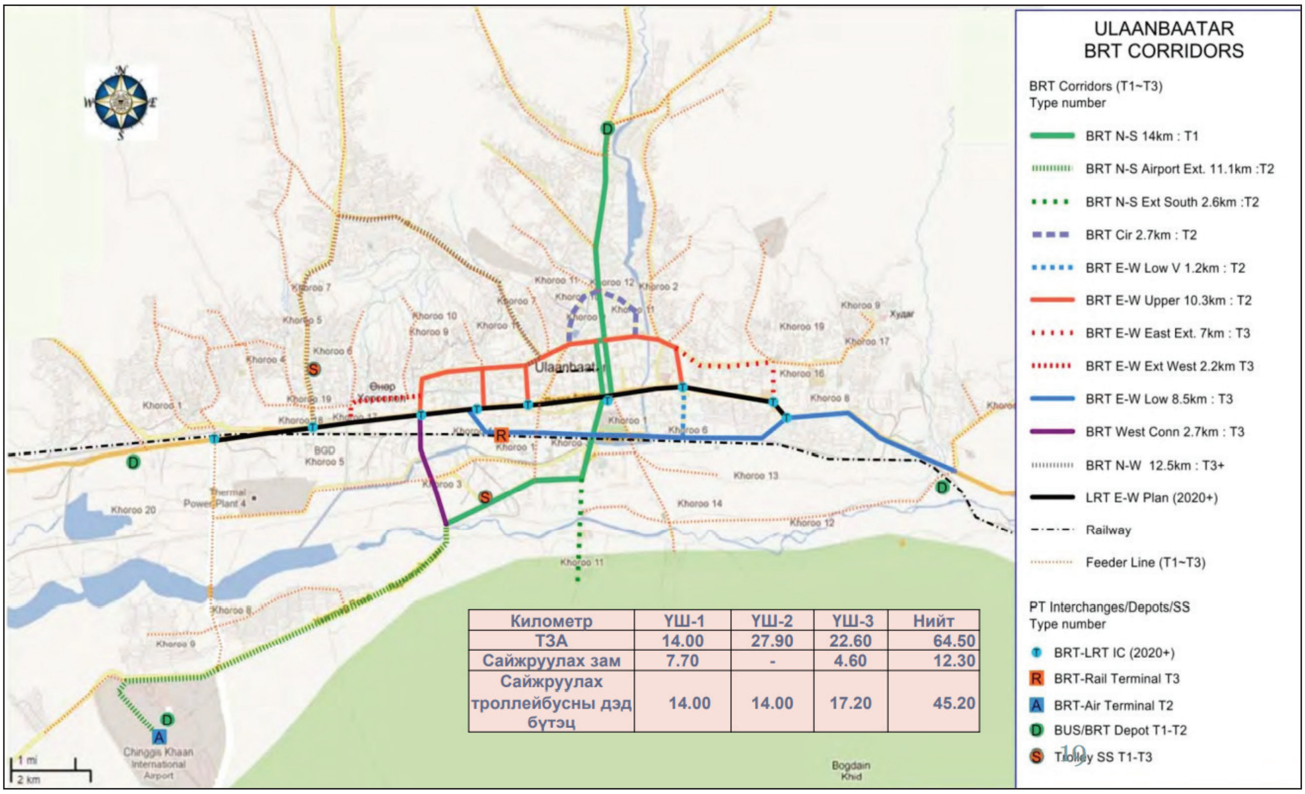

Figure 1. Ulaanbaatar's proposed BRT system. Note: LRT stands for "light rapid transit." Source: Tsevegjav (2014).

mickrobus services operate in some areas of the city, and a black market exists for the transportation of passengers in private cars, a practice common during the socialist period. Otherwise, Ulaanbaatar has few motorbikes or three-wheeled auto-rickshaw vehicles that provide cost-effective on-demand services in other Asian cities. Motorbikes, in particular, are not suitable vehicles given the difficult terrain, exceedingly cold winters, and the poor state of the roads encountered in many areas of the city. This means that difficulties in accessing public transport from the ger districts are likely to persist in spite of developments in the strategic transport network.

The above question of how access for non-car users can be improved is reflected upon later in this article, in Section 4. Following the methodology presented in Section 2, the article turns to two questions that guide the empirical research: Firstly, who are the car users of Ulaanbaatar's ger districts? Secondly, what access and mobility advantages do car users have over non-car users?

2. Methodology

The empirical research consisted of two rounds of a household travel survey undertaken in three ger district study sites across the north of the city, representing a range of access and mobility conditions as described by (Hamiduddin et al., 2021). The three study sites were as follows: the 18th Khoroo of Sukhbaatar District (SBD-18), the ninth Khoroo of Bayanzurkh District (BZD-9), and the 31st Khoroo of Songinokhairkhan District (SKD-31). The travel survey was advertised on the social media platform Facebook, using specific groups for each of the three communities. Participants were offered a 1,500 MNT ($0.5) phone voucher incentive to complete a questionnaire remotely by phone interview. Due to the Covid-19 pandemic, all surveys were undertaken remotely by phone, potentially limiting the range of participants to those who had internet access and membership in Facebook and to those willing to participate remotely. The nature of the survey itself, with its focus on work-related travel, overwhelmingly attracted responses from residents in employment. A total of 957 travel surveys were collected across the three study sites from two rounds of data collection. The first survey round was undertaken in March 2020 to capture winter travel patterns (n = 498), while the second data collection round took place in September 2020 to capture summertime patterns of life (n = 459). The survey was modified slightly for the second round of data collection to include household income. Broadly, the survey covered four different topic areas: (a) personal characteristics, including time spent at the address and car access; (b) travel patterns, including a breakdown of journey stages and travel times; (c) travel limitations, including neighbourhood barriers to access and mobility; and (d) neighbourhood life, including social activities and ride-sharing. Approximately 160 responses were obtained from each of the three sampling sites to provide an overall sample of approximately 480 responses from each survey round, giving an aggregated 95% confidence level with a 4.3% overall margin of error.

The overall population of each study site is given below in Table 1, together with district-level indicators from a recent UN and Swiss Development Agency study (International Organization for Migration, 2022a, 2022b, 2022c, 2022d) giving unemployment rates and the relative proportion of minors and elderly residents living across the overall district in order to provide a general characterisation of the demographic balance across each of the study sites. Table 1 also shows the proportion of respondents from the author's survey who have lived at their address for more than 10 years, indicating that more than 45% or more residents had lived at their address for more than 10 years across the three study sites, a threefold increase over the course of a decade (Caldieron & Miller, 2013). Long-term residents across the three districts are likely to have moved to the city during the waves of high rural-urban migration experienced earlier in this century (Xu et al., 2021), a process that was discouraged more recently through the imposition of official restrictions on newcomers to Ulaanbaatar between 2017 and 2020 (Schoening, 2020).

3. Findings

This section is structured in accordance with the three research questions, RQ1, RQ2, and RQ3.

3.1. The Car Users

Data from the second household travel survey (*n* = 459), which captured both household income and car ownership, shows a broadly positive correlation between income and car ownership overall (Table 2). However, the income categories selected for the survey are not sufficiently granular to reveal detailed sensitivity between household income and car ownership, particularly among lower-income households. In 2019, the average monthly salary in Ulaanbaatar was reportedly 966,000 MNT or $394, with the lowest regular salary recorded at 420,000 MNT or $120 (GogGo Mongolia, 2017). The survey findings show, surprisingly, that almost half of those deemed to be on a below-average household income of 1 million MNT or below owned a car. It is possible that a restructured survey with tighter income categories would reveal a greater variability of car ownership with income. Alternatively, however, this finding could also be attributed to significant variabilities in household income, with reported annual income representing the anticipated income of that year (during the Covid-19 pandemic), whereas earnings may have been substantially higher in previous years, perhaps when a vehicle was purchased outright. It is possible that for some households that are long-term residents of the city, vehicle ownership is a legacy of more prosperous times, particularly Mongolia's pre-2014 economic boom that fuelled growth across different economic sectors including construction. As discussed in the next section, car ownership not only improves access to employment opportunities across the city, including for those employed in manual trades but is also one of the few viable ways for urban households to reach family members that have remained in the countryside.

The survey data also showed that households that had more recently moved into their current address were less likely to be car owners (Table 3), with car ownership rates approximately 10% lower among households resident at their address for five years or fewer compared to those resident at their address for more than six years. Furthermore, the survey found that two-thirds of households who had been residents at their address for less than one year had moved directly to their address from the countryside. This adds weight to the evidence reported elsewhere in the literature (cf. Barbary, 2019; Mayer, 2015) that rural migrants tend to be less affluent than long-term urban residents, reflecting both the economic opportunities of the city,

Table 1. Population and employment characteristics of the three study sites.

Study site (Khoroo)	Study site (Khoroo) population	Unemployment rate	Population aged under 18 years of age	Population aged over 65 years of age	Respondents at current address for more than 10 years
SKD-31	7,200	30%	34%	5%	51%
BZD-9	14,400	33%	34%	6%	45%
SBD-18	10,100	33%	32%	7%	48%

Sources: Author's own survey data; International Organization for Migration (2022a, 2022b, 2022c).

Table 2. Income and car ownership.

Household income (MNT)	Proportion of respondents (%)	Car ownership level (%)
Higher (>2 million)	4	88
Upper medium (1.5–2 million)	12	60
Lower medium (1–1.5 million)	27	59
Lower (<1 million)	57	47

on the one hand, and the fluctuating environmental and economic conditions facing traditional pastoralists in the countryside, on the other (International Organization for Migration, 2022d). An increasingly prominent factor is the increasing amount of livestock lost to *dzud* conditions in the countryside—a very dry summer followed by an extremely harsh winter. These events appear to be increasing with climate change (Mayer, 2015). Field et al. (2012, p. 502) note in their IPCC report: "The most critical consequences of *dzud* are increased poverty and mass migration from rural to urban and from remote to central regions....Many migrants travel from Western Mongolia to the capital city Ulaanbaatar."

Mapping of the surveyed households showed a tendency for newer households to be located in the more peripheral areas of the ger districts and away from public transport routes and the mixed land uses and amenities associated with the more mature and centrally located areas. Newer households tended to be located towards the furthest reaches of the sub-district and away from transport routes, including the informal share-taxi services and were more likely to be without a car. Furthermore, the later introduction of a transport trial also revealed that some of the tracks that homes had been established along had not been surveyed and were therefore not represented officially on maps, with homes not registered on the Mongolian official addressing system. This posed a further and significant barrier to access to neighbourhood transport services including taxis, which are more difficult to obtain when residents do not possess an official home address.

3.2. Access and Mobility Compared

The travel survey asked households to describe the stages of their work commute. Despite the different built environment characteristics of the three survey neighbourhoods, the majority of all commutes by public transport began with a walk to the bus stop, an aggregated summary of findings of which are presented below in Table 4. The superior road infrastructure across SBD-18 has meant there has been more extensive development of bus routes through the neighbourhood and therefore almost an equal number of residents were able to catch the bus within a convenient distance from their homes as those who had to walk a considerable distance. Informal transport in the form of share taxis featured as the first journey stage for roughly a fifth of public transport commutes in the two sub-districts of SKD-31 and SBD-18, whereas in the outermost of the three neighbourhoods, BZD-9, three-quarters of commutes began with a walk, with no other mode of transport representing a significant share of the first journey stage.

Thereafter, for the second stage of the journey, the vast majority of commuters from each of the three sub-districts transferred onto a bus (Table 4). SKD-31 is a slight exception with significant proportions of commuters continuing their journey either on foot (15%) or by share taxi (19%). This pattern is almost certainly associated with the distribution of employment-intensive mixed land uses in the formally planned area of the city immediately adjacent to the southerly access point of SKD-31. Logically, therefore, a resident travelling by share-taxi from deep within the sub-district would travel to the drop-off point on the southern edge and continue by foot, while a resident living in close proximity to the southerly edge of the sub-district would walk to the share-taxi stand to take a vehicle to employment a greater distance away.

Residents were also asked about the cost of their work commute. The research found that the 500 MNT cost of a relatively short journey in an informal shared taxi tended to be the same price as a single ticket for a longer bus trip. Journeys by share taxi are therefore expensive as a relative share of the overall commute. However, as Table 5 shows, it is those in the lowest income bracket that represent the greater proportion of share-taxi users (11%). Many share-taxi users combine a

Table 3. Duration at current address and car ownership.

Years at address	Moved from the countryside (%)	Car ownership (%)
<1 year	66	46
1–5 years	50	47
6–10 years	51	57
>10 years	44	56

Table 4. Showing journey-to-work modal share averaged across the three study sites.

First journey stage		Second journey stage	
Own car	18%	Own car	—
Taxi	6%	Taxi	8%
Walk	56%	Walk	10%
Bus	18%	Bus	69%
Mickrobus	1%	Mickrobus	7%
Other	—	Other	4%

Table 5. Income and informal taxi ridership.

Income (MNT)	Informal taxi ridership (%)
<1 million	11
1–1.5 million	6
1.5–2 million	4
>2 million	0

first-stage neighbourhood journey by share taxi with a longer journey by bus, at an overall cost of 1,000 MNT per commute journey or 40,000 MNT per month for a resident making the commute in both directions. With the addition of other travel costs, such as for grocery shopping, accessing health facilities, education, and socialising, residents on a low monthly wage of 420,000 MNT would spend over 10% of their income on travel—a threshold associated with "transport poverty" in Global North countries such as the UK (Lucas, 2012).

A closer analysis of the journey to work by public transport (Table 6) shows that lower-income residents have slightly longer overall journey times compared to those on higher incomes, generated both by the longer walking distances of the lowest-income residents and a slightly longer onward second-stage bus connection, although Table 6 also illustrates the extremely long overall journey to work times experienced by all income groups because of Ulaanbaatar's chronic traffic congestion. Of those surveyed in the lowest income category (500,000–1 million MNT) and who began their journey to work by walking, approximately one-third (34%) reported a walk of longer than 15 minutes to access public transport, compared to 24% among those in the highest income category (more than 2 million MNT). As none of the highest-income residents uses share-taxis to access bus services, the implication from the data shown in Table 6 is that the small number of more affluent residents (n = 9 or 52% of most affluent residents) who use public transport for the work commute do so both because the bus stop is within easy reach and that the transport services themselves offer straightforward access. To underline this point, almost all (8 out of 9) of the most affluent residents owned a car within their household and the greater majority (7 out of 9) stated that they had access to their car whenever they needed it.

Higher levels of informal transport ridership among lower-income residents can be explained both by the tendency for these households to live outside of the walkable catchment for public transport and for car ownership to be lower. The spatial pattern can be observed below in relation to sub-districts SKB-31 and BZD-9 (Figure 2), where red indicates the location of households belonging to the lowest income category and green for those in the two highest income categories. Public transport stops are indicated in orange and the yellow line in SKB-31 indicates the share-taxi route. The maps show proportionately few higher income residents living in the furthest reaches of each sub-district. Expenditure on share taxis, therefore, appears to be an outcome of residential location, itself the product of underpinning economic and social factors discussed earlier that also have a bearing on car ownership.

The spatial distribution of commuting data (Figure 3) does not appear to show pronounced differences in the geographical distribution of employment between car drivers and public transport users overall. Two notable features of the data include, firstly, the lower level of car-based commuting into central Ulaanbaatar from the three neighbourhood study sites and, secondly, a tendency for more car-based commuting to employment localities in the south of the city away from the main transport routes, particularly during the summer months (Figure 3, bottom). Lower levels of car-based commuting into the city centre likely reflect the overall modal share patterns shown earlier in Table 4, and a reluctance on the part of a significant proportion of car owners to commute by car—a product of Ulaanbaatar's poor driving conditions and shortage of available parking in the downtown. The summertime distribution of employment, shown in the bottom part of Figure 3, supports similar observations made in a different study by Hamiduddin et al. (2021), which attributed these peripheral localities with employment in the construction of new residential developments that takes place largely during the warmer months of the year. Indeed, the higher car use found during the summer months likely reflects seasonal employment patterns. One of the most

Table 6. Income and journey-to-work travel.

Income (MNT)	First stage journey time: Min (n)		Second stage (bus) journey time: Min (n)	Overall journey time envelope (min)
	Walk	Share-taxi		
<1 million	12 (172)	10 (29)	45 (123)	**55–57**
1–1.5 million	11 (78)	10 (7)	45 (66)	**55–56**
1.5–2 million	9 (35)	20* (2)	41 (28)	**50–70***
>2 million	10 (11)	— (0)	43 (9)	**53**

Note: * Should be treated with caution due to the low response rate.

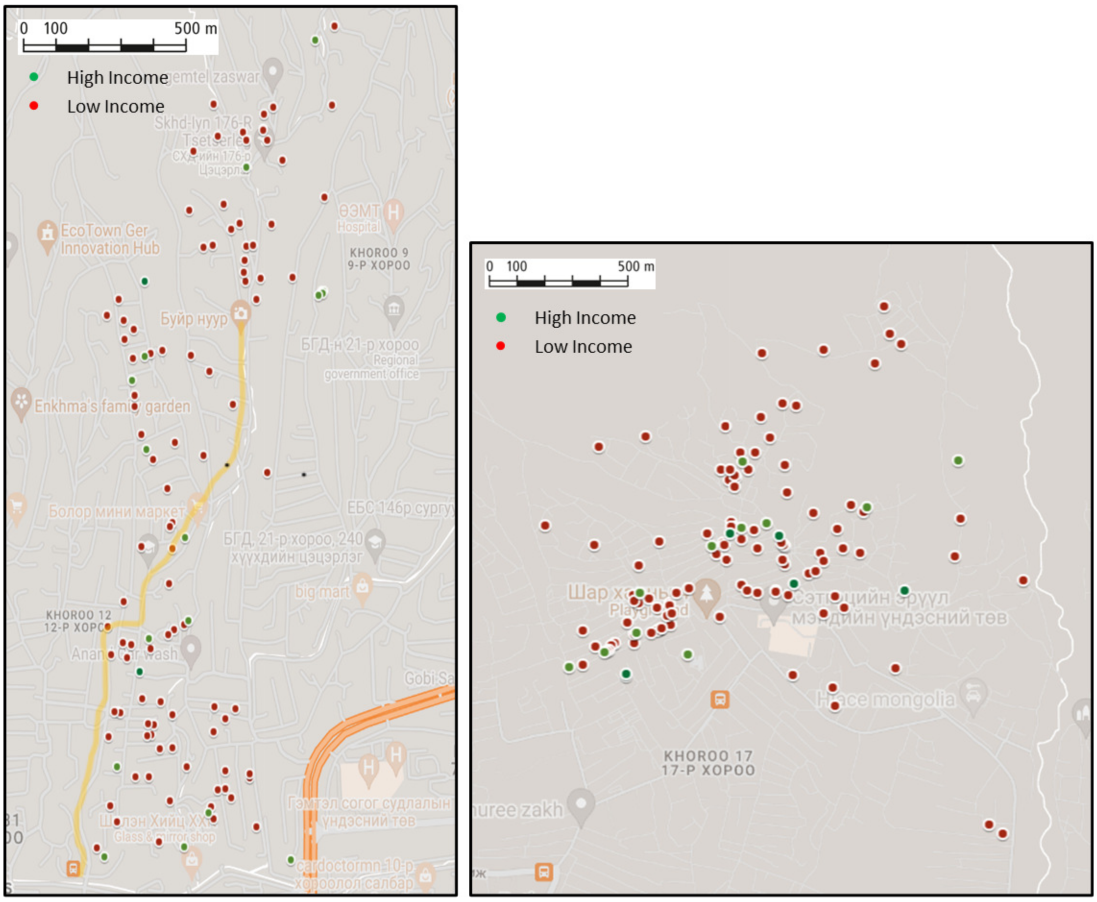

Figure 2. Disposition of low- and high-income households in SKD-31 (left) and BZD-9 (right).

significant differences between commuting by car and by public transport is in the very different journey times between the commutes.

The survey data revealed rather surprising differences between patterns of household car ownership and individual access and actual use for work commutes and other regular travel as illustrated by grocery shopping (Table 7). Just under half of households (47%) surveyed during the two survey campaigns reported that their household owned a car and, within those car-owning households, the greater majority (87%) of survey respondents reported that they had unrestricted access to the vehicle. However, fewer than half of respondents (44%) used the car that they claimed access to for the journey to work—an aggregate figure between the two survey data sets that showed only marginal differences between winter (47%) and summer (42%). The findings appear to support the earlier finding, in relation to Table 4, that a proportion of car owners use public transport for the work commute when there is relatively convenient access to public transport from the home and when transport services stop close to the workplace. In other words, household car ownership and access are not automatic predictors of car use for the journey to work, despite the superior convenience and comfort of the car, particularly during the harsh Mongolian winter. It is possible that specific factors such as congestion and difficulties in finding car parking close to the workplace may also present barriers to car use. However, such factors do not adequately explain the similar shortfall in car use for grocery shopping (53%) for those with unrestricted car access—an aspect of life that usually attracts higher levels of car use for those with access to a vehicle (Handy & Clifton, 2001). Reading across these findings (Table 7), it is more likely that car use is more generally constrained by broader factors such as vehicle operating costs in relation to household income and the utility benefits of using public transport, to read or socialise.

The data presented above in Table 7 provides some grounds for optimism for policymakers looking to constrain future car use in the city. It signals that half of car owners—the majority of whom are higher earners—are prepared to forgo using the car for regular journeys to work and for grocery shopping provided that there are convenient and affordable public transport alternatives. This condition presents very significant policy challenges that will be explored in Section 4 and not least because 82% of all survey respondents agreed that car ownership was important "for improving daily quality of life in Ulaanbaatar." However, existing car owners appeared much more emphatic in their agreement (93%) compared to non-car-owning households (74%). The data from the three study ger districts, therefore, indicates that approximately half of the car-owning households do

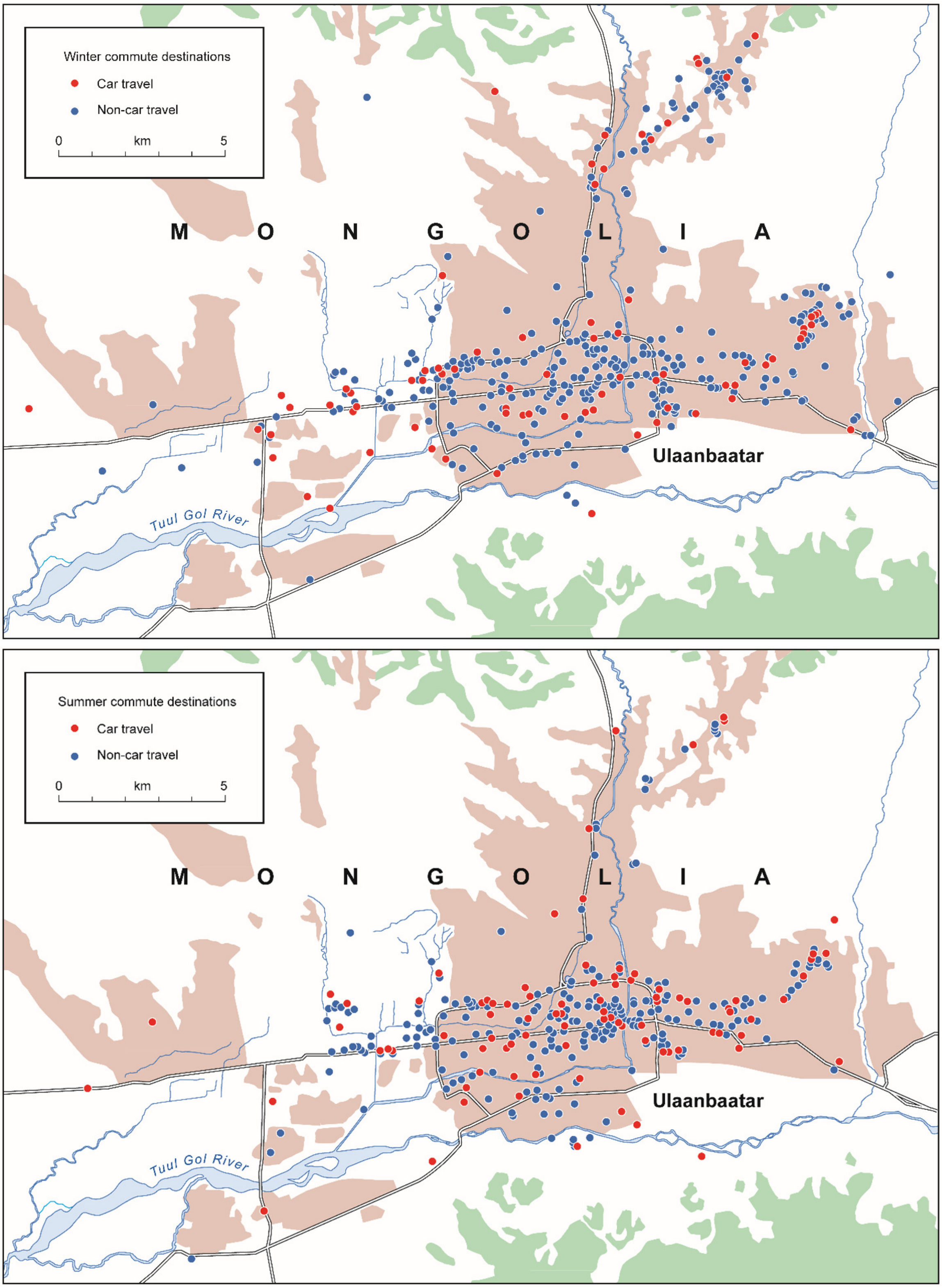

Figure 3. Commuting geography of car users in winter (top) and summer (bottom). Source: Courtesy of Sandra Mather based on author's survey data.

Table 7. Car ownership: Access and use.

Survey sample	Household car ownership	Unrestricted car access for commuting	Car for work commute	Car for grocery shopping
n = 957	47% (*n* = 453)	87% (*n* = 395)	44% (*n* = 174)	53% (*n* = 211)

not use their car for two of the most significant aspects of regular travel within the city and that a substantial minority of residents do not necessarily recognise car ownership as being important for improving their quality of life. These are headline findings that require significant exploration and unpacking to determine; however, they at least show some promise as areas for future policy to limit further rises in motorisation across the city.

4. Concluding Discussion

At the present time, and in common with many cities across the Global South, Ulaanbaatar has a public transport system that is remote for many residents living in the city's peripheral ger districts. The evidence presented earlier in this article shows that the least affluent residents living in the more distant areas of the ger districts experience higher levels of travel disadvantage because of longer walking distances or because of the need to take disproportionately expensive taxis to reach public transport services. Thus, although the city plans to upgrade its strategic public transport network through the introduction of a BRT system, existing proposals show only limited plans to create feeder services into the ger districts. In view of the myriad challenges that creating new transport infrastructure in the ger districts would entail, including terrain, land ownership, urban structure, and the overall scale of these areas in relation to the formally planned city, these limited plans might be considered realistic in terms of achievability. Yet, the plans also mean that residents located in more accessible areas of the ger districts closer to main roads and the transport services carried on them, are likely to experience improved access to the city. As the data shows, these households are likely to be more affluent with the highest levels of car ownership—even if only about half of car owners currently use their vehicle for the work commute. Therefore, although improvements to public transport may encourage more affluent, car-owning residents to keep their vehicles at home during the working week, representing a significant policy success in view of the city's acute air pollution and congestion problems, poorer residents will continue to experience mobility disadvantage that might encourage higher car ownership among non-car owning households as economic uplift and/or available credit allows.

There appears to be both a gap in existing policy and practical action in addressing access and mobility disadvantages among Ulaanbaatar's poorest and geographically peripheral households. To address the final research question regarding measures that could improve access and mobility amongst the most disadvantaged groups, access and mobility at the periphery presents a clear and present problem that needs urgent address if residents are to improve their livelihoods through access to the opportunities of the city, employers are able to access the widest possible labour market and to suppress latent motorisation and automobile use. It is evident from delays to the implementation of the BRT system that have now stretched for a decade, that urban authorities have limited capacity to act—even with the additional resources provided by external bodies such as the Asian Development Bank and the World Bank. Community-led initiatives provide an alternative point of approach, where there are sufficiently well-developed and supportive community networks and community leaders willing to organise activities or support community-led initiatives. Adilbish et al. (2022) demonstrate how citizen-led activities can strengthen social relations within ger district communities in ways that improve community resilience in different dimensions.

There are some examples of access- and mobility-focused "bottom-up" initiatives in Ulaanbaatar. For example, in SKD-31, the "C176" neighbourhood taxi scheme has brought together a number of taxi drivers who have set up a cooperative fund to support drivers in maintaining passenger transport services across the different areas of the district (see Hamiduddin et al., 2021). The cooperative fund effectively subsidises taxi services to outlying areas in order to maintain flat fares that are accessible for low-income households. Another initiative that aims to improve resident access to essential services within the same district focuses on the delivery of domestic solid fuel to households located away from fuel supply depots. This delivery trial follows the recent ban on the use of coal across Ulaanbaatar in a bid to improve air quality, but which also made domestic fuel less accessible to many households because it is available from a smaller number of state-approved distributors and it is retailed in 25 kg sacks that present considerable logistical difficulties to households without access to a car or alternative transport. The clean fuel trial aims to improve cost-effective access to domestic fuel for non-car-owning households by aggregating orders to create cost-effective wintertime delivery runs, using small flatbed vehicles used in the construction industry during the summer months to access areas that larger vehicles would struggle to negotiate. A limited trial conducted in February 2022 delivered 6.4 tons of clean fuel to 87 households over a two-week period and a more extended trial undertaken during the winter of 2022–2023 delivered a further 31 tons of the fuel.

The two examples above illustrate how community-based activities have begun to address critical aspects of ger district access and mobility. However, the further growth of mobility services that provide reliable access to the city's public transport network may be constrained by the existing range of vehicles available and how they are managed by policy managers. A striking feature of Ulaanbaatar in comparison with other middle- and lower-income cities is the rather limited range of vehicles in operation to provide a wide range of different transport services. Ulaanbaatar's transportation system is currently dominated by just two types of vehicles—buses and automobiles—with smaller mickrobuses providing important niche local transport operations in specific areas of the city. The city transport authority has recently sought to restrict mickrobus operations in order to limit congestion at main city bus stops. However, other Global South cities such as Dar-es-Salaam demonstrate ways to accommodate local feeder services operated by smaller vehicles alongside trunk bus routes, by providing dedicated facilities in close vicinity to bus stops. This approach would help grow mickrobus operations into effective and integrated feeder services for the ger districts, in support of main bus routes. Due consideration could also be given to the operation of smaller, auto-rickshaw-style vehicles that provide ubiquitous demand-responsive transport services across cities of the Global South (Cervero & Golub, 2011; Itokawa, 2020) and that are able to cope with the dirt roads and steep terrain of informal settlement areas. Being relatively inexpensive to operate, they could also be well-suited to the relatively "thin" transport conditions presented by the low-density built form of the ger districts. This approach would be less radical or costly than current plans to build a 6 km cable car line to connect the centre of Ulaanbaatar with Bayankhushuu district ("Are cable cars the future of transport in UB," 2020). Although Ulaanbaatar is well-known for its harsh winter climate, which acts as a major constraint on the utility of certain modes including motorbikes, bikes, and other forms of micromobility during the wintertime, it is worth noting that auto-rickshaw vehicles have operated for a long time in regions such as Kashmir and Ladakh, where winter conditions are comparable.

To conclude, although the private car has not yet come to dominate journeys from ger districts into the centre of Ulaanbaatar, despite relatively high levels of reported household car ownership, this is likely to reflect a combination of factors including chronic road congestion, the lack of available car parking, and the relative cost of motoring. The separation of car ownership from actual car use can be viewed positively in so far as it is the outcome that policymakers globally are attempting to achieve through policies to limit or reduce infrastructure for private car travel, or to increase the cost of motoring. Less positively, Ulaanbaatar's situation also means that any alteration to the current balance of private car infrastructure and cost of motoring is likely simply to result in gridlock but with a greater number of vehicles using the city's roads. Ulaanbaatar's planned BRT and feeder system will undoubtedly help most residents to travel around the city more quickly, but the existing proposals also carry the risk that communities living in peripheral areas away from bus routes and feeder services may experience only marginal benefits and that without the "great leveller" of traffic congestion, the access and mobility gap between core and periphery will widen. Given the scale of Ulaanbaatar's transport challenges and the relative scale of the ger districts in proportion to the city's population, community-led initiatives may provide an important means for connecting residents living on the periphery to the core functions of the city.

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Conflict of Interests

The author declares no conflict of interests.

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Article

Zero-Car Households: Urban, Single, and Low-Income?

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Abstract

This article unravels, by employing two binary logistic regressions, the socio-economic profiles of zero-car households in Flanders (Belgium) and sheds light on their residential environment. The employed dataset contains information regarding the socio-economic status and car ownership of all individuals with a home address in Flanders. Furthermore, the study explores the proportion and size of voluntarily car-free and car-less households due to constraints within the Flemish population. It does so by classifying zero-car households based on a spatial typology and the income decile these households belong to. Results indicate that zero-car households are overrepresented at the bottom of the income distribution and are overwhelmingly single. Children's presence contributes to the likeliness that a household owns a car. The spatial typology (urbanised, suburban, or rural) and the presence of public transport are minor but remain significant contributors. The main contribution of this article is that it highlights that despite the evidence that zero-car households are strongly present in urban areas, the share of zero-car households living in remote areas may not be underestimated. For the total population in Flanders, 5.47% of households may face problems due to their residential location and lack of a car, which comes on top of dealing with modest or low household budgets. Almost 37% of the zero-car population lives in an urbanised area and has a low income. This corresponds with 8.4% of the Flemish population. This group likely experiences a latent demand for car ownership. The households we can confidently identify as car-free, deliberately and voluntarily living without a car, are a minority group and account for approximately 5% of the Flemish population. The article concludes with the notion that involuntarily carlessness can be considered a proxy for vulnerability. However, urban planning centred around proximity, accompanied by housing policy that benefits low-income groups, can act as a buffer against transport vulnerability.

Keywords

car ownership; Flanders; urban planning; zero-car households

Issue

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1. Introduction and Literature Review

Many scholars amply demonstrated that navigating in a car-dependent society without access to a car can be challenging. Hence, every household comes to a point where they negotiate on purchasing a car. The outcome of that negotiation bears consequences: it matters whether households forego buying a car due to constraints, for instance financial, or they do so voluntarily, by choice. Hess (2022) found that voluntarily getting rid of a car can increase well-being, but, at least in the short run, enforced carless living can reduce it. Mitra and Saphores (2020) also registered an impact on well-being, as zero-car households are less mobile, which may lead to isolation. Moreover, Morris et al. (2020) linked carlessness to a substantial "activity penalty" mainly in but not restricted to rural areas. Without a car, leisure activities are more associated with friction and inconvenience, even for families who voluntarily live without a car (Baumgartner et al., 2022; Lagrell et al., 2018). Furthermore, a meta-analysis established that car ownership significantly increases individual employment probabilities (Bastiaanssen et al., 2020). Against this background, it is no surprise that a limited household budget, rather than choice, steers car ownership (Brown, 2017). However, these findings contrast sharply with a current circulating discourse that associates the relinquishment of the ownership of a private vehicle with feelings of freedom. Media interview members of zero-car households from Flanders (Belgium) consider car-free living a goal to pursue and easy to reach, as these quotes illustrate: "In my view, the luxury and freedom of the car is overestimated" (De Roo, 2022); "Our children prefer the bike over the car" (Poppelmonde, 2021); "Without a car? In our view, it is peanuts. Just change your mindset" (Lanssens, 2018). A recent campaign in Flanders called "thirty lesser car days" recruited with arguments such as "embarking on an adventure" and "beneficial for budget and health." Participants were complimented as instigators of change (Buggenhout et al., 2022).

Hence, it is clear that zero-car households are not a homogeneous group. In order to stress their heterogeneity, Brown (2017) suggested a distinction between car-less households, due to constraints, vs. households that are car-free by choice. She argued that this distinction is more than semantic novelty. Indeed, the diversity among zero-car households has important policy implications for urban planning.

In a European context, higher education correlates with being voluntarily car-free (Kühne et al., 2018). Similarly, Baehler and Rérat (2020) note an overrepresentation of highly educated families in German and Swiss housing developments where residents consciously commit to living without a car. Car-free households are clear-cut examples of residential self-selection, as they can self-select themselves into dense urban neighbourhoods, well connected with public transport (Baehler & Rérat, 2020; Mitra & Saphores, 2020). Paijmans and Pojani (2021) concluded that voluntary carlessness is an educated middle-class phenomenon for people willing to challenge automobility as the societal norm.

A completely different picture emerges when we draw attention to the involuntarily car-less group. Mattioli (2014) demonstrated that zero-car households in peripheral and rural areas are often characterised by a marginal socio-demographic status. Car-less households more often have lower income and education levels (Karjalainen et al., 2021; Mitra & Saphores, 2020) and, in that sense, are a vulnerable group, especially when combined with residential locations in remote areas, as this strongly reduces accessibility levels.

Blumenberg et al. (2020) studied the issue of latent demand for car ownership in the US and found that this demand mainly occurs at the bottom end of the income distribution. In the same vein, in Europe, "not being able to afford a car" is a major reason for not having one (Dargay et al., 2008, p. 48).

Therefore, it is necessary to further unravel the socio-economic profiles of zero-car households and shed light on their residential environment. Doing so will inform us about the levels of accessibility zero-car households can enjoy. Also, following the call of Brown (2017), I aim to explore the proportion and size of the voluntarily and involuntarily zero-car households in the Flemish population, as currently, far more attention flows to the group that has consciously chosen to live without the private ownership of a car. Is that attention commensurate with their actual share?

These research goals translate into three research questions:

(1) What key socio-economic and spatial variables contribute to car ownership in Flanders?

(2) What is the share of car-less (by constraint) and car-free (by choice) households in Flanders?

(3) Do these households and the members of these households differ in socio-economic background?

Regarding the first research question, our knowledge is quite extensive already. Zero-car households are more likely to reside in dense urban neighbourhoods, well-connected with public transport access (Cao et al., 2007; Clark et al., 2016; Van Acker & Witlox, 2010). However, for the Helsinki Metropolitan Area, Karjalainen et al. (2021) found that this was mainly the case for affluent car-free households. Less affluent households reside in more car-dependent locations or accessible yet expensive areas, which might pressure household budgets. Kühne et al. (2018) revealed that employment density and public transport had a higher impact on the presence of car-free households in Germany than in California. For the Netherlands, Oakil et al. (2016) found a more substantial influence of the built environment on car ownership for young couples than for young families or singles. Concerning socio-demographic characteristics, research points in the same direction. Income, the number of household members and the presence of children emerge as the most important predictive variables (see, for instance, Baehler & Rérat, 2020; Clark et al., 2016; Kühne et al., 2018; Mitra & Saphores, 2020; Nolan, 2010). Having young children raises additional travel needs. A car is considered the best option, irrespective of where these families live (Oakil et al., 2016). Regarding individual characteristics, ageing correlates with a decline in car ownership. This is due to retirement and the accompanying changes in travel patterns, loss of income, or the deterioration of cognitive and psychomotor skills (Clark et al., 2016; Dargay et al., 2008; McNamara et al., 2013). Single pensioners and students are most likely to be car-less (Karjalainen et al., 2021). Dargay et al. (2008) and Oakil et al. (2018) found that car ownership is gendered: Women own a car less often than men.

Concerning the second and third research questions, only a handful of studies estimate the proportion of car-free and car-less households. Haefeli and Arnold (2015) found for Switzerland that the proportion of car-free young urban residents with high education and income doubled between 1994 and 2010. Brown (2017) found that within zero-car households 79% are involuntarily car-less in California. For Europe, we largely remain in the dark. Hence, Karjalainen et al. (2021) argued that zero-car households require increased attention, especially regarding choice or constraint. This study is an attempt to increase our knowledge on the subject. I particularly focus on the size and proportion of zero-car households by choice on the one hand and by the constraints on the other hand, and their specific socio-economic characteristics.

2. Study Area and Methodology

The research area is the Flemish Region, part of Belgium. Belgium is a federal state, divided into three regions: the Flemish Region (Flanders), the Walloon Region (Wallonia), and the Brussels Capital Region (Figure 1). The Brussels Capital Region, which is the largest agglomeration in Belgium with over one million inhabitants, is geographically situated in the centre of Flanders, although it is not administratively part of it. For a study of car ownership in Brussels, I refer to Ermans and Henry (2022). The employed dataset for this study was provided by Statbel, the Belgian Office for Statistics. It contains information regarding the socio-economic status (gender, age, employment, education, household composition, and statistical ward of the residence) and car ownership of all individuals with a home address in Flanders (for the study area: individuals >18 years old *n* = 5,228,915 and households *n* = 2,769,599) for the year 2018.

To investigate the impact of built environment characteristics on car ownership, I complemented the data from Statbel with those collected in the Flemish *Spatial Report*, which describes and analyses the current state of affairs of the land use and the built environment in the Flemish Region. The report distinguishes three typologies of land use: urbanised, suburban, and rural (see Figure 2). The distinction resulted from an analysis by which three main variables were taken into account: population density, the density of job accessibility, and the share of land taken by development, which is the amount of land dedicated to buildings and infrastructures (Pisman et al., 2018). The distinction is made on the level of statistical wards. The urbanised part of the Flemish Region is characterized by a high use of space (≥32.5%, which is above the average in the Flemish Region), a population density of a minimum of 1,185 inhabitants per square kilometre or an employment rate of more than 1014 employees per square kilometre, and this within a cluster of at least 15,000 inhabitants. Urbanised areas mainly include city centres and employment sites in the urban fringe. The suburban part of Flanders is characterized by a high use of space (≥32.5%) but a low employment density. Suburban clusters are situated adjacent to the urbanised areas, typically consisting of allotments with residences and villas on substantial parcels or expanded villages that gradually merged with the urban fringe. The rural part of the Flemish Region includes one of the following features: (a) a use of space below 32.5%; (b) a use of space ≥32.5% and a high employment density but not situated adjacent to an urban cluster of 15,000 residents; and (c) a use of space that is above average, a low activity rate and not adjacent to an urban part. These areas consist mainly of scattered land use and centres of villages or minor cities that do not reach the threshold of 15,000 inhabitants (Pisman et al., 2018).

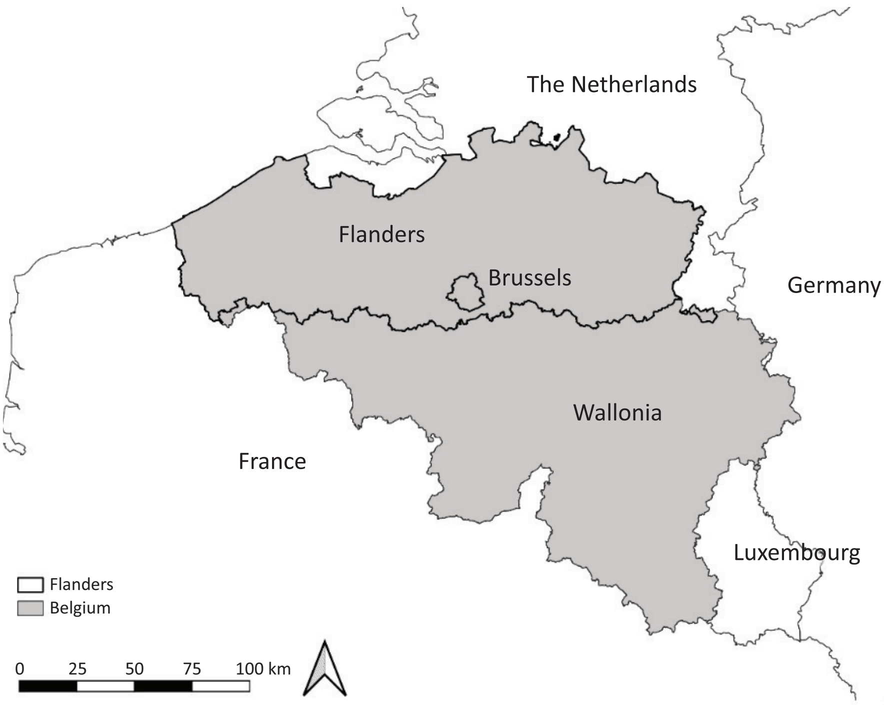

Figure 1. Flanders situated in Belgium.

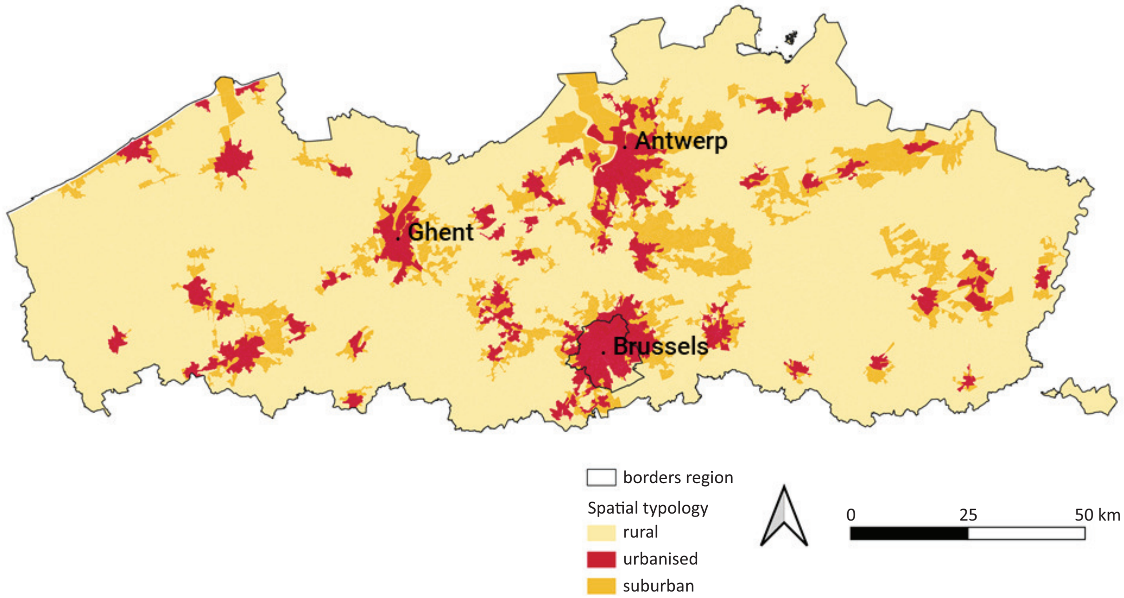

Figure 2. Spatial typology of Flanders. Source: Based on Pisman et al. (2018).

This spatial typology does not contain information on accessibility by public transport in the Flemish Region. I collected this from a study by Verachtert et al. (2016), which methodology was based on Spatial Network Analysis for Multi-Modal Urban Transport Systems (Curtis & Scheurer, 2010). Spatial Network Analysis for Multi-Modal Urban Transport Systems analyses the accessibility characteristics of public transport systems based on five indicators: closeness centrality, degree centrality, contour catchment, nodal betweenness centrality, and nodal connectivity. Verachtert et al. (2016) added a sixth variable—slow traffic infrastructure density—which refers to infrastructure for pedestrians and cyclists. In this article, I use these six indicators' aggregate variables, summarised into a node value. The value ranges from one to eight, whereas one implies minimal access by public transport, and eight refers to high access by public transport (train stations including international stops, ample opportunities to transfer to local train network and bus/tram, and a fine-grained network for pedestrians and cyclists; Figure 3).

I first describe the method to answer my first research question: what are the pivotal socio-economic and spatial variables predicting car ownership? As the decision to purchase a car is expected to be taken at the household level, I primarily use the household as a unit of analysis. However, also individual characteristics play a role in the decision-making process of a household. Therefore, the second part of the analysis takes these into account. My main interest is in the variables contributing to households having zero cars, not in which ones contribute to owning two or multiple cars. Dargay and Hanly (2007) concluded that households switch relatively easily between one and two cars but rarely between one and zero. Moreover, motivations to purchase a second car can deviate strongly from motivations to buy a first one (Clark, 2009; Witte et al., 2022). Therefore, I ran two binary logistic regressions, one with the household as the research unit, and one with the individual as the research unit. The presence of at least one car (yes/no) functions as a dependent variable. I do not distinguish between a car purchased by the household or a company car provided by an employer. The company car is attributed to the address of the household that can benefit from it. A company car is defined here as a car made available to an employee by his/her company that may also be used for private purposes. In Belgium, company cars are used by employers as a partly tax-exempt component of the remuneration package companies offer to their staff and are therefore often called "salary car" (May et al., 2019). Statbel identified the households that can benefit from a company car via the tax declaration ("benefit of all kinds"). However, approximately 25% of the company cars (n = 150,000), which refers to 3% of all cars in Belgium, could not be assigned to a household. This is because the benefit of all kinds was not always specified (see also Ermans & Henry, 2022). This is important when interpreting results, as this means that the share of zero-car households is slightly lower than the results will suggest.

For the analysis of the level of the household, I included the following independent variables: household composition (categorical variable), income decile (ordinal variable), spatial typology (categorical variable), and node value (ordinal variable). I tested for potential multicollinearity between the variables. Multicollinearity occurs when two or more predictors in the model are correlated and provide redundant information about the response. Multicollinearity was measured by variance inflation factors (VIF) and tolerance. If the VIF value exceeds 4.0, or by tolerance is less than 0.2, then there is a problem with multicollinearity (Midi et al., 2010).

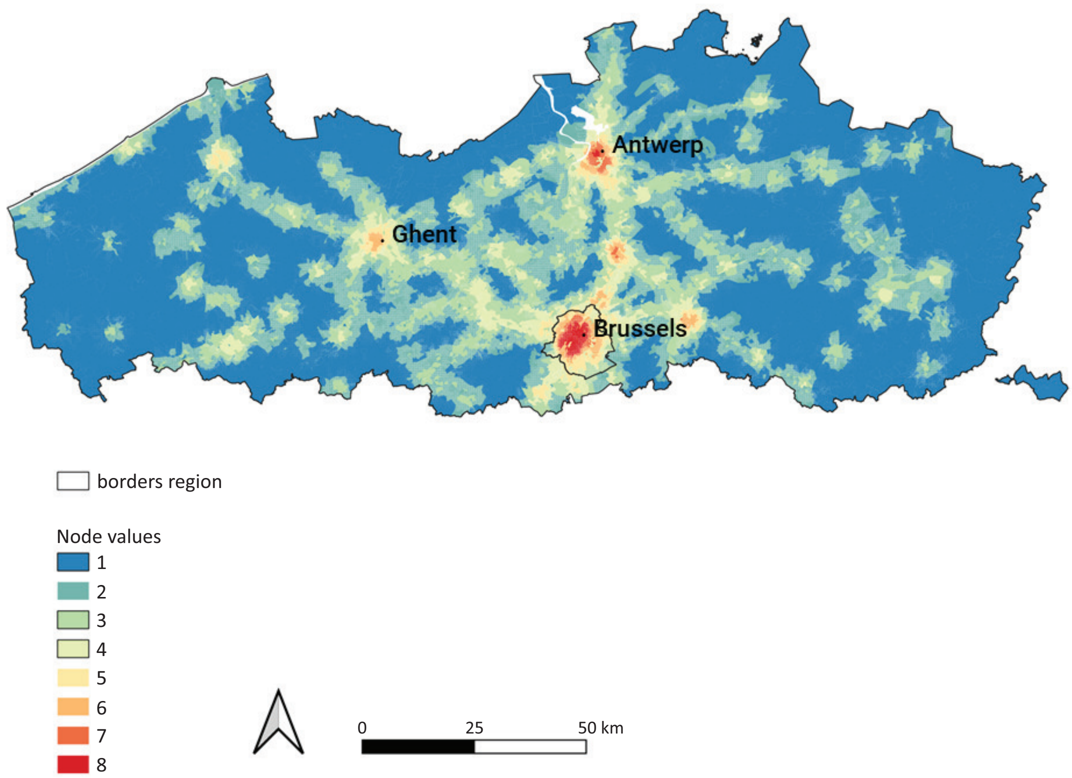

Figure 3. Node value for the Flemish Region. Source: Based on Verachtert et al. (2016).

VIF values ranged from 1.030 to 1.100, and tolerance from 0.909 to 0.971, safely below the threshold.

Although the household is the level on which the decision to purchase a car is taken, individual socio-economic characteristics do play a role, as the introductory literature review indicated. Therefore, I also ran an analysis on individual characteristics, and additionally assessed for the impact of age (categorical variable), education (categorical variable), and gender (categorical variable). Concerning multicollinearity tests, VIF values ranged from 1.070 to 1.217 and tolerance from 0.822 to 0.890.

To answer the second and third research questions—what is the share of voluntarily and involuntarily zero-car households in the study area and how do they differ socio-economically?—I build on the theoretical and empirical contributions of Brown (2017) and Karjalainen et al. (2021) and combine these with the results of the regression. The central assumption is that zero-car households in rural and suburban areas in the lowest income deciles are car-less by constraint. High-income households residing in an urbanised area are expected to be voluntarily car-free. I elaborate more on assumptions and methods in Section 4. All analyses were conducted using SPSS 28.

3. Results: Key Spatial and Socio-Economic Variables

3.1. Descriptive Analysis

Household motorisation rates in Belgium are slightly below the European average (506 vs. 560 per 1,000 inhabitants) (ACEA, 2022). 22.8% of Flemish households do not own a car. However, the share of zero-car households is distributed unequally. Figure 4 visualises a geographical imbalance. The figure highlights the locations of the most prominent Flemish cities: Ghent and Antwerp. For Brussels, not included in the study, the percentage of zero-car households amounts to 51.9%.

Figure 5 and Figure 6 illustrate the unequal distribution of car ownership along income lines, organised based on income deciles (whereas income decile one refers to the 10% of households with the lowest income in the population, and income decile 10 to the 10% with the highest income). The figures distinguish between one adult and two adults (or more) households. We observe that the lower the income, the less likely that a household will possess a car. At the upper half of the income distribution, zero-car households are a rare phenomenon. This trend applies to both one-adult and two-adult households. Higher incomes can benefit more often from a company car. For decile 10, more than 35% of households have a company car. For the deciles below six, this percentage drops far below five. If we compare both graphs, we note that the percentage of zero-car single households is higher in all income groups compared to the two adult households. This is a particular observation, as this indicates that, regardless of income, households with more than one adult will quickly proceed to purchase a car than a one-adult household with a similar income level.

Figure 7 below compares different household compositions in relation to car ownership. More than half

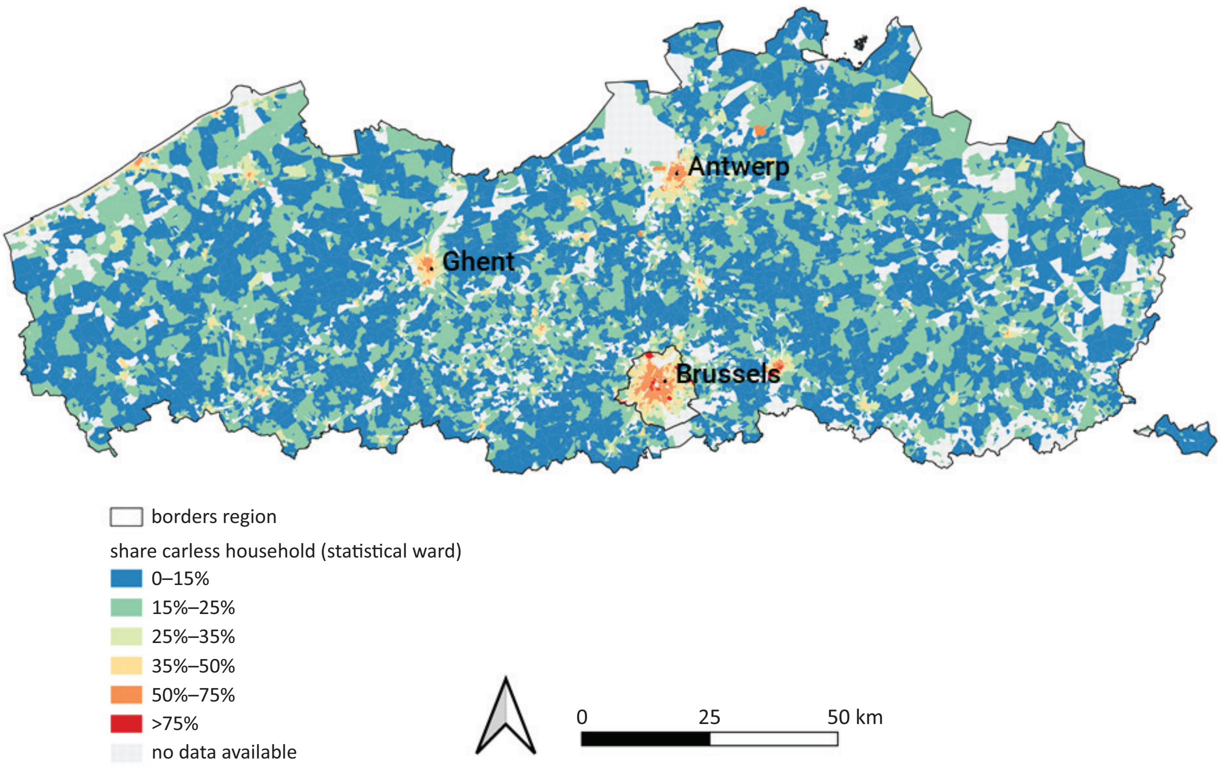

Figure 4. Geographical distribution of zero-car households in Flanders and Brussels.

of the singles are zero-car households—which was to be expected considering the previous graphs—and families with at least two adults are underrepresented in the zero-car group. The figure also makes clear that the presence of children affects car ownership levels.

3.2. Results of Binary Logistic Regression at the Level of the Household

The regression reports on the odds of a household having no car divided by the odds of a household having at

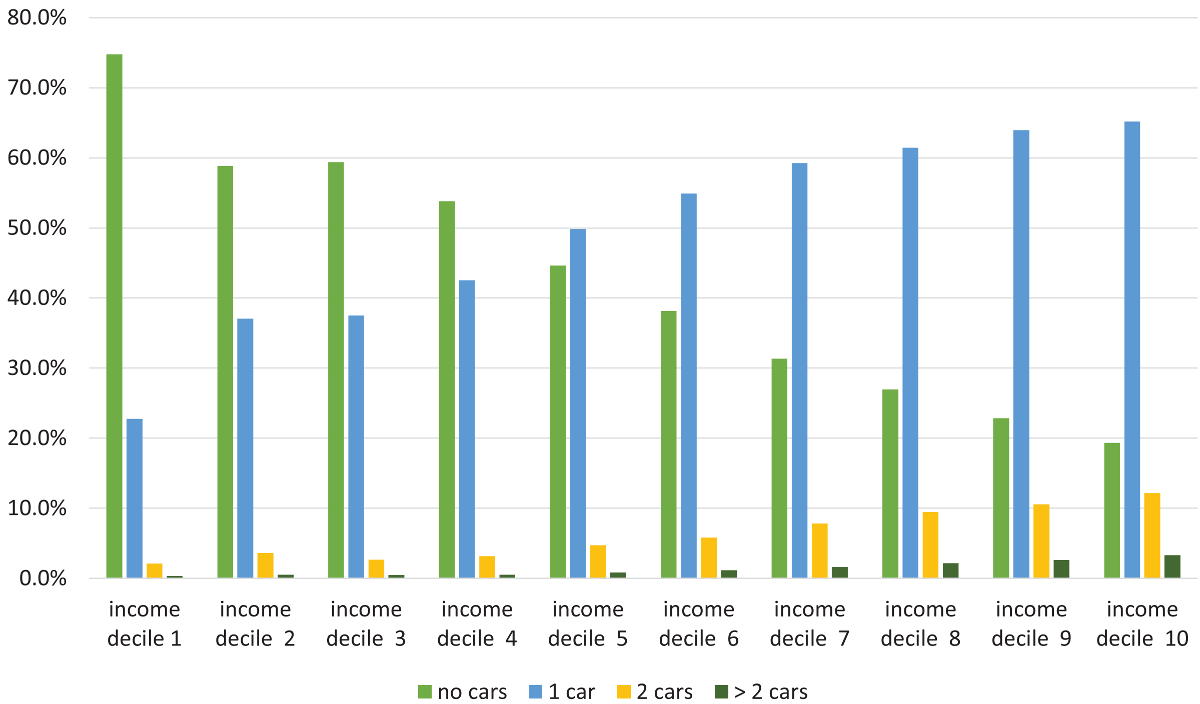

Figure 5. Distribution of car ownership vs. income decile, for households with one adult.

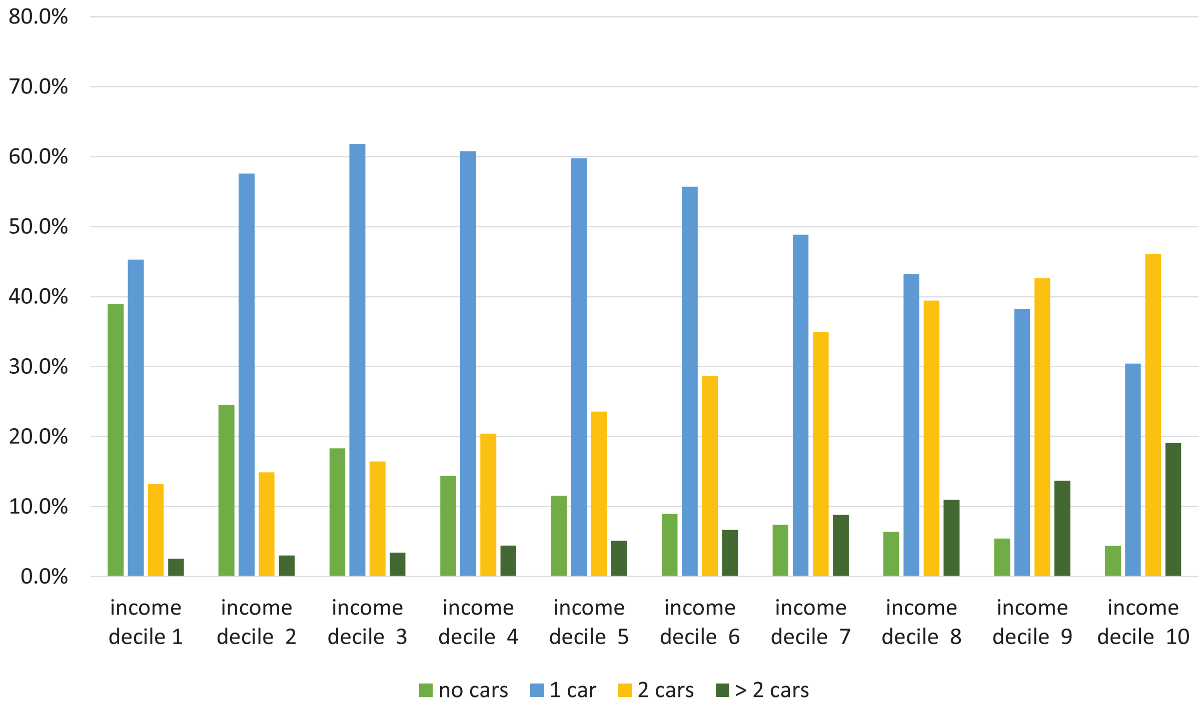

Figure 6. Distribution of car ownership vs. income decile, for households with at least two adults.

least one car. A zero-car single household without children residing in a rural area is the reference category for the regression. Exp(B) are the odds ratios for the predictors (the independent variables) and signals the predicted change in odds for a unit increase in the predictor. The "Exp" refers to the exponential value of B, the estimated coefficient. As Exp(B) is easier to interpret, I only added Exp(B) and the respective Confidence Intervals (CI) in the Table. When Exp(B) is less than 1, increasing values of the variable correspond to decreasing odds of the event's occurrence. The analysis shows that all variables are significant (<.01). The model (Table 1) confirms that, when controlled for income and household composition, built environment characteristics like spatial typology and node value influence car ownership. A household's likelihood of owning a car decreases as node value increases. Also, the odds of having no car in an urbanised area is 1.17 times (1/0.855) the odds of having no car in a rural area. It is more likely that a household does not own a car in a rural area than in a suburban area, although the Exp(B) is close to 1. Thus, a household residing in a rural or suburban area with a low node value is

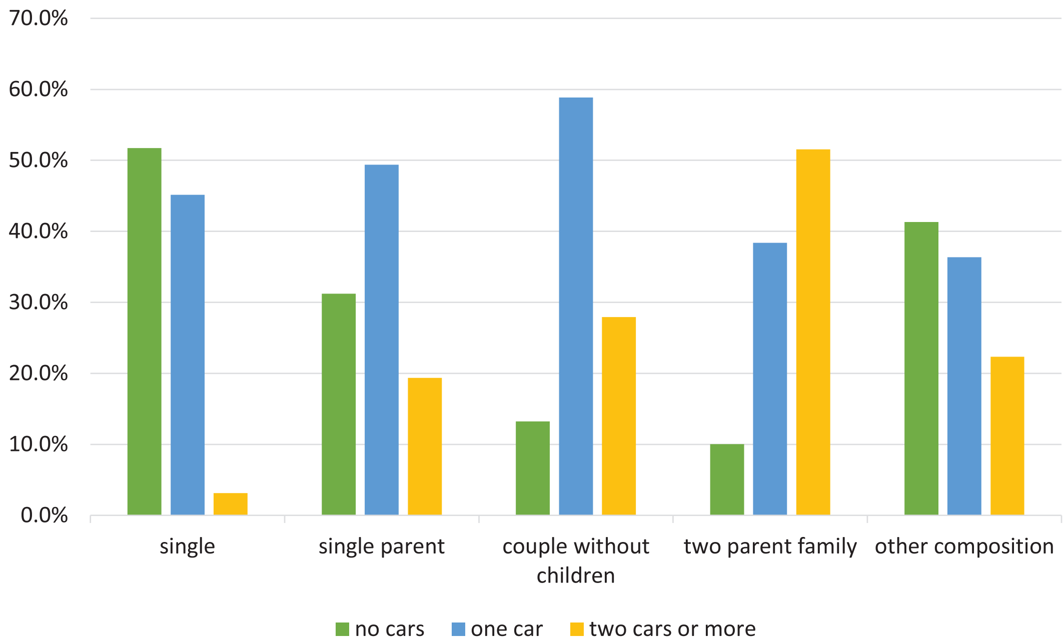

Figure 7. Distribution of household car ownership (%) per household composition.

Table 1. Results of binary logistic regression for households in the Flemish Region.

	Sig.	Exp(B)	CI. lower	CI. upper
Spatial typology (ref. rural)				
Suburban	<.01	1.040	1.029	1.050
Urbanised	<.01	0.855	0.847	0.864
Node	<.01	0.822	0.820	0.824
Household type (ref. single)				
Single parent	<.01	3.436	3.397	3.475
Partners no children	<.01	5.395	5.349	5.442
Partners children	<.01	9.053	8.966	9.142
Other	<.01	1.622	1.589	1.656
Income	<.01	1.322	1.321	1.324
Constant	–0.570			

Notes: Nagelkerke Pseudo R square: 0.349; McFadden: 0.243. Dependent variable: at least one car in the household (yes/no); reference category: single, no children, rural area; $p < .01$.

much more likely to own a car than a similar profile in an urbanised area.

Household composition emerges as a powerful predictor. The presence of children (<18) is related to the decision to purchase a car. The odds that single parents own a car is 3.436 times the odds for singles without children. Households with more than one adult are more likely to own a car. However, this does not imply that both adults have equal access to a car. For one-car households, when one partner uses the car, the other partner is without a car. In that sense, singles' car access is more guaranteed. This is a blind spot I do not address in this article.

Furthermore, the regression indicates that the odds of having a car increase per decile increase. This might feed the assumption that high-income households not only have a car because they consider needing one but also for the simple reason that they have more than sufficient purchasing power. Moreover, higher incomes are much more likely to receive a company car.

The regression indicates that both built environment characteristics and socio-demographic features influence car ownership. However, the influence of household composition surpasses that of node value and spatial typology.

Running the regression with only spatial typology and node value produces lower Pseudo R Squares compared to household composition (Nagelkerke: 0.204 vs. 0.229; McFadden: 0.134 vs. 0.153). Running the regression with income as the single independent variable, Pseudo R Squares notes 0.164 (Nagelkerke) and 0.106 (McFadden).

3.3. Results of Binary Logistic Regression at the Level of the Individual

In this part, I again ran a binary logistic regression, but now with individuals as the unit of inquiry. The regression thus reports on the influence of individual socio-demographic variables that might impact car purchases (Table 2). The reference category is a single male, born between 1990 and 1999 and a low education (no education, primary education, or lower secondary education) living in a rural area. All independent variables are significant ($p < .01$). Spatial typology, node value, income, and household composition produce similar odds ratios as in the regression conducted on the household level. Compared to the reference category, the age group most likely to own a car is born between 1940 and 1959. The odds ratio declines firmly for people born before 1940, with the odds of owning a car vs. not owning a car of 1.430 (1/0.699). The odds for groups born between 1970 and 1989 are close to 1. The likelihood of people possessing a car is highest for those aged 60 to 79. The likelihood decreases slightly in the groups born between 1970 and 1989. It is more likely that a person born between 1990 and 1999 will own a car than someone born between 1980 and 1989.

Concerning education level, the regression finds that individuals with a degree in secondary school or a bachelor's degree are more likely to own a car compared to the lowest educated group. The odds ratio for the highest educated groups is higher than for the reference group, indicating that highly educated people are more likely to own a car than low-educated people. However, the odds ratios for the highly educated group are smaller than those with a bachelor's or a secondary school degree. Finally, men are more likely to possess a car than women, although the odds ratio approaches 1.

4. Results: Zero-Car Households—Voluntarily or by Constraint?

The second aim of this study is to distinguish between voluntary and involuntarily zero-car households. In doing so, I build on the work of Brown (2017) and Karjalainen et al. (2021) and the regression results.

Table 2. Results of binary logistic regression for individuals in the Flemish Region.

	p-value	Exp(B)	CI. lower	CI. upper
Spatial typology (ref. rural)				
Suburban	<.01	1.038	1.029	1.047
Urbanised	<.01	0.858	0.850	0.866
Node	<.01	0.833	0.831	0.835
Income	<.01	1.260	1.259	1.262
Household type (ref. single)				
Single parent	<.01	3.748	3.706	3.790
Partners, no children	<.01	5.206	5.167	5.245
Partners, children	<.01	10.119	10.029	10.211
Other	<.01	2.095	2.066	2.125
Year of birth (ref. 1990–1999)				
1980–1989	<.01	0.877	0.866	0.889
1970–1979	<.01	1.030	1.017	1.044
1960–1969	<.01	1.373	1.356	1.391
1950–1959	<.01	1.688	1.666	1.710
1940–1949	<.01	1.691	1.668	1.714
1917–1939	<.01	0.699	0.690	0.708
Education (ref. no degree, primary school, or lower secondary school)				
Secondary school	<.01	1.296	1.287	1.305
Bachelor	<.01	1.510	1.494	1.527
Master	<.01	1.195	1.180	1.210
Gender (ref. male)				
Female	<.01	0.891	0.885	0.896
Constant	–0.530			

Notes: Nagelkerke Pseudo R square: 0.309; McFadden: 0.230. Dependent variable: at least one car in the household (yes/no); reference category: single, no children, rural area; *p* <.01.

The regression illustrated that the presence of children and having more than one adult in the household increases the likelihood of having a car in the household. Also, income emerged as a significant predictor: the regression demonstrated that a higher income increases the likelihood of car ownership. Age matters as well: From the age of 80, people are less likely to own a car. Built environment characteristics are significant but are by far the largest predictor of car ownership. However, their importance may not be underestimated, especially concerning zero-car households. The presence of an urban tissue with amenities in or in the vicinity of the neighbourhood, a higher density regarding work locations, and public transport provision guarantees minimum levels of accessibility for people without cars. This level of accessibility is less present in rural and suburban areas.

Therefore, we can safely assume that zero-car households in rural and suburban areas, especially those of lower income and with children in the household or over 80 years old, are car-less by constraint. On the other side of the spectrum, we may expect high-income and highly educated partners with children living in an urbanised area to be voluntarily car-free. However, there is a lot of diversity and variety between both ends of this spectrum. Iacobucci (2022) identified a grey area between choosing to save money and affordability issues and balancing supportive conditions for non-car travel. The purchase of a car remains open for negotiation in households and is strongly related to the specific context a household finds itself. Indeed, we must situate car-less, the latent demand for cars, and car-free on a continuum (Figure 8).

Table 3 organizes the zero-car households according to their residential area (urbanised, suburban, or rural) and income. The low-income group refers to households with income deciles one to four; the middle income refers to income deciles five to seven; the high income to eight to ten.

15.36% of the zero-car population lives in a rural area, and 8.69% in a suburban area. Of these car-less groups, respectively, 17% and 19% have children in the household. We may assume that these low-income households with children are the core group being car-less by constraint. Both suburban and rural households combine several characteristics that highlight their potential vulnerability. Their characteristics echo what Mattioli (2014) labelled double vulnerability: combining low accessibility with vulnerable socio-demographic

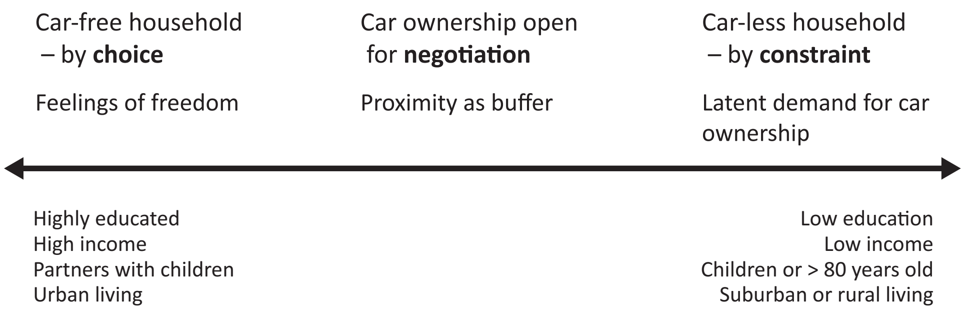

Figure 8. Zero-car households and their archetypical characteristics situated on a continuum from choice to constraint.

characteristics. Only 6.3% (rural) and 7.5% (suburban) obtained a bachelor's or master's degree. Approximately one-third of the members of these households are over 80 years old. To a certain extent, for them, zero-car ownership is an imposed choice which also makes them car-less by constraint and dependent on a network of family, friends, and neighbours. For the total population in Flanders, 5.47% of households may face problems due to their residential location and lack of car.

When moving to the medium-income groups in rural and suburban areas, we notice that the size of these groups is half of that of the low-income groups (7.02% for rural areas, and 4.18% for suburban areas). The presence of children in these households equals that of the lowest income groups. The share of people over 80 years old is smaller and approaches one-fifth of the people belonging to that group.

Finally, concerning the highest income groups in rural (3.67%) and suburban (2.18%) areas: their presence is at odds with what would be expected. Why not purchase a car in an area that is, when interpreted through the lens of accessibility, quite car-dependent? One explanation

Table 3. Distribution of Flemish zero-car households along spatial typology and income.

Rural	Low-income (15.36% or *n* = 96,826)	Children in household: 17.0% Individuals age > 68: 44.3% (>80: 31.5%) Bachelor +: 6.3%
	Medium-income (7.02% or *n* = 44,257)	Children in household: 19.5% Individuals age > 68: 33.7% (>80: 20.7%) Bachelor +: 14.4%
	High-income (3.67% or *n* = 23,114)	Children in household: 23.5% Individuals age > 68: 20.5% (>80: 14.4%) Bachelor +: 36.1%
Suburban	Low-income (8.69% or *n* = 54,800)	Children in household: 19.0% Individuals age > 68: 40.0% (>80: 28.4%) Bachelor +: 7.5%
	Medium-income (4.18% or *n* = 26,379)	Children in household: 17.2% Individuals age > 68: 38.1% (>80: 24.3%) Bachelor +: 14.3%
	High-income (2.18% or *n* = 13,750)	Children in household: 23.1% Individuals age > 68: 23.5% (>80: 15.3%) Bachelor +: 38.2%
Urbanised	Low-income (36.92% or *n* = 232,756)	Children in household: 21.3% Individuals age > 68: 25.8% (>80: 15.7%) Bachelor +: 9.2%
	Medium-income (14.77% or *n* = 93,120)	Children in household: 13.5% Individuals age > 68: 35.6% (>80: 22.8%) Bachelor +: 15.7%
	High-income (7.21% or *n* = 45,458)	Children in household: 14.8% Individuals age > 68: 23.2% (>80: 14.7%) Bachelor +: 43.9%

Note: All on the level of the household, except for the variables age and education; only people 18+ included.

could be that they might not be a zero-car household due to the missed company cars (see Section 2 on methodology), mainly because here we find more than one-fifth of the households with children and a limited number of older people.

The zero-car households in urbanised areas are the largest group and the most heterogeneous regarding socio-economic characteristics. On the one hand, there is a group with a low income (36.92%) and low education, and in 21.3% of these households, children are present. They account for 8.4% of the total Flemish population. The low-income households in urbanised areas are, compared to all others, the youngest group with the smallest share of people over 80. For them, it is conceivable that there is a latent demand for car ownership, and they consider purchasing a car in case of an increasing household budget. Despite their vulnerable characteristics, they can benefit from high accessibility. In that sense, they are less vulnerable in terms of mobility options than the zero-car rural households.

What is remarkable for the households of urbanised areas is that we can identify a transition from vulnerable socio-demographic characteristics to the exact opposite. For the highest incomes, more than 43.9% have a bachelor's or master's degree. Interestingly, only 14.8% of these car-free households have children, which is the second-lowest percentage. When this group starts having children, they might purchase a car after all. When we sum up medium and high-income households in urbanised areas, we arrive at 5% of the total Flemish households. The number is likely even smaller, as we can also expect some not-assigned company cars in this group.

The likelihood that people with a master's degree have a car in a household is smaller than those with a secondary or bachelor's degree. This could be because they are more likely to be white-collar workers with an office at a central location close to a public transport hub and ample opportunities for teleworking, which makes a car for commuting redundant.

Regarding the role of the built environment for car ownership, spatial typology and accessibility by public transport are minor but remain nevertheless significant contributors.

5. Conclusion and Discussion

In this article, I first focused on the diversity regarding socio-economic and spatial variables correlating with car ownership. Secondly, I aimed to distinguish households between car-free by choice and car-less by constraints and gauge their respective shares within the population. The outcomes for the first question strongly concur with previous findings: Zero-car households are strongly overrepresented at the bottom of the income distribution. The most prevalent household composition is singles. Children contribute strongly to the likeliness that a household owns a car, and single parents are likelier to own a car than singles without children. However, the overall financial burden for single parents is often heavier than for singles without children, and a car seizes firmly on the household budget. It is more likely that households with two adults possess a car, also in the lower income groups. Probably, these households are more assured of a permanent, stable income which is known to increase the likelihood of car ownership (Nolan, 2010). However, for one-car households, when one partner uses the car, s/he leaves the other without one. In that sense, singles' car access is more guaranteed. This is a blind spot I did not address in this article.

Concerning the second and third research questions, my study yielded a similar result as Karjalainen et al. (2021) for Helsinki and Mattioli (2014) for the UK: Households without cars also reside in car-dependent rural and suburban areas. For the studied region, this is even the largest group. The main contribution of this article is that it highlights, based on a dataset that contains the whole population, that despite the evidence that zero-car households are strongly present in urban areas, the share of zero-car households living in remote areas may not be underestimated. In these areas, accessibility by public transport is limited, which comes on top of dealing with modest or low household budgets. Also, zero-car urban households are overwhelming low-income. The households we can confidently identify as car-free, deliberately and voluntarily living without a car, are a minority group, however very present and visible in media coverage. In Flanders, car-free households are an educated middle-class phenomenon, which corroborates with the findings of Paijmans and Pojani (2021). The group that likely experiences car-freedom and thus voluntarily has refrained from car ownership remains an exception, especially when children are involved. Members of zero-car households are overwhelmingly low-income, low-skilled, and often also of higher age.

As a reduction in car ownership is likely to help reduce emissions (Aguilera & Cacciari, 2020), it is vital to avoid future car purchases. Public transport is of utmost importance to make car-free living feasible and to maintain and improve accessibility levels of other, non-voluntary zero-car households. However, when considering car purchase restriction policies, it is essential to keep the findings of this study in mind. For instance, with a general increase in car ownership cost, lower income groups will likely have to drop out first for car ownership. This is questionable in terms of fairness.

Moreover, previous research highlighted that higher-income groups travel more kilometres with their cars (see, for instance, Van Eenoo et al., 2022, for the case study region). Consequently, the effect of reduced car ownership will be limited in carbon emissions when only the low incomes drop out. Therefore, governments could experiment with price settings that proportionate household income or type of vehicle. In that sense, the main goal is to reduce car ownership at the top, not, or not in priority, at the bottom. For households with children, public transport or the bicycle currently needs to compete sufficiently with the comfort, convenience, and feelings of safety attached to the car. A planning policy centred around proximity and accessibility—to reduce travel time and distance to schools, sports, and hobbies to prioritise walking and cycling—is essential here. Moreover, traffic safety measures are pivotal, especially for young cyclists and pedestrians.

The current tendency to scale up amenities such as schools and hospitals in the studied region (Matthyssen et al., 2019; Storme et al., 2015) could impact car ownership. Urban planning can act as a buffer against transport vulnerability. Maintaining and strengthening proximity is crucial, as this guarantees minimum levels of accessibility and avoids the risk of car-related economic stress or transport poverty in the case of a move towards suburban or rural areas. This requires a planning and housing policy that centres around affordable housing, the proximity of amenities, and accessibility by public transport (Mattioli, 2017). This is all the more important as the Flemish Region is ageing rapidly (Volckaert et al., 2021) and the elderly tend to refrain from car ownership.

My findings align with the argument of Brown (2017) and Karjalainen et al. (2021). Although the media strongly focuses on voluntarily car-free households, involuntarily carlessness should be considered as a proxy for vulnerability. The needs of zero-car households should be recognised as a particular group in sustainable urban planning (Karjalainen et al., 2021; Nieuwenhuijsen & Khreis, 2016). The biased view leaves zero-car households due to financial or other constraints largely out of sight, risking too limited attention from policymakers.

This study remains exploratory, and it is essential to highlight some limitations. Although the dataset consists of all households and individuals in Flanders, it comes with some restrictions. An important one is that it lacks personal motivations and reasons for zero-car ownership. Furthermore, there is the issue that not all company cars were assigned to a household. Also, co-parenting was not taken into account: Children are registered with one parent, so it is conceivable that, in reality, there are more single parents than the dataset reveals. The dataset does not allow us to identify which households are members of a car club or are part of car-sharing initiatives or informal car-sharing between families. It is imaginable that some of the zero-car households, especially those living in an urbanised area where car sharing is well established, are acquainted with car sharing and hence often travel by car, for instance, during leisure time. Moreover, a longitudinal study could inform us about evolutions in household motorisation rates in the identified groups and areas, for instance, when children are born or when people move house. Finally, the dataset does not contain information on, for instance, the physical ability of people to drive a car, nor does it on driving anxiety. Both influence car ownership (Witte et al., 2022) but are out of the scope of this article. Nevertheless, the adopted approach allows differentiation among zero-car households, exploring proportions and describing characteristic features for each group.

Finally, I formulate some avenues for further research. Thus far, the topic of unmet or latent demand for car ownership and the relationship between residential location and car ownership is underexplored and deserves more research attention, for instance, how households negotiate between living in an, on average, more expensive central urban area and as a result are no longer able to afford a car and living in a more remote area with a car. The same goes for "car-deficit" households (Blumenberg et al., 2020), which refers to households where there are more adults than cars. Finally, qualitative research can shed light on the practices of the identified zero-car households to unravel how they navigate in a car-dependent society.

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Conflict of Interests

The author declares no conflict of interests.

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Article

Investigating the Nonlinear Relationship Between Car Dependency and the Built Environment

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Abstract
Car-dominated daily travel has caused many severe and urgent urban problems across the world, and such travel patterns have been found to be related to the built environment. However, few existing studies have uncovered the nonlinear relationship between the built environment and car dependency using a machine learning method, thus failing to provide policymakers with nuanced evidence-based guidance on reducing car dependency. Using data from Puget Sound regional household travel surveys, this study analyzes the complicated relationship between car dependency and the built environment using the gradient boost decision tree method. The results show that people living in high-density areas are less likely to rely on private cars than those living in low-density neighborhoods. Both threshold and nonlinear effects are observed in the relationships between the built environment and car dependency. Increasing road density promotes car usage when the road density is below 6 km/km^2. However, the positive association between road density and car use is not observed in areas with high road density. Increasing pedestrian-oriented road density decreases the likelihood of using cars as the main mode. Such a negative effect is most effective when the pedestrian-oriented road density is over 14.5 km/km^2. More diverse land use also discourages people's car use, probably because those areas are more likely to promote active modes. Destination accessibility has an overall negative effect and a significant threshold effect on car dependency. These findings can help urban planners formulate tailored land-use interventions to reduce car dependency.

Keywords
built environment; car dependency; machine learning; nonlinearity; Puget Sound; threshold effects

Issue
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1. Introduction

During the past several decades, car use has become a severe problem across the world. For example, almost half of the trips in European countries (e.g., Germany, Switzerland, and Austria) are made by private car (Buehler et al., 2017). The growth rate of car ownership in China has also been dramatic, which is similar to the historical process of developed countries (International Monetary Fund, 2005). Car-dependent issues in the U.S. are even worse. The rate of car ownership in the U.S. ranked first in the world, significantly higher than that in other countries (Pucher & Lefevre, 1996). Low density and urban sprawl in the U.S. have led to severe car dependency issues (Gilbert & Perl, 2011) since facilities and services (e.g., healthcare, and shopping centers) are sparsely distributed and cannot be reached and served efficiently by public transit and/or active modes. The extensive use of cars across the world has resulted in severe problems, such as traffic congestion, air pollution, and noise pollution (McIntosh et al., 2014). Understanding what contributes to the decline in car dependency can help planners reduce the detrimental effects of car use.

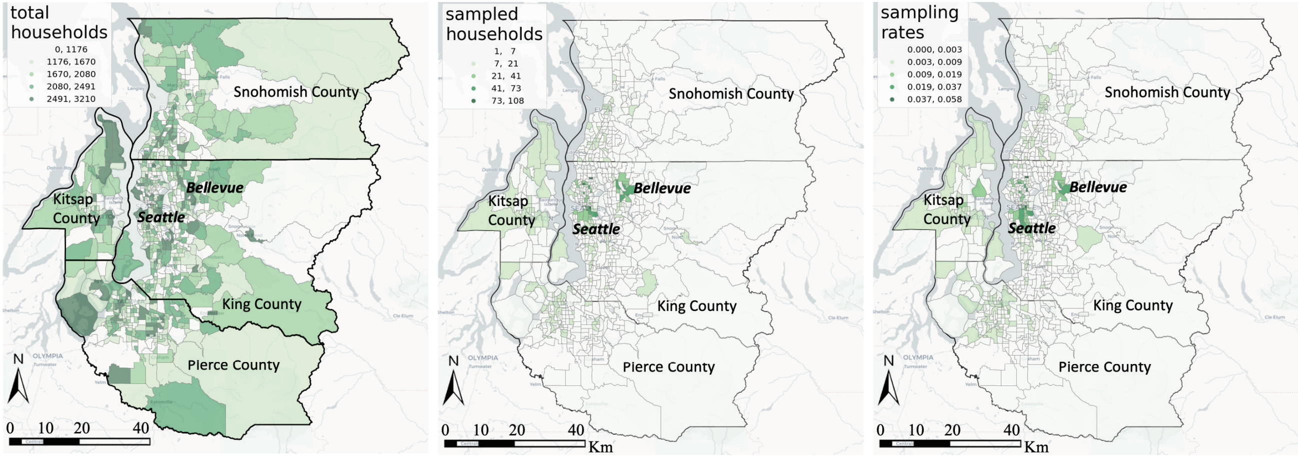
After "car dependency" was first introduced by Newman and Kenworthy (1989a, 1989b) in a study analyzing the relationship between travel patterns and land use factors from 32 global cities, extensive studies have discussed the influencing factors on car dependency. Socio-demographic characteristics can influence people's car use, such as age, gender, income level, education, and employment status (Naess, 2014). Manaugh et al. (2010) found that the number of automobile trips is positively associated with people's income level in Montreal, Canada. Another research in Detroit reached a similar finding and further found that education and employment status also has a positive effect on car use. People who have full-time jobs are more likely to use cars compared to those unemployed. How the built environment affects car use has also been extensively discussed in previous studies (Ding & Cao, 2019; Pinjari et al., 2011). Most existing studies concluded that built environments such as density, design, and destination accessibility have significant effects on car use. High density can lead to less car dependency (Van Acker & Witlox, 2010). Housing density has a negative impact on car dependency (Hong, 2017). Evidence from California witnessed that a decrease in density below 1,000 housing units per square mile is associated with a 5.5% increase in fuel consumption per household and a 4.8% increase in vehicle kilometers traveled (VKT) per capita (Zegras, 2010). Another study in Flanders, Belgium supported this finding that higher density increases the use of other modes, such as walking, cycling, and public transit (De Vos & Witlox, 2013). Car ownership is negatively associated with both residential density and employment density (Cervero & Arrington, 2008; Holtzclaw et al., 2002; Li et al., 2010). People living in areas with more diverse land uses are less likely to own a car (Potoglou & Kanaroglou, 2008). Those living in neighborhoods with pedestrian-friendly streets have fewer cars since these streets promote the use of non-motorized travel modes (e.g., walking, cycling; Zuo et al., 2018). Good access to transit services may encourage people to travel by public transit and thus decreases the possibility to use cars (Mavoa et al., 2012; McIntosh et al., 2014).

While most of the existing studies assumed a linear association between the built environment and car dependency (Van Acker & Witlox, 2010; Zegras, 2010), some researchers tried to uncover the nonlinear relationships between car use and urban form using exponential functions. Theoretical reasons for such nonlinear effects can be related to location theory and threshold theory for goods and services (Eldridge & Jones, 1991). For example, Newman and Kenworthy (1989a, 1989b, 1991, 2006, 2011a, 2011b) found that car use decreases exponentially with population density increasing by analyzing a group of global cities. The exponential function used by Newman and Kenworthy is one of the first attempts to uncover the nonlinear effects between car use and urban density. Exponential functions have been used in many previous studies to introduce nonlinearity (Holtzclaw et al., 2002), with the advantage of being smooth and differentiable and being able to derive the backpropagation algorithm. Unlike exponential function as a traditional statistical method that follows a constrained statistical assumption and is usually pre-defined, machine learning methods, such as the XGBoost model used in this research, are data-driven and are not statistically constrained, which will provide more sophisticated results. Many other researchers have also attempted to uncover the nonlinear built effects on travel patterns using machine learning methods, including driving distance (Ding et al., 2018), metro ridership (Ding et al., 2019), usage of shared mobility services (Cheng et al., 2023; Cheng, Wang, et al., 2022; Jin, Cheng, Zhang, et al., 2022), and public transit ridership (Chen et al., 2021). Relaxing the assumption of linearity using a machine learning method has several advantages in travel behavior analysis (Cheng et al., 2019; Liu et al., 2021; Xu et al., 2021; Zhang et al., 2020). First, former studies that assume linear relationships can only uncover a negative or positive effect of the influencing factors on travel behavior (Boarnet et al., 2008; Van Acker & Witlox, 2010; Zegras, 2010). The nonlinear relationships can illustrate a more complex relationship instead of a monotonous trend or effect. Moreover, the nonlinear relationships captured by machine learning methods can present more accurate estimates of the effects of influencing factors within different intervals of associated factors on travel behavior, which can help policymakers make targeted policies. This study, taking the Puget Sound Region, U.S, uses a machine learning method to explore the nonlinear associations between the built environment and car dependency.

The rest of this article is as follows. Section 2 introduces the data and variables. Section 3 explains how the gradient boost decision tree (GBDT) can be used to analyze nonlinear relationships. Section 4 discusses the nonlinear effects of the built environment on car dependency. Section 5 summarizes this research and proposes future research avenues.

2. Data and Variables

This study is based on the Puget Sound Region Travel Surveys from 2017 to 2021. The Puget Sound region (Figure 1) is in the U.S. state of Washington and consists of King, Kitsap, Pierce, and Snohomish counties, with the city of Seattle located in the region. The region includes 82 cities and towns with a total of over four million people and 1.5 million households (Figure 1a). As illustrated



(a) Total households **(b)** Sampled households **(c)** Sampling rates

Figure 1. Spatial distribution of total households, sampled households, and sampling rates in the Puget Sound Region.

in Figure 2, this region has multiple types of neighborhoods, such as high-density neighborhoods in downtown areas of Seattle, and low-density neighborhoods in Parkwood, Kitsap County. The surveys collected sociodemographic and geographic information about individuals and households, as well as detailed travel information. There are 136,079 trips involved in this research, which contains 8,287 households and 14,112 individuals. Travel information includes the number of trips, travel time, and travel mode. The travel surveys aim to help local and regional planning agencies prioritize transportation and land-use improvements. It should be noted that the Puget Sound Region Travel Survey uses a stratified address-based random sampling method, which combines proportional geographic sampling and compensatory sampling based on predicted response rates and targeted oversampling. Low-income households, those with no vehicles, and non-auto commuters are more targeted for policy goals (Puget Sound Regional Council, 2021). As illustrated in Figure 1c, those census tracts that have high sampling rates are located in the city of Seattle and Bellevue, two of the largest cities in the region. Since this research focuses on explaining the relationships between built environment variables and car use rather than on describing car use per se, these differences are not expected to materially affect the results (Babbie, 2009).

The dependent variable is whether a car is used as the main mode during one trip. It is a dummy variable, with one indicating that a car is used as the main mode, while zero otherwise. Among all trips surveyed, 63.47% of the trips use a car as the main mode while 36.53% use other modes. The explanatory variable is built environment attributes while the control variables include individuals' socioeconomic and demographic characteristics, household characteristics, and trip purposes (Table 1). While characteristics of individuals and households, as well as trip purposes, are sourced from the travel survey, built environment characteristics are collected from the U.S. Environmental Protection Agency's Smart Location Dataset (SLD), OpenStreetMap, and GTFS dataset. The SLD can be downloaded using the following link: https://www.epa.gov/smartgrowth/smart-location-database-technical-documentation-and-user-guide. The SLD data are all aggregated at the census block level with United States customary units (i.e., miles). Since the geographic information of the Puget Travel Survey is based on the census tract level, the SLD-sourced variables are conversed to the census tract level using the weighted average values with SI units (i.e., kilometers).

(a) High-density area (Downtown area of Seattle) **(b)** Median-density area (Everett, Snohomish County) **(c)** Low-density area (Parkwood, Kitsap County)

Figure 2. Representative photos of high-, median-, and low-density neighborhoods in the Puget Sound Region.

Table 1. Variable definition and descriptive statistics.

Variable	Frequency	Percentage
Dependent variables		
Whether or not a car is used as the main mode during one trip		
Yes (= 1)	86,376	63.47%
No (= 0)	49,703	36.53%
Independent variables		
Individual's socioeconomic and demographic characteristics (N = 14,112)		
Age		
16–34	4,440	31.46%
35–54	4,400	31.18%
55+	5,272	37.36%
Gender		
Male	6,808	48.24%
Not Male	7,304	51.76%
Education (Bachelor's degree or higher)		
Yes	8,684	61.54%
No	6,808	48.24%
License (Valid driver's license ownership)		
Yes	11,668	82.68%
No	2,444	17.32%
Household characteristics (N = 8,287)		
Household size		
1	3,048	36.78%
2	3,336	40.26%
3	957	11.55%
4+	946	11.42%
Household income		
Under $49,999	2,066	24.93%
$50,000–$99,999	2,359	28.47%
$100,000 or more	3,336	40.26%
Prefer not to answer	526	6.35%
Vehicle ownership		
0	1,222	14.75%
1 vehicle	3,796	45.81%
2 or more vehicles	3,269	39.45%
Residential type		
Single-family house	3,234	39.02%
Apartment/condo/others	5,053	60.98%
House ownership		
Yes	4,170	50.32%
No	4,117	49.68%

Table 1. (Cont.) Variable definition and descriptive statistics.

Variable	Frequency		Percentage	
Trip purpose (N = 136,079)				
Trip purpose of origins *				
Home	44,234		32.51%	
Work	15,156		11.14%	
Work-related	5,338		3.92%	
School	2,981		2.19%	
Meal	11,244		8.26%	
Shop	14,744		10.83%	
Social/recreation	19,708		14.48%	
Escort	7,323		5.38%	
Change mode	773		0.57%	
Errand/other	13,892		10.21%	
Non-response	686		0.50%	
Trip purpose of destinations *				
Home	43,879		32.25%	
Work	15,106		11.10%	
Work-related	5,383		3.96%	
School	2,991		2.20%	
Meal	11,265		8.28%	
Shop	14,775		10.86%	
Social/recreation	20,278		14.90%	
Escort	7,345		5.40%	
Change mode	780		0.57%	
Errand/other	13,783		10.13%	
Non-response	494		0.36%	
Built environment variables (Census Tract level)	Mean	Min	Max	Std
Density				
Residential density (10^3 housing units/km^2) **	0.97	0.001	15.82	1.49
Employment density (10^3 jobs/km^2) ***	1.50	0.00	124.36	6.90
Design				
Road density (km/km^2) ****	0.65	0.00	12.36	1.37
Intersection density (counts/km^2) ****	1.07	0.00	68.97	4.37
Pedestrian-oriented road density (km/km^2) *****	9.27	0.32	24.82	5.02
Building density (km^2/km^2) ****	0.16	0.00	0.49	0.08
Diversity				
Land use mix ******	0.70	0.23	0.96	0.11
Destination accessibility				
Transit service frequency (counts/km^2) *******	82	0.00	4567	372
10^3 jobs reached by public transit within 45 minutes ********	130.19	0.00	1121.77	194.23

Notes: * Trip purpose of origins (home) and destinations (work) means the respondent leaves home for the workplace. ** Pedestrian-oriented road density is network density in terms of facility kilometers of pedestrian-oriented links per square kilometer. It is sourced from D3apo in the SLD. Pedestrian-oriented facilities refer to any link having a low speed and pedestrian is permitted. *** Residential density is sourced from D1a in the SLD, which is the gross residential density (Housing Units/km^2) on unprotected land. **** Road density, intersection density, and building density variables are sourced from OpenStreetMap. ***** Employment density is sourced from D1c in the SLD, which is the gross employment density (jobs/km^2) on unprotected land. ****** Since land use data are not accessible for this region, employment entropy is used to represent the land use mix (Ozbilen et al., 2021; U.S. Department of Transportation, 2015). Employment entropy is sourced from D2b_E8Mix based on eight employment categories, including retail, office, service, industrial, entertainment, education, healthcare, and public administration. The entropy mixture of employment types can be calculated as: $H = -(\sum_{i=1}^{n} p_i * \ln(p_i)) / \ln(n)$, where p_i represents the share of each employment category i; and n is the number of employment types in each census tract. The value ranges from 0 to 1. The larger the value, the more mixed the job types are. A higher employment entropy can be assumed to represent more diverse land uses. ******* Transit service frequency per square kilometer is sourced from D4d in the SLD, which calculates the frequency of public transit services for each transit route during the weekday evening peak hour (from 4:00 PM to 7:00 PM). Transit stops within 0.4 kilometers of crow-fly distance from the boundary of the census block group were identified. ******** Jobs reached by public transit within 45 minutes variable is sourced from D5br in the SLD. It is distance decay weighted, which considers walking network travel time and GTFS schedules simulation.

3. Methodology

3.1. XGBoost Model

The GBDT method is a tree-based ensemble machine learning method (Friedman, 2001). As illustrated in Figure 3, multiple decision trees are built iteratively, and the outcomes of all trees are then combined to construct the final model. Each single tree aims to minimize a loss function, with more weights assigned to cases with a wrong prediction. The GBDT method has the advantage of excellent prediction power, making it one of the most widely recognized machine learning methods. The XGBoost is an advanced tree learning algorithm (Chen & Guestrin, 2016), which is able to deal with sparse and parallel data with a high computation speed. These improvements have made XGBoost a reputational and popular machine learning method in data science. While XGBRegressor is used for continuous outcome variables, XGBClassifier is used for categorical outcome variables.

For each tree, an outcome (i.e., whether a car is used as the main mode during a trip) y_i exists. The XGBoost model is built based on the features and K additive functions:

$$\hat{y}_i = \sum_{k=1}^{K} f_k(X_i), \quad f_k \in \mathrm{F} \tag{1}$$

where f_k is a tree with leaf weights, and F indicates the space of decision trees. For each tree, the aim is to minimize the following:

$$L(\phi) = \sum_i l(\hat{y}_i, y_i) + \sum_k \Omega(f_k) \tag{2}$$

where l is the difference between $\hat{y}_i$ and y_i. Ω is a term that penalizes the complexity of the model.

$$\Omega(f_k) = \gamma T + \frac{1}{2}\lambda \left\| \omega_i \right\| \tag{3}$$

$$\omega_i = -\frac{\sum_{i \in I_j} \partial^2_{\hat{y}^{(t-1)}} l\left(y_i, \hat{y}^{(t-1)}\right)}{\sum_{i \in I_j} \partial^2_{\hat{y}^{(t-1)}} l\left(y_i, \hat{y}^{(t-1)}\right) + \lambda} \tag{4}$$

where T indicates how many leave nodes in the tree, and ω_i represents the score of the i^{th} leaf, and γ and λ represent regularization parameters.

3.2. Interpretation of Results of the XGBoost

Explanatory variables are iteratively chosen randomly to construct a single decision tree in XGBoost. Relative importance is related to how many times a variable is selected to construct the model (Friedman, 2001). Relative importance is rescaled, the sum of which is one. Higher relative importance means a greater contribution of the variables. The relative importance of variable x_i can be obtained as follows:

$$I^2_{x_i} = \frac{1}{t}\sum_{k=1}^{t} I^2_{x_i}(T_k) \tag{5}$$

$$I^2_{x_i}(T_k) = \sum_{j=1}^{J} d_j \tag{6}$$

where J is the number of leaves in each tree; k is the number of additive trees; t is the number of iterations; T_k is the k^{th} tree function; d_j indicates the improvement in the square error term by making the j^{th} split based on the variable x_i.

How the outcome is influenced by independent variables can be illustrated by partial dependence plots (Tu et al., 2021). The x-axis represents the data distribution of the independent variable (Cheng et al., 2020). The partial dependence of $F(x)$ on x_S can be defined as follows:

$$F_{x_S}(x_S) = E_{x_C}\left[F(x_S, x_C)\right] = \int F(x_S, x_C)\,P(x_C)\,dx_C \tag{7}$$

$$F_{x_S}(x_S) = \frac{1}{n}\sum_{i=1}^{n} F(x_S, x_C^i) \tag{8}$$

where x_S are the features of which we want to estimate specific effects on car dependency and x_C are other variables; $P(x_C)$ is the probability density of x_C; n represents the number of samples.

Python "XGBoost" package is used to model the data. Model parameters are important for XGBoost, including

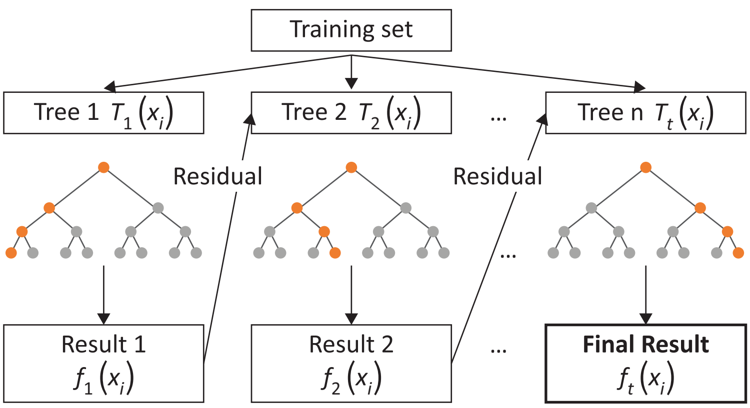


Figure 3. Schematic diagram of the GBDT method. Source: Authors based on Jin, Cheng, Liu, et al. (2022, p. 54).

the number of trees (n_estimators), shrinkage coefficient of each tree (learning_rate), and tree complexity (max_depth). Five-fold cross-validation was applied to search for optimum parameter values until the smallest F1 score occurs. Finally, the n_estimators, learning_rate, and max_depth was set as 200, 0.3, and 5 respectively for the model. To further help readers have a better understanding of the model performances of both the machine learning method and the binary regression model, we provide a table that illustrates more sophisticated performance metrics (i.e., precision, recall, F1_score, accuracy) for classification results. How these metrics can be calculated is illustrated from Equations 9 to 12, where TP indicates the correctly predicted positive class outcome of the model, TN demonstrates the correctly predicted negative class outcome, FP represents the incorrectly predicted positive class outcome, FN showing the incorrectly predicted negative class outcome. Precision is the rate of total correctly predicted instances of a class over total instances predicted as that class. Recall is the rate of total correctly predicted instances of a class over the total actual number of instances of that class. Accuracy is the rate of correctly predicted instances over the total number of instances. Accuracy represents a biased tendency towards the majority class in the imbalanced dataset as most of the data are from that class. Precision and recall can only illustrate the performance of each class. F1 score considers both values of precision and recall, and thus is regarded as a better representative model performance metric for the classification model. As illustrated in Table 2, all four model performance metrics of the XGBoost model are better than those of binary regression models.

$$\text{Precision} = \frac{TP}{TP + FP} \quad (9)$$

$$\text{Recall} = \frac{TP}{TP + FN} \quad (10)$$

$$\text{F1\_score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \quad (11)$$

$$\text{Accuracy} = \frac{TN + TP}{TN + TP + FP + FN} \quad (12)$$

4. Results

4.1. Relative Importance of Independent Variables

Higher relative importance means a greater contribution of the variables. Regarding the average relative importance of different factor categories, household characteristics have the highest average relative importance, followed by destination accessibility and trip purpose (Table 3). In terms of the relative contribution of single variables, vehicle ownership is the most important variable, accounting for 33.27%. This is reasonable since people are more likely to use cars as their main travel mode when they have more cars in households (Buehler, 2011; Van Eenoo et al., 2022). Except for the highest contribution of vehicle ownership, the built environment has a higher average relative importance than individuals' and household socioeconomic and demographic characteristics. Some researchers have generally acknowledged the importance of socio-demographic characteristics in people's travel choices (e.g., Lanzendorf, 2010; Singh et al., 2018; Stead, 2001), such as the formulation of households and life domains. They claimed that individuals' travel behaviors are significantly influenced by their age, gender, and employment status. Others reached different findings that urban design and transportation infrastructure have a highly significant influence on car use, even after the correction for socio-economic effects (Holtzclaw et al., 2002; Lewis, 2018). This research aligns with the latter conclusion, which provides new insight into understanding the importance of the built environment on car dependency.

For built environment factors, destination accessibility variables have the highest relative importance, followed by design variables. The diversity variable has the lowest relative importance. In terms of single built environment variables, transit service frequency has the highest relative importance (12.03%), followed by pedestrian-oriented road density (7.74%). This is not surprising since transit service frequency may play a more important role in promoting people to use public transit while pedestrian-oriented road density also encourages people to take more active modes.

Table 2. Performance metrics of XGBoost and binary regression models.

		Recall	Precision	F1 score
Using car as a main mode	XGBoost	0.81	0.88	0.84
	Binary regression	0.74	0.85	0.79
Not using a car as a main mode	XGBoost	0.76	0.64	0.69
	Binary regression	0.64	0.48	0.55
Accuracy	XGBoost			0.79
	Binary regression			0.71

Table 3. Relative importance of independent variables.

Variable	Relative importance (%)	Average relative importance (%)
Individual's socioeconomic and demographic characteristics		
Age	1.74	2.32
Gender	1.77	
Education	3.47	
Employment	2.15	
License	2.49	
Household characteristics		
Household size	2.27	8.46
Household income	2.21	
Vehicle ownership	**33.27**	
Residential type	2.38	
House ownership	2.15	
Trip purpose		
Trip purpose of origins	4.37	4.55
Trip purpose of destinations	4.72	
Built environment variables		
Density		
Residential density (10^3 housing units/km^2)	2.70	2.40
Employment density (10^3 jobs/km)	2.51	
Building density (km^2/km^2)	2.00	
Design		
Road density (km/km^2)	2.31	4.12
Intersection density (counts/km^2)	2.30	
Pedestrian-oriented road density (km/km^2)	**7.74**	
Diversity		
Land use mix	2.07	2.07
Destination accessibility		
Transit service frequency	**12.03**	7.69
Jobs reached by public transit within 45 minutes	3.35	

4.2. Nonlinear Effects of the Built Environment Factors on Car Dependency

Partial dependence plots (Figures 4, 5, 6, and 7) are used to visualize the marginal effects of the built environment factors on car dependency (Tu et al., 2021). The x-axis presents the distributions of the built environment variables, and the x-axis presents the probability of using a car as the main mode. As illustrated in Figure 4a, car dependency is positively associated with residential density when the residential density is low. Such a positive effect turns into a negative one when the population density is high. Both high residential density and employment density will decrease people's car dependency, which aligns with previous research (Chatman, 2013; Newman & Kenworthy, 1989a, 1989b; Zegras, 2010). Increasing building density can also decrease people's car dependency. Cervero and Arrington (2008) found that there is a decline in car ownership as residential density increases. These neighborhoods may be equipped with more public services (i.e., healthcare, shopping center, and educational institutes), so that people may not need to drive a long distance to reach these public facilities. Moreover, densely populated neighborhoods are more likely to have more transportation facilities (e.g., buses, rails, shared services) so that people may have other travel options instead of car use. A significant threshold effect is observed when the population density is over 7,000 housing units per square kilometer. A significant decline is observed in the curve for employment density when the value is below 1,000 jobs. A similar threshold effect is also witnessed for the curve of building density. Newman and Kenworthy (2006) also found a threshold of the urban intensity (residents and jobs) at around 3,500 per square kilometer where car use significantly decreased. They further explained that below the threshold density of residents and jobs, the physical constraints of distance and time enforce car use as the norm.

Design variables have nonlinear effects on car dependency (Figure 5). The probability of using a car as the main mode increase continuously when the road density is below 6 km/km^2, afterward, the curve remains

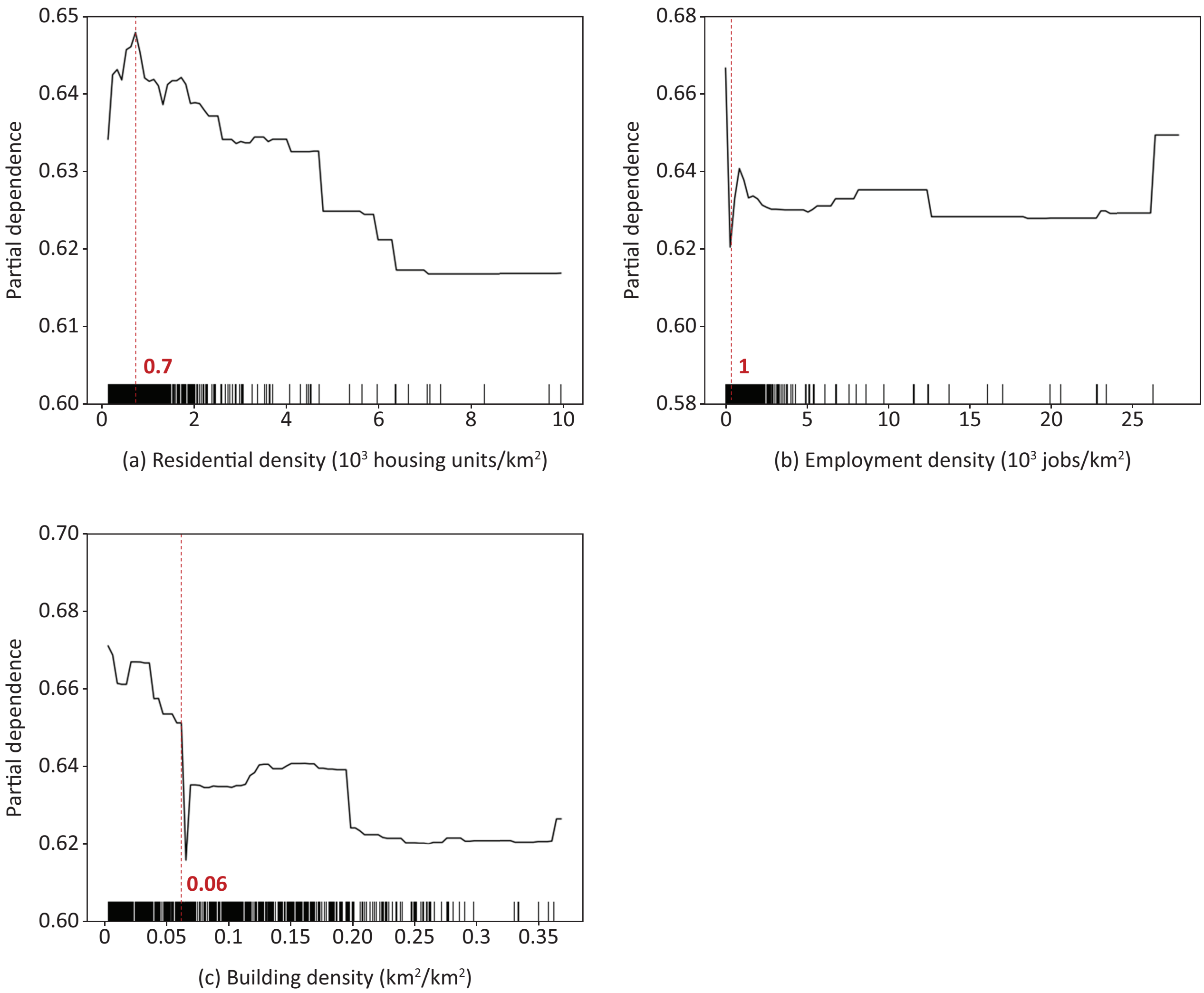


Figure 4. Nonlinear relationship between density variables and car dependency. Note: Y-axes represent the probability of using a car as the main mode.

unaffected. An efficient road network will promote car use. The positive association between road density and car use does not exist in areas with high road density, probably because these areas are more likely to be equipped with sufficient transportation infrastructures, such as public transit services (e.g., bus stops and metro stations) and shared mobility services (e.g., bike-sharing, ridesourcing). Car dependency is positively associated with intersection density when the intersection density is below 18. After the intersection density exceeds 38, the curve drops slightly and remains unchanged. Increased intersection density when the value is low means a good road network may facilitate car use. However, extremely high intersection density may be often accompanied by heavy traffic lights that may reduce people's willingness to drive. Increasing pedestrian-oriented road density decreases car dependency. This is not surprising since a high pedestrian-oriented road density can promote active travel modes, which are alternative options for car use. This research further found that the most effective range of pedestrian-oriented road density to decrease car use is 14.5 km/km^2, which can provide an evidence-based policy for local government and urban planners.

Car dependency has a positive association with land use mix in neighborhoods with a relatively low land use mix and a negative association in areas with highly mixed land use (Figure 6). Our finding indicates that areas with highly mixed land use are less likely to use cars as the main mode. This is probably because diverse land use promotes the use of active modes (e.g., walking, cycling; Cheng, Jin, et al., 2022), which, in turn, will decrease the use of private cars. Such restraint is not observed in areas with relatively lower land use mix. A similar finding was reached by Cervero (1996), who found that people are more likely to travel by transit, foot, or bicycle when mixed land development within several blocks. Beyond this distance, mixed-use activities appear to induce auto use since automobiles can efficiently link work and shopping activities.

Destination accessibility has an overall negative effect on car dependency (Figure 7). This is consistent with previous studies (Wiersma et al., 2017) that higher

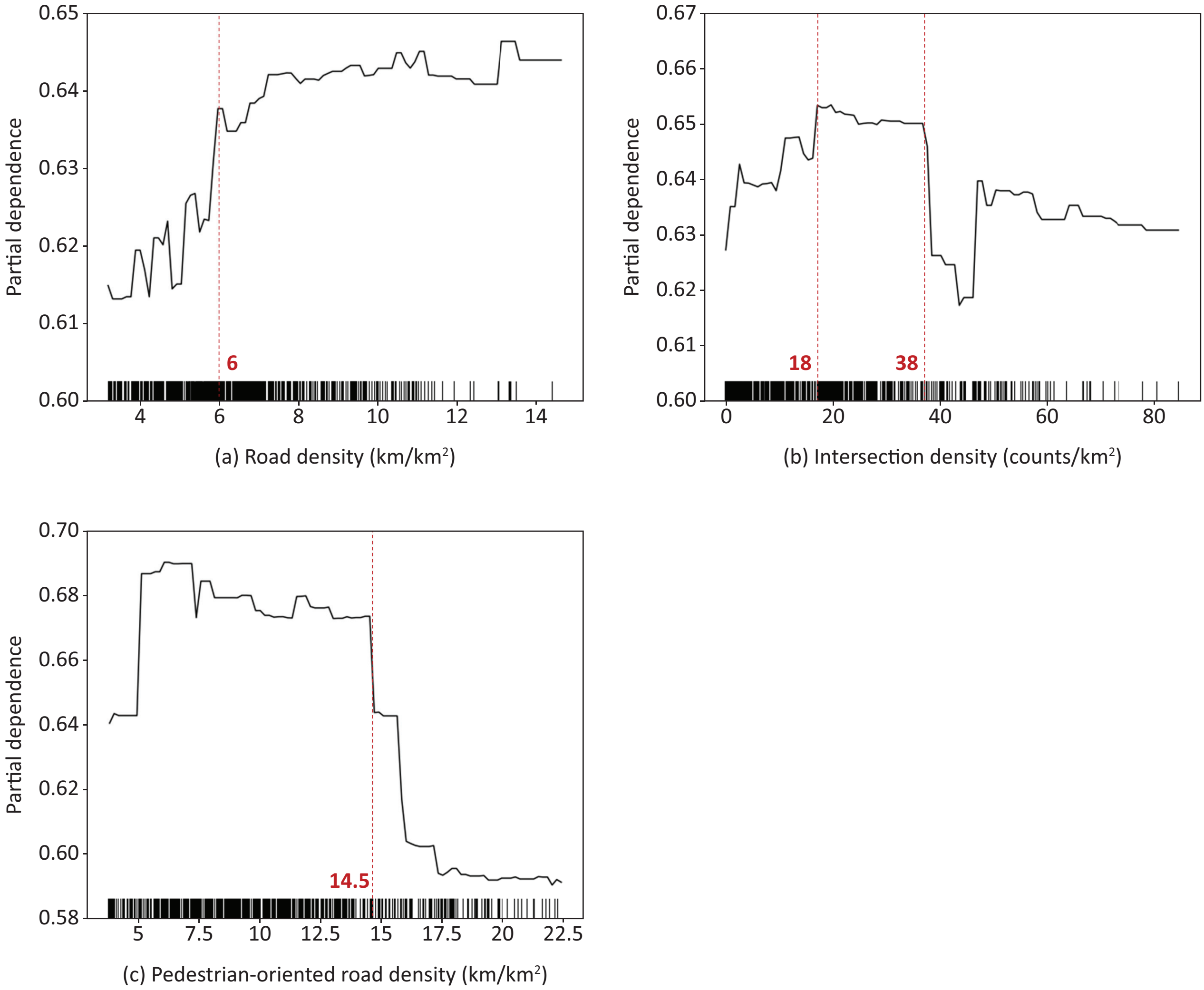


Figure 5. Nonlinear relationship between design variables and car dependency. Note: Y-axes represent the probability of using a car as the main mode.

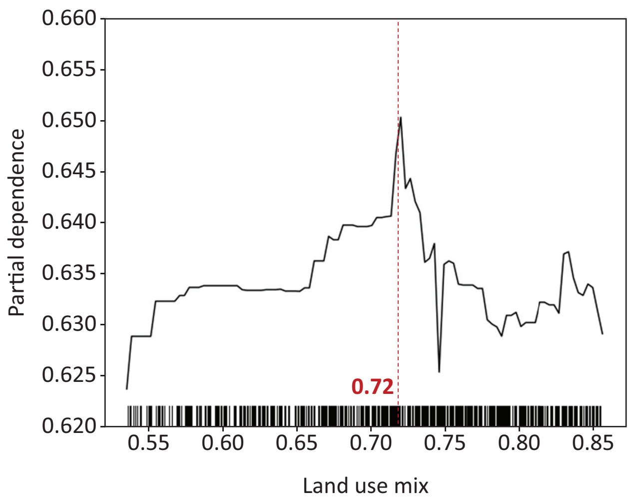
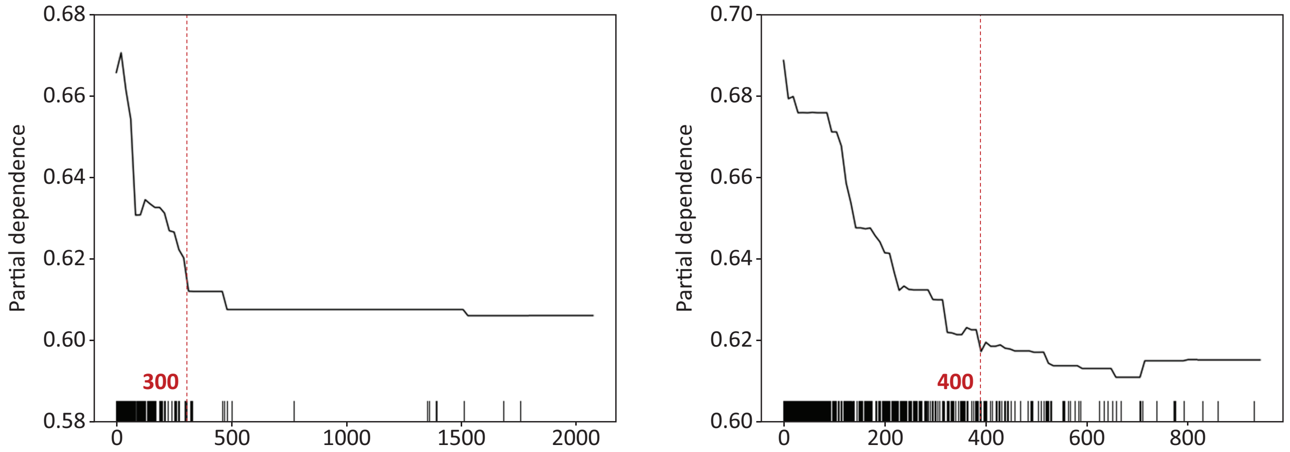


Figure 6. Nonlinear relationship between diversity variable and car dependency. Note: Y-axes represent the probability of using a car as the main mode.



(a) Transit service frequency per square kilometer (counts/km²)

(b) 10^3 jobs reached by public transit within 45 minutes

Figure 7. Nonlinear relationship between destination accessibility variables and car dependency. Note: Y-axes represent the probability of using a car as the main mode.

public transit accessibility increases the possibility of public transit use, and in turn, reduces car use. A significant threshold effect is observed for both transit service frequency and jobs reached by public transit. Car dependency witnesses a dramatic decline when the transit service frequency is below 300 per kilometer, afterward, the curve remains unaffected. This may suggest that people's demand for public transit services is satisfied when the transit frequency per square kilometer is 300. Further increasing transit frequency may not be able to decrease car dependency significantly. A similar pattern is also observed for job accessibility. Areas with high job accessibility are favored by public transit more. One explanation is that these areas can provide enough demand that can well maintain the efficiency of public transit systems. Moreover, these areas have high commuting demand, and car use is normally restricted to avoid severe congestion, such as high parking costs.

5. Conclusions

The extensive use of private cars has caused many problems for society. Reducing car dependency and thus relieving the severe issues caused by car dependency has become one of the key objectives of transportation development and land use interventions. Many previous studies have confirmed that compact development and transit-oriented development could be effective strategies to reduce car use and lower the externalities of car dependency (Saeidizand et al., 2022). How to implement efficient planning policies is vital for policymakers and transportation planners. This study analyzed the nonlinear relationship between the built environment and car dependency using a machine learning method, taking Puget Sound Region as the case area. Results show that except for the highest contribution of vehicle ownership, the built environment has a higher average relative importance than individuals' and household socioeconomic and demographic characteristics. This differs from some previous studies, suggesting that the way people travel is strongly affected by individuals' age, gender, income, and employment status (Boussauw & Witlox, 2011). The finding also provides new evidence to further support that built environment factors have more significant impacts on car use (Holtzclaw et al., 2002; Lewis, 2018). For built environment factors, destination accessibility variables have the highest relative importance, followed by design variables. The overall effects of the built environment factors on car dependency are consistent with previous studies (Ding & Cao, 2019; Newman & Kenworthy, 1989a, 1989b; Pinjari et al., 2011). For example, high density leads to low car dependency. Sufficient public transit services and high public transit accessibility can decrease the possibility of using a car as the main mode of a trip. This study further found that built environment factors have significant nonlinear and threshold effects on car dependency, which also provides new insight into the previous nonlinearity studies using the exponential function method. Moreover, the nonlinear relationship captured using a machine learning method releases the pre-defined statistical assumptions that will gain more sophisticated results. This research uncovered that the effect of a built environment variable is only effective within specific intervals of this attribute, which also provides evidence-based guidance for nuanced land use interventions, at least for the government of the Puget Sound Region.

Our results will be useful to provide policy implications for Puget Sound Region to reduce car dependency. First, both high residential density and employment density can lead to low car dependency, which comes with no surprise to further support population densification and increasing employment opportunities near the neighborhoods can reduce people's car use. Second, an efficient road network and pedestrian-friendly street design are helpful to reduce car dependency. An effective road network can encourage people to use shared mobility services more (e.g., bike-sharing, ridesourcing) based on previous studies (e.g., Cheng, Jin, et al., 2022; Jin, Cheng, Zhang, et al., 2022). High pedestrian-oriented road density can also encourage active travel modes, which in turn, reduce car use. Third, good access to public transit services can increase people's use of public transit services and decrease people's car use. Increasing density (i.e., population density, employment density, and building density) can reduce people's car use, which is a valuable strategy for urban planning. However, we should also acknowledge that it is not easy to implement densification since it is faced with challenges for some cities to increase density. Promoting road design and increasing public transit services can be much more operational ways to reduce car dependency. This research further found that the negative association between design and destination accessibility variables and car dependency is effective when the values of built environment variables are within a specific range. These can provide evidence-based guidelines to help policymakers to use limited resources to reduce car dependency through targeted strategies.

The study has several limitations, which promote future research agendas. First, the built environment may have not only a direct impact on travel behavior but also an indirect influence through residential self-selection, which was not considered in this research. Second, the nonlinear relationships between the built environment and car dependency are analyzed only in the Puget Sound Region, validated evidence from other case areas should be provided to test the generalizability of our findings. Nonetheless, this study examines how the built environment affects car dependency, which would help to support targeted and nuanced planning policies to encourage sustainable transportation systems.

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Conflict of Interests

The authors declare no conflict of interests.

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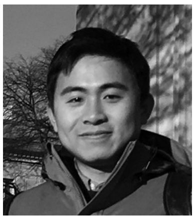

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Article

Car Use: A Matter of Dependency or Choice? The Case of Commuting in Noord-Brabant

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Abstract

Car use in the sprawled urban region of Noord-Brabant is above the Dutch average. Does this reflect car dependency due to the lack of competitive alternative modes? Or are there other factors at play, such as differences in preferences? This article aims to determine the nature of car use in the region and explore to what extent this reflects car dependency. The data, comprising 3,244 respondents was derived from two online questionnaires among employees from the High-Tech Campus (2018) and the TU/e-campus (2019) in Eindhoven. Travel times to work by car, public transport, cycling, and walking were calculated based on the respondents' residential location. Indicators for car dependency were developed using thresholds for maximum commuting times by bicycle and maximum travel time ratios between public transport and car. Based on these thresholds, approximately 40% of the respondents were categorised as car-dependent. Of the non-car-dependent respondents, 31% use the car for commuting. A binomial logit model revealed that higher residential densities and closer proximity to a railway station reduce the odds of car commuting. Travel time ratios also have a significant influence on the expected directions. Mode choice preferences (e.g., comfort, flexibility, etc.) also have a significant, and strong, impact. These results highlight the importance of combining hard (e.g., improvements in infrastructure or public transport provision) and soft (information and persuasion) measures to reduce car use and car dependency in commuting trips.

Keywords

built environment; car dependency; car use; infrastructure; Noord-Brabant; preferences

Issue

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1. Introduction

Since Benz developed the first car in 1885, it has become the dominant mode of transport on our streets. In addition to the practical advantages for individuals such as speed and flexibility, cars are also considered a symbol of social status and identity and an enabler for economic growth (Alshammari et al., 2022; Lau, 2013). However, this individual freedom comes with a price of increasing negative externalities such as greenhouse gas emissions, congestion, air and noise pollution, social exclusion, and physical inactivity (Merom et al., 2018; Saeidizand et al., 2022; Van Wee, 2013). To counteract these negative externalities, governments have implemented policy measures to promote the use of sustainable transport and reduce car usage. However, moving away from the car system is no easy feat. This difficulty of moving away from a car-dominated system, for both individuals and society at large, is also referred to as "car dependency" (Mattioli et al., 2016). Car dependency is associated with elevated levels of car ownership and use, a lack of attractive sustainable transport alternatives, and a sprawling, decentralised, and unattractively built environment (Jeekel, 2013; Newman & Kenworthy, 1989; Saeidizand et al., 2022).

The extent to which people experience car dependency varies. At elevated levels of car dependency, a viable alternative for car use is not available. This structural car dependency is related to factors such as the lack of a supporting built environment and transport infrastructure for alternative modes. Research has shown that these two factors are strongly intertwined. Extensive car use goes hand in hand with the suburbanisation of residential neighbourhoods and the decentralisation of employment, amenities, and retail facilities. This in turn leads to the marginalisation and stigmatisation of sustainable transport modes which increases dependency on the car. These feedback mechanisms lead to a self-reinforcing cycle of car dependency (Litman & Burwell, 2006; Wegener & Fuerst, 2004). Previous studies also showed that the characteristics of the built environment have a significant effect on the extent and the share of car use, although results are mixed. The built environment indicators in these studies can be summarised under the 5 Ds: density, diversity, design, destination accessibility, and distance to public transport (hereafter PT; Ewing & Cervero, 2010). Overall, the accessibility indicators (e.g., distance to downtown, job accessibility by car/PT) proved to exert the strongest influence on travel behaviour. This is probably because accessibility integrates the potential proximity effects of other Ds such as density, diversity, and distance to PT (Ewing & Cervero, 2010). While most studies focused on the residential built environment, others also incorporated the characteristics of the employment locations. Results showed that the employment location and the multimodal accessibility and availability of free parking at these locations are important determinants of commuter modal choice (Maat & Timmermans, 2009; Vale et al., 2018; Wang et al., 2015).

In addition to structural factors, car dependency also stems from personal and household factors. For instance, dual-earner households with children may consciously choose to own one or more cars because they have to combine multiple activities and destinations in their daily schedule which requires speed, flexibility, and convenience (Mattioli et al., 2016). Furthermore, psychological factors such as car-oriented habits, perceptions, and attitudes can contribute to people's perceived level of car dependency and higher levels of car use (Anable, 2005; Gärling et al., 1998; Haustein & Hunecke, 2007; Schwanen et al., 2012; Van de Coevering et al., 2016). Importantly, characteristics of the transport network and transport-related attitudes also play a role in people's long- and medium-term life choices regarding their residential environment and work location. Due to the increase in travel speeds, people have reduced residential mobility and instead increased commuting distances (Beige & Axhausen, 2017; Cullen, 1978; Van Acker et al., 2010). In that sense, it can be argued that people make themselves car-dependent as they increasingly organise their lives around the car, slowly developing a car-oriented lifestyle over time (Van Acker & Witlox, 2010). Longitudinal analyses have also shown that (a) long- and medium-term choices regarding the residential environment and places of employment, (b) decisions around vehicle ownership and PT season tickets, and (c) daily choices regarding commuting are strongly intertwined (Beige & Axhausen, 2008).

While a rich body of literature has developed around the structural, personal, and psychological determinants of car use, fewer studies conducted a detailed assessment of the level and nature of car dependency on trip level (Mattioli et al., 2016). This study aims to contribute to the current knowledge by assessing the level of structural car dependency and determinants of car commuting among non-car dependent commuters towards two separate campus locations, the Campus of the Technical University of Eindhoven (TU/e-campus) and the High-Tech Campus Eindhoven (HTCe), in the Brainport region around Eindhoven in the Netherlands. We specifically aim to address the following research question: To what extent is car commuting towards the campus locations a matter of car dependency or choice, and what factors contribute to car use among non-car-dependent commuters?

This article uses the results of a questionnaire that was distributed among employees of businesses in both campus locations. It starts with an assessment of the level of car dependency. Different thresholds were used to distinguish between people that are structurally car-dependent (due to the lack of alternatives) and people that are not structurally car-dependent but use the car based on choice (related personal and psychological factors). Subsequently, bivariate descriptive analyses and binomial logit modelling are conducted for the non-car-dependent commuters to determine which factors contribute to their car use, including socio-demographics, mode choice preferences (comfort, flexibility, etc.), characteristics of the residential location, and the quality of different transport modes for the commute trip.

This article adds to the existing knowledge through the development of indicators for car dependency based on travel time ratios of PT and cycling times to car travel times. Travel time ratios have been used more often, especially in PT-related research, but there are few studies which incorporated travel time ratios for PT and cycling simultaneously. In addition, this study analyses the determinants of car commute choice for non-car-dependent commuters who have at least one viable alternative (PT or cycling) available. To date, few studies on commute mode choice took car dependency into account.

We start this article with a description of the questionnaire and the data. Subsequently, we will elaborate on the methods for determining the level of car dependency and the development of binomial regression models for car use. Thirdly, the results of the descriptive analysis and the logit models will be discussed. Finally, we will discuss the implications of research outcomes for policy.

2. Questionnaire and Data

2.1. Questionnaire

The data used for this research was derived from a self-administered online questionnaire that was conducted amongst employees of the TU/e-campus and HTCe in 2019 and 2018, respectively. The geographical location of the campuses and their characteristics differ considerably (Figure 1). The TU/e-campus (1) is located in the central part of Eindhoven and is close to the central railway station enabling an easy egress trip either on foot or by bicycle. The campus is also easily accessible by car, although roads in the city are prone to congestion. For employees, parking is available for a fixed fee of €2 per day. The HTCe (2) is located on the city fringe, next to the A2/A67 highway and has direct highway access. The campus is accessible by PT via a bus line that takes approximately 30 minutes from the central railway station. Parking is free. In line with the strong bicycle culture in the Netherlands, both campus locations have a high-quality bicycle infrastructure which enables safe and smooth accessibility.

The questionnaire was developed by Brabant Mobiliteitsnetwerk (BMN), a collaboration between regional road authorities and 260 companies, divided over 21 communities. BMN started in 2014 and aims to actively facilitate employers to promote behavioural change from car commuting to more sustainable modes of transport. A standardised survey was developed to offer leads to employers about effective access and mobility facilities, interventions and incentives, and the possibility to benchmark one with the other.

The questionnaire was divided into three main parts distinguishing home and work location data, mode choices, and socio-demographic control variables. In the first part, the mobility perspective was questioned, where the survey aimed to gain insights into home-work distances, travelling in peak hours, and flexibility in working hours. In the second part, respondents were asked about their current modal choice and were also asked to select three mode choice preferences that were important for this choice from a total list of eight factors including speed, flexibility, comfort, reliability, cost, health, weather conditions, and the environment. The third part of the questionnaire included questions regarding sociodemographics including gender and age.

2.2. Data About Transport and the Built Environment

To derive the travel distances and travel times per employee, the survey asked for the zip codes (four digits) of the home locations. Based on the home and work location of each employee, the fastest route was calculated using digital networks for car, bicycle, and PT. To distinguish car travel times with and without congestion, a distinction was made between on- and off-peak period networks using average observed car travel speeds per network segment. For cycling, network speeds and travel times were derived from empirical GPS cycling data from a national cycling incentive project (the National Bike Counting Week). Travel times for PT were based on the actual bus services, incorporating travel times, the number of transfers, and waiting times. For each employee, the fastest route between the home and work location was calculated using the different networks as input for the analyses, where the insights of multimodal travel times were combined with the main mode of transport stated in the survey.

The combination of the questionnaire data and the travel time data provided a unique dataset that enabled us to determine the level of structural car dependency and to develop a modal that explains why non-car-dependent commuters choose to use the car. In addition,

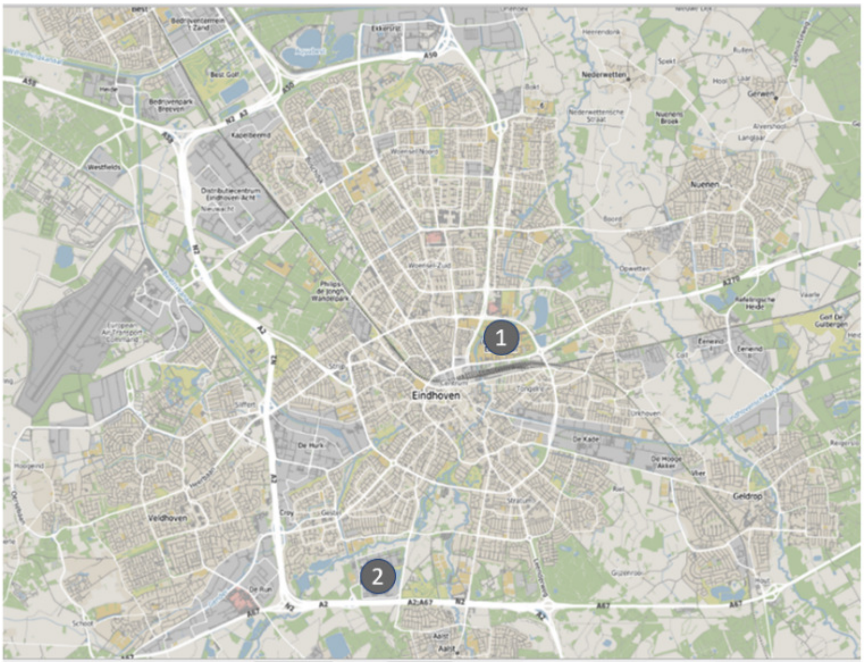

Figure 1. Campus locations.

characteristics of the respondents' residential location (PC4 level) were retrieved from Statistics Netherlands (CBS), including residential density, zonal car ownership, and distances to train stations and the main road (CBS, 2020).

2.3. Data Description

BMN distributed the questionnaires to the employees of the companies located at both campus locations. Unfortunately, we do not have detailed information about the response rates. However, generally, the response rates for the BMN questionnaires were high (averaging around 50%) as all companies are actively involved in the regional BMN community. After data cleaning, the total number of records in the combined dataset was 3,244. Around 40% of the respondents work at TU/e-campus and the remaining 60% are HTCe workers. Table 1 summarises the basic description of the dataset after data cleaning. It includes the basic demographic characteristics of respondents, information about their residence and work location, and travel modes for commuting.

As can be seen in Table 1, the majority of respondents are male. Due to the technical nature of the jobs on these two campuses, this is in line with expectations. Almost all the respondents are between 25 and 65 years old and evenly distributed in this range with a slight peak for the level of 45- to 55-year-olds. More than 75% of respondents work more than four days a week and can be categorised as full-time workers. Less than 10% of the sample are occasional workers with one or two working days. The majority of the respondents (54%) work at home at least once a week. The primary mode for commuting is the mode of travel that commuters often use for work trips. Besides the primary mode, some of them (60%

Table 1. Basic description of total respondents in the cleaned dataset (*N* = 3,244).

Variable	Level	Number	Share
Age (year)	Under 25	61	2%
	25 to 34	40	23%
	35 to 44	780	24%
	45 to 54	919	28%
	55 to 64	696	22%
	Over 65	48	1%
Gender	Male	2,214	68%
	Female	1,030	32%
Work location	TU/e-campus	1,321	41%
	HTCe	1,923	59%
Working days in a week	1	129	4%
	2	171	5%
	3	467	14%
	4	1,018	32%
	5	1,459	45%
Working from home	At least one day a week	1,742	54%
Primary mode for commuting	Car	1,570	48%
	PT	345	11%
	Bicycle	1,222	38%
	Walk	51	1%
	Other	56	2%
Secondary mode for commuting	Car	724	22%
	PT	467	15%
	Bicycle	530	16%
	Walk	126	4%
	Other	94	3%
	Non	1,303	40%
Urbanisation level of residence location (Density: Number of addresses per square km)	Extremely urban (>2,500)	779	24%
	Strongly urban (1,500–2,500)	888	28%
	Moderately urban (1,000–1,500)	649	20%
	Hardly urban (500–1,000)	660	20%
	Not urban (<500)	268	8%

of respondents) also use another mode for commuting, although less frequently. Two modes of car and bicycle form the major modes for commuting as primary as well as secondary modes. Nearly half of the sample uses the car as the primary mode for commuting, while 38% use a bicycle. PT, walking, and other modes are used less often. Except for the non-urban areas, the shares of urbanisation level of respondents' residence locations are quite evenly distributed over the other four categories with slightly higher shares in the higher urbanisation levels.

3. Methodology

The flow chart depicted in Figure 2 illustrates the analysis structure of this research. An important step in this research was identifying to what extent car use is a necessity and to what extent it is a matter of choice. We defined different indicators and thresholds to categorise the respondents into car-dependent and non-car-dependent commuters and conducted a sensitivity analysis to show the effect of different assumptions on the calculated level of structural car dependency. Based on the sensitivity analyses we chose a fixed set of indicators and thresholds and clustered commuters into the car-dependent and non-car-dependent groups. Based on these clusters, we used descriptive analyses and developed a binomial logit model to analyse which factors influence the choice for car commuting when viable sustainable alternatives are available. Next, we will elaborate on the measures of car dependency and the model structure.

The literature overview in the introduction showed that structural and personal factors affect people's level of car dependency. Our measure for car dependency focused on the structural part and specifically on the multimodal accessibility of the work locations in the form of travel time as described in Section 2.2. As shown in Table 1, car, bicycle, and PT are the main modes of commuting. For each respondent, the travel time by car is compared to the travel time by PT and bicycling. People are considered to be car-dependent if travel times of PT and bicycling are not competitive enough.

Two measures were defined to determine car dependency based on these three modes' travel times: acceptable cycling time (ACT) and PT/car travel time ratio (PTC ratio). For bicycling a maximum ACT was chosen as, due to the lower average speed, the bicycle is mainly a competitive option for relatively short commutes. For PT, a ratio between PT and car travel time was chosen as a basis for the indicator of car dependency as both travel modes allow for longer-distance commuting. When travel times for both modes are comparable (ratio = 1.0), commuters are distributed evenly over car and PT, but the share of PT users decreases rapidly as the PT/car travel time ratio increases (Van den Heuvel & Van Goeverden, 1993).

For the ACT and PTC ratio, cut-off values were selected to enable the allocation of respondents to the car-dependent and non-car-dependent commuter groups. To arrive at a well-considered choice, a sensitivity analysis was conducted. Figure 3 shows the relationship between the values for the ACT and the PTC ratio and the resulting number of car-dependent commuters. For both measures, the line represents the effects of different values assuming that the other measure remains constant (ACT = 25 minutes and PTC ratio = 2). The graph reveals that the number of car-dependent commuters strongly depends on the selected thresholds. An ACT of

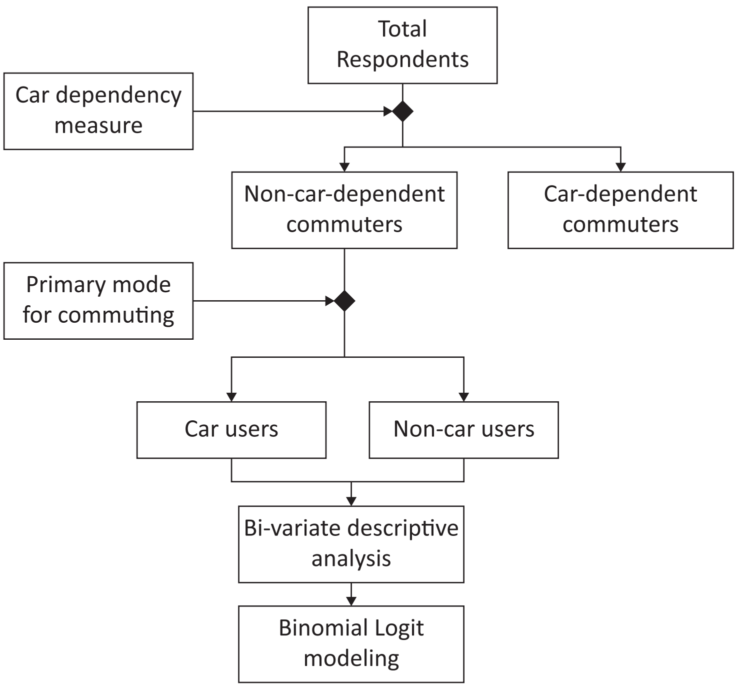

Figure 2. Analysis structure and respondent classification.

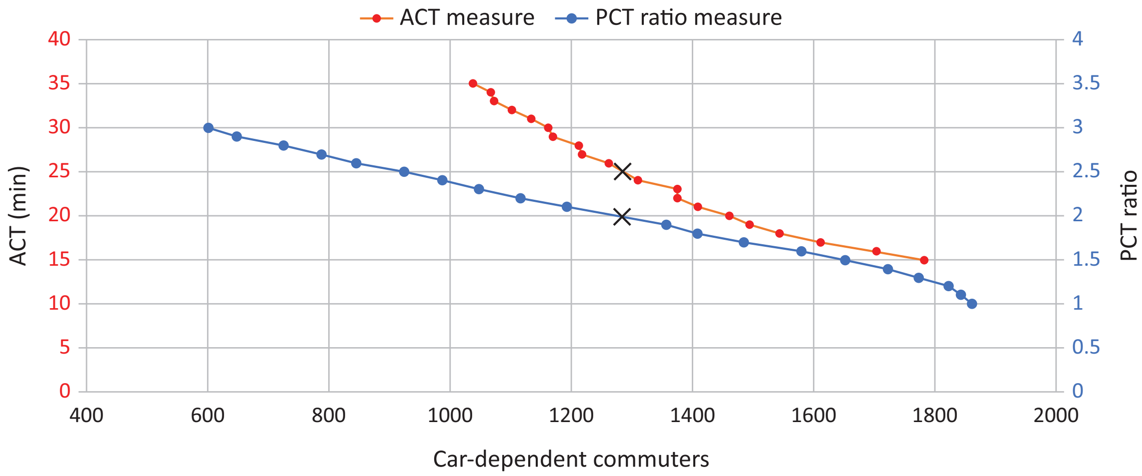

Figure 3. ACT and PCT ratio effects on the number of car-dependent commuters.

35 minutes results in 1,037 car-dependent commuters (32%), while an ACT of 15 minutes would mean that 1,782 commuters (55%) are car-dependent. A PTC ratio of 2, which means that commute times for PT are allowed to be twice as long as the travel time by car, leads to 1,284 car-dependent commuters (40%), while a ratio of 1 (same travel time) would result in 1,862 commuters (57%) being identified as car-dependent.

To select an appropriate value for the ACT, an additional travel time decay function for bicycle commuting was calibrated using data from the Dutch National Travel Survey (ODiN; CBS, 2022). This function reveals the relationship between travel time and the share of bicycle commuting. Specifically, it shows the share of bicycle commuters who currently travel for the corresponding travel time or less. For this research, we used the 80% cut-off value for the ACT which equals 25 minutes. This means that 80% of bicycle commuters in the Netherlands travel 25 minutes or less for commuting purposes. For commuters with an estimated bicycle time towards the work location above 25 minutes, bicycling is not considered a viable alternative. This applies to 1,868 respondents (58%) in our sample. This cut-off value is in line with previous research in this field that considers 7.5 km and approximately 25 to 30 minutes of cycling time as the maximum for bicycle commuting (Milakis & Van Wee, 2018; Scheepers et al., 2015).

For the PCT ratio, we used the results from the sensitivity analysis and the literature and selected a conservative value of 2.0, which means that for commutes where travel time by PT is more than twice the travel time by car, PT is not considered a viable alternative. Using this threshold, the campus locations are not sufficiently accessible by PT for approximately 80% of the commuters. This shows that the competitive position of PT is not favourable for commute trips, a finding that is supported by a recent study into the accessibility of jobs and amenities in the Netherlands by Bastiaanssen and Breedijk (2022). The combined effect of the ACT and PTC ratios provides insight into the overall car dependency of respondents. Considering an ACT of 25 minutes and a PCT ratio of 2.0, the number of car-dependent commuters equals 1,284 (40%). For these respondents, PT or bicycling is not a viable alternative. The remaining 1,960 respondents (60%) have at least one option available and are considered to be non-car-dependent commuters. The next section explores the level and the determinants of car use for these non-car-dependent commuters using bivariate analysis and binomial logit modelling.

4. Results

4.1. Bivariate Analysis of Non-Car-Dependent Commuters

The non-car-dependent commuters differ from the overall sample in several characteristics. Regarding age and gender, the non-car-dependent commuters are a bit younger, and the share of females is a bit higher. Table 2 presents the characteristics of car-dependent and non-car-dependent commuters with the most significant differences. Regarding the work location, a larger share of non-car-dependent commuters works at the TU/e-campus. Not surprisingly, compared to the overall sample, the share of car use among non-car-dependent commuters is lower (31%) and the share of bicycle use is higher (53%). The shares of PT use (13%) and walking (3%) are also higher but to a lesser extent. This shows that the travel times for the bicycle and PT compared to the travel time by car are important determinants of commute mode choice. At the same time, almost one-third of the non-car-dependent commuters use the car while an alternative is available. Also, the differences in modal choice indicate that especially the bicycle competes with car usage while this applies to a much lesser extent to PT and walking. In Table 2, the modal choices of non-car-dependent commuters and their determinants are explored in more detail.

Table 3 shows the average commuting times by different transport modes for all non-car-dependent

Table 2. Basic description of the car-dependent and non-car-dependent commuters (*N* = 3,244).

Variable	Level	Car-dependent commuters		Non-car-dependent commuters	
		Number	Share	Number	Share
Work location	TU/e-campus	228	18%	1,093	56%
	HTCe	1,056	82%	867	44%
Primary mode for commuting	Car	969	76%	601	31%
	PT	95	7%	250	13%
	Bicycle	180	14%	1,042	53%
	Walk	1	0%	50	2%
	Other	39	3%	17	1%
Urbanisation level of residence location (Density: Number of addresses per square km)	Extremely urban (>2,500)	113	9%	666	34%
	Strongly urban (1,500–2,500)	235	18%	653	33%
	Moderately urban (1,000–1,500)	271	21%	378	19%
	Hardly urban (500–1,000)	452	35%	208	11%
	Not urban (<500)	213	17%	55	3%

commuters and their subgroups of car commuters and non-car commuters. A comparison of the average commuting times shows that travel times for car commuters are significantly higher compared to their non-car commuting counterparts. The travel time by bicycle differs in particular, indicating that the car commuters reside at significantly larger distances from their work location.

Table 4 shows the characteristics of commuters' work and residence locations. The results indicate that the work location and the built environment characteristics of the residential location play a role in the non-car-dependent commuter's modal choice. Commuters towards the HTCe use the car more often than their counterparts at the TU/e-campus even if they are in the

Table 3. The average transport network factors for non-car-dependent commuters.

Variable	Unit	All non-car-dependent	Car commuters non-car-dependent	Non-car commuters non-car-dependent
Travel time to work by bicycle	Minutes	69	110	51
Travel time to work by PT	Minutes	42	54	36
Travel time to work by car (peak)	Minutes	22	30	18
Travel time to work by car (off-peak)	Minutes	16	22	13

Table 4. Built environment factors for non-car-dependent commuters.

Variable	Unit (Level)	All non-car-dependent	Car commuters non-car-dependent	Non-car commuters non-car-dependent
Work location	TU/e-campus	1,093	266	827
	HTCe	867	335	532
Density of residence location	Number of addresses per km^2	2,229	1,749	2,442
Distance to the nearest train station	Km	4.1	5.0	3.7
Distance to the nearest main train station	Km	5.5	7.4	4.7
Distance to the nearest main road	Km	2.6	2.8	2.5
Car ownership	Vehicle per household	1.0	1.1	0.9

Note: Main roads are provincial or national roads.

non-car-dependent commuter group. Among car commuters, the density of the residence location is significantly lower (1,749 versus 2,442 addresses per square kilometre). This implies that commuters residing in residential areas with lower densities are more inclined to commute by car. This may be because distances to train stations are beyond the distance that people are willing to walk or cycle. Although the Dutch are famous for their extensive bicycle use towards railway stations (Kager & Harms, 2017), these feeder trips to the railway station usually do not exceed 3 or 4 kilometres (CBS, 2022). Of course, residents can also take the bus to a railway station, but this often involves suboptimal transfers at the railway station due to the lack of synchronisation between bus and train services or due to travel time variations that result in missed transfers (Gkiotsalitis & Maslekar, 2018). The distance to the main road is larger for car commuters which may be related to the fact that car commuters reside more often in hardly urban and non-urban areas. Average zonal household car ownership levels are also slightly higher in car commuters' residential areas.

In addition to the structural factors, personal and psychological factors affect car commute choice. Table 5 includes preferences for respondents' modal choices. Each respondent was asked to choose the three most important factors that influence their modal choice. Overall, speed was the factor that was chosen most often, among car commuters as well as non-car commuters. So even though speed is an important asset of car usage, it does not seem to be the decisive factor as non-car commuters also attach value to speed. Compared to non-car commuters, car commuters attach more importance to the flexibility and the comfort of car use. In line with findings from Koetse and Rietveld (2009), commuters also seem more inclined to use the car due to weather conditions. For non-car commuters, factors such as environmental issues, health, cost, and to a lesser extent reliability play a role. The latter is probably related to the fact that most non-car commuters use the bicycle for commuting which is less sensitive to delays. As commuters to and from the HTCe are inclined to use the car more often, we analysed their mode choice preferences separately. As expected, the HTCe commuters select factors that are associated with car commuting (speed, comfort, and weather) more often and select the cost of the commute, associated with less car commuting, less often. Interestingly, not all factors preferred among HTCe commuters are associated with car commuting. They choose flexibility less often compared to the TU/e-campus commuters while they choose health more often. As for considerations regarding the environment, scores are comparable.

4.2. Binomial Logit Model

To evaluate which factors influence non-car-dependent commuters' mode choices, a logit model was calibrated which predicts the odds of a certain outcome occurring based on a set of independent variables. As our primary focus was on the choice between car commuting versus non-car commuting, we decided to fit a binary logit model which predicts the odds of people choosing to commute by car rather than by an alternative commute mode (PT, cycling, walking, and other modes). To check for mode-specific effects, we also calibrated a multinomial logit model, on all 3,244 respondents, yielding specific coefficients for each transport mode. As the coefficients of this model were in line with the results of the binomial model, and because we were interested in the odds of car use amongst non-car-dependent commuters, we decided to include only the results of the binomial model in this article. Table 6 shows the model results, including the coefficients, *p*-values, and odds ratios. The coefficients show the direction of influence (positive or negative), and the *p*-values show the level of significance. Only variables with a p-value of 0.05 or less were included in the model. As the coefficients of the models are in logit units, they are difficult to interpret. Therefore, they are exponentiated and translated into odds ratios. In this model, the odds ratios can be interpreted as the increase in odds of car commuting relative to non-car commuting for each unit increase in the independent variable. What's important to note, is that the odds ratios in logit models are not standardised. This means that odds ratios and the relative influence of

Table 5. Distribution of mode choice preference factors for non-car-dependent commuters.

Variable	Factor	All non-car-dependent	Car commuters non-car-dependent	Non-car commuters non-car-dependent	TU/e-campus employees	HTCe employees
Mode choice preferences	Speed	47%	54%	44%	45%	50%
	Flexibility	38%	48%	34%	39%	36%
	Comfort	21%	31%	16%	16%	27%
	Reliability	19%	13%	22%	17%	23%
	Cost	21%	8%	27%	28%	12%
	Health	28%	7%	38%	23%	35%
	Weather	20%	30%	15%	13%	28%
	Environment	21%	1%	29%	21%	20%

Table 6. Binomial logit model coefficient estimation (car versus non-car commuting).

Variable category	Variable code	Variable description	Coefficient	*p*-value	Odds ratio
Demography	Age 35	If the respondent is younger than 35 years old = 1 Otherwise = 0	−0.7582***	0.0000	0.4685
	Gender	If the respondent is male = 1 Female = 0	−0.3858***	0.0050	0.6799
Transport network	Bikettfac	Ratio of travel time by bicycle over travel time by car (peak period)	0.2804***	0.0000	1.3237
	Carttfac	If the ratio of travel time by car in off-peak over peak period is less than 0.5 = 1 Otherwise = 0	−0.3769**	0.0500	0.6860
Urban design/form	Density	One thousand dwellings per Km^2 in the city of residence	−0.4122***	0.0000	0.6622
	Maintraindist	Distance from residence location to the nearest main train station (km)	0.0778***	0.0001	1.0809
	TU/e	If the work location is TU/e-campus (near the city centre and central train station) = 1 If the work location is HTCe = 0	−0.4084**	0.0109	1.5044
Travel preference	Comfort	If "Comfort" is one of the factors considered by the respondent for choosing travel mode = 1 Otherwise = 0	0.4079***	0.0076	1.5036
	Weather	If "Weather condition" is one of the factors considered by the respondent for choosing travel mode = 1 Otherwise = 0	0.8804***	0.0000	2.4119
	Flexible	If "Flexibility" is one of the factors considered by the respondent for choosing travel mode = 1 Otherwise = 0	0.7485***	0.0000	2.1137
	Environment	If "Environmental impacts" is one of the factors considered by the respondent for choosing travel mode = 1 Otherwise = 0	−2.9678***	0.0000	0.0514
	Cost	If "Cost" is one of the factors considered by the respondent for choosing travel mode = 1 Otherwise = 0	−1.1754***	0.0000	0.3087
	Reliable	If "Reliability" is one of the factors considered by the respondent for choosing travel mode = 1 Otherwise = 0	−0.6945***	0.0001	0.4993
	Health	If "Health" is one of the factors considered by the respondent for choosing travel mode = 1 Otherwise = 0	−1.8417***	0.0000	0.1586
CST	Constant		0.0798	0.8041	—

Notes: Reference category is non-car commuting; log-likelihood = −747.6971; McFadden's pseudo-R squared/adjusted = 0.376; *N* = 1,960 (601 car commuters and 1,359 non-car commuters); Significance = ***99% and **95%.

explanatory variables on the odds of car commuting cannot be compared if the variables do not share the same metric. As the dummy variables in our model do share the same metric (0 or 1), their relative influence can be compared. The model was calibrated based on 1,960 respondents and has a pseudo-R-squared (McFadden's pseudo-R squared/adjusted) of 0.3763. As values above 0.2 indicate a good model fit this means that our model fits the data very well (Louviere et al., 2000). The variables are classified into four categories: demography, transport network, urban design/form, and travel preferences. For a more detailed description of the variables, we refer to the second section (questionnaire and data).

The model shows that the ratio of travel time by bicycle over travel time by car has a highly significant effect on the odds of using the car for commuting. A one-unit increase in the ratio of travel time by bicycle over travel time by car (OR = 1.3237) leads to 32% higher odds of using the car for commuting. So, shorter travel times by bicycle (compared to car travel times) decrease the odds that people use the car for commuting. The overall ratio of travel time by car in off-peak over peak period was not significant, but a dummy for more extreme congestion, where peak travel times are more than twice as long, was. When this happens, the odds of using the car for commuting are reduced by 31% (OR = 0.6860). Contrary to expectations, the travel time ratio for PT did not yield any significant results.

The urban form factors also have a significant impact. An increase of 1,000 dwellings per km^2 results in a reduction of the odds of commuting by 34% (OR = 0.6622). The distance to the nearest railway station also has a significant influence (OR = 1.0809). When people live one km further from the main railway station, they have 8% higher odds of using the car for commuting. We also included a dummy variable for the work location to determine the effect of commuting to a central campus location versus a location on the city fringe. Interestingly, this proves to be one of the dummy variables with the strongest influence on commute mode choice. After controlling for the other variables, working at the TU/e-campus (compared to the HTCe) decreases the odds of car commuting by 50% (OR = 1.5044).

Travel preferences have a strong impact on the choice of car commuting. Except for the factor speed, the influence of all preferences is significant. People who considered weather (OR = 2.4119) and flexibility (OR = 2.1137) as important factors for their commute choice, have 141% and 111% higher odds respectively to commute by car. Comfort (OR = 1.5036) has a smaller, but still highly significant impact and increases the odds to commute by car by 50%. The other travel preferences have a negative impact on the odds of car commuting. For people who considered the environmental impact (OR = 0.0514) as an important factor, the odds of commuting by car are reduced by 95%. In descending order, health (OR = 0.1586), cost (OR = 0.3087), and reliability (OR = 0.4993) also reduce the odds of car commuting by 84%, 69%, and 50%, respectively.

The influence of age and gender is also significant. A dummy variable for the age variable, including respondents younger than 35 years old has a negative sign as expected (OR = 0.4685). So, the odds that people younger than 35 years old take the car for commuting is 53% lower compared to the older age groups. The negative sign for male respondents (OR = 0.6799) is surprising and implies that for males the odds of commuting by car are 32% lower than those of their female counterparts. Perhaps this is because household responsibilities for women are higher, especially when there are children involved which increases the need for speed and flexibility that is still best facilitated by the car. Contrary to our expectations, the number of working days and the number of days working at home did not significantly affect the odds of using the car when other variables were accounted for.

5. Conclusions

This study aimed to add to the current knowledge regarding car dependency by assessing the level and determinants of car dependency for commuting trips to and from two campus areas in the Netherlands. Two indicators for car dependency were defined, one based on the travel time ratio between PT and car and the other based on the ACT. A sensitivity analysis was conducted to determine the cut-off values for car-dependent and non-car-dependent commuters and descriptive bivariate analysis and binomial logistic regression models were used to explore which factors determine car commuting among the non-car-dependent respondents.

So, to what extent is car usage a matter of dependency or choice? Currently, 48% of the respondents in our sample use a car for commuting. Our results reveal that approximately 40% of these respondents can be categorised as being structurally car-dependent because cycling distances are too long, and the quality of the PT system is insufficient. This implies that commuters for which PT and/or cycling are a viable alternative, already use these modes quite often. This does not apply to all commuters, however, as 31% of the non-car-dependent commuters in our sample commute by car. Our bivariate descriptive analysis and the logit model provide a better understanding of the determinants behind this choice. As the results of both analyses are mostly aligned, we will primarily refer to the logit model for interpretation and discussion.

As our indicators for car dependency are based on travel time, the influence of travel time ratios is important in the context of this article. In line with findings from previous studies, the travel time ratio for cycling showed that more competitive bicycle travel times reduce the odds of car commuting. Interestingly, this does not apply to the travel time ratio for PT. The latter is not consistent with the literature (e.g., Lunke et al., 2018) and indicates that improvements in PT travel time do not have a significant influence on the choice for car commuting. Apparently, in this specific Dutch context, the bicycle is a stronger competitor for car commuting than PT. We also found that severe congestion reduces the odds of car commuting which implies that car congestion could trigger people to shift to PT or cycling (see also Sweet & Chen, 2011).

Like many researchers before us, we found that the built environment matters (e.g., Ewing & Cervero, 2010; Van de Coevering et al., 2016). A lower density of the residential location and longer distances towards the nearest railway station increase the odds of car commuting. What is interesting is the strong effect of a dummy variable for the work location which reveals that commuters to the HTCe have much higher odds of car commuting compared to their TU/e-campus counterparts. Probably, the difference in built environment characteristics is an important underlying factor as the TU/e-campus is located close to the centre and main train station while the HTCe is located at the city fringe near the highway. In addition, differences in mobility management such as company car policies and parking regulations could be factors of influence. This corroborates the findings of Maat and Timmermans (2009) who found that the characteristics of the work environment are at least as important as the residential environment for people's commuting behaviour.

Importantly, our research findings point out the significant and strong role of travel preferences. Weather and flexibility have a positive and, of all dummy variables in the model, by far the strongest influence on the odds of commuting by car. To a lesser extent, this applies to preferences for comfort. Environmental impact has the strongest negative influence on the odds of commuting by car followed by health, costs, and reliability. Previous studies also found significant influences on travel preferences (e.g., Barr et al., 2022; Koetse & Rietveld, 2009). Interestingly, while speed is considered most often an important factor for commuting, it does not significantly affect the odds of commuting by car. So, although the respondents consider speed to be an important factor for commuting (see Table 5), it does not affect people's commute mode choices.

Before we discuss the policy implications, some remarks should be made. First, we would have preferred to include more socio-demographic control variables, but they were not included in the questionnaire of BMN. Therefore, we cannot exclude the possibility that some of the model results stem from the intervening influence of other variables such as income and household composition. In particular, the higher odds of women commuting by car could be related to children in the household. Women likely have caring responsibilities for children more often which requires more flexibility (e.g., Maat & Timmermans, 2009; Vance et al., 2005). Second, this study does not take trip chaining (e.g., visiting a grocery store after work before returning home) into account. As the car is often used for trip chaining, this could lead to an underestimation of the level of car dependency in our research. Finally, our analysis involves two campus locations in the high-tech sector with unique characteristics and a clear overrepresentation of men. This means that the results of this study may reasonably be generalised to comparable campus locations but not to the general population.

For the policy implications, the high level of structural car dependency and the significant impact of mode choice preferences are of crucial importance. First, policies should aim to reduce structural car dependency in the region. One option is to build on the success of the bicycle which proved to be competitive with the car for commuting at shorter distances. Its reach can be increased by targeted investments in fast cycling routes, especially as e-bikes are gradually becoming the norm in the Netherlands. Another option is to invest in a quality leap for PT by investing in bus rapid transit systems in combination with efficient feeders and facilities for cycling, as many towns are not well connected to the railway system, a situation that is not likely to change in the future. Second, the use of PT, cycling, and walking can be encouraged among non-car-dependent commuters. Examples are psychological interventions focusing on the commuters' preferences and attitudes, financial programmes that promote PT and bicycle use, and schemes or promotional interventions that encourage a modal shift such as cycle-to-work days. Ideally, investments in the transport system are combined with these behavioural interventions to maximise their impact on sustainable commuting in the region.

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Conflict of Interests

The authors declare no conflict of interests.

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Article

Is It Possible to Compete With Car Use? How Buses Can Facilitate Sustainable Transport

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Abstract
The need to prioritise the development of bus transport has attracted widespread attention in the literature. This study aims to investigate how buses can be used to facilitate a sustainable transport system, using Heze, in China, as a case study. Our results show that older people, unemployed residents, and those whose points of departure or arrival are within the city centre are more likely to travel by bus. In addition, compared to other travel modes, travel by bus tends to become more popular as travel time and distance increase. We predict the probabilities of people using buses for journeys of different travel times and over varying distances and rank them in order. The results suggest that bus travel could potentially replace car travel when the travel time is between 15 and 30 minutes or the travel distance is more than 9 km. In terms of policy implications, governments and planners should pay more attention to creating additional bus lanes, extending the bus network and its infrastructure, optimising bus-related facilities and services, particularly for older adults, and increasing the punctuality and reliability of bus travel.

Keywords
bus travel; car dependency; sustainable mobility; transport planning; travel behaviour

Issue
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1. Introduction

Currently, many countries are making strenuous efforts to provide better public transport services to encourage the public to use them, in order to reduce traffic congestion (Yao et al., 2021). Buses are often the only form of public transport available in small- and/or medium-sized cities in China. Since 2004, the Chinese government has issued a series of documents to promote the development of public transport (Zhang et al., 2016). Although the length of bus routes increased fivefold and the number of buses doubled between 2004 and 2017 (Yao et al., 2020), the number of private cars on the roads increased by a factor of almost 14 from 2005 to 2019 (National Bureau of Statistics of China, 2020). Car dependency and its impacts remain a serious problem in China. The potential of public transport for easing traffic congestion in China has therefore not yet been realised, especially with regard to replacing car travel with bus travel.

Existing studies on bus travel can be roughly divided into two types: first, those investigating factors affecting the use of buses (Brechan, 2017; Buehler, 2011; Chakrabarti & Joh, 2019; Chng et al., 2016; Ding et al., 2017; Ha et al., 2020; Ng & Acker, 2018; O'Fallon et al., 2004; Paulley et al., 2006; Rachele et al., 2015; Rasca & Saeed, 2022), and second, studies exploring the relationship between car ownership and bus use (Balcombe et al., 2004; Chakrabarti, 2017; Eriksson et al., 2008; Lee et al., 2003; Liu & Cirillo, 2015; Yao et al., 2021). Although some studies have considered the effect of car ownership and car use on bus travel (Rasca & Saeed, 2022; Yao et al., 2021), few have examined the influence of other travel modes, such as walking and cycling. Additionally, previous studies have paid scant attention to discussing the possibility of using buses for journeys of different travel times or over different distances. Furthermore, previous studies have primarily focused on large cities and metropolises rather than medium or small cities, meaning that the resulting policy implications may not be transferable to different types of cities. Our research, therefore, aims to address these gaps.

The rest of our article is organised as follows. Section 2 presents a review of the existing literature regarding bus service planning and bus travel. Section 3 explains the case study context, the data collection process, and the methodology. The key findings and a discussion of the empirical research are provided in Section 4. The final section presents the conclusions of our study together with policy implications.

2. Literature Review

2.1. Factors Affecting the Use of Buses

While various strategies for increasing the use of public transport have been studied in different contexts around the world, no standardised solution has yet been agreed on (Rasca & Saeed, 2022). Lanzendorf (2002) used the "mobility style" model to clarify the relationship between individuals' travel mode choices and a range of factors. Vij et al. (2013, p. 164) developed the concept further to encompass what they referred to as "'modality styles,' or behavioural predispositions, characterized by a certain travel mode or set of travel modes that an individual habitually uses."

For nearly seven decades, researchers have been closely studying the factors that affect human daily mobility behaviour and travel mode choices (Reeder, 1956). Demographic factors can affect the use of public transport. Several existing studies have demonstrated that younger (under 25) and older adults tend to use public transport to a greater extent (Coogan et al., 2018; Ding et al., 2017; Ha et al., 2020; Litman, 2004; O'Fallon et al., 2004), while middle-aged people appear to be more dependent on cars (Ding et al., 2017). Research from Buehler (2011) and Ng and Acker (2018) found that there is an association between gender and the use of public transport: Females tend to use public transport more than males. A link has also been found between educational levels and the use of public transport. Individuals with higher educational levels are more likely to use public transport (Rachele et al., 2015).

Ding et al. (2017) and Rasca and Saeed (2022) found that higher levels of accessibility can increase public transport use. According to the definitions provided by Litman (2008) and Saghapour et al. (2016), bus accessibility encompasses several factors: access to bus stops, travel time and distance by bus, frequency of the buses, and ticket prices. Having to travel a longer distance from home to the nearest bus stop has a negative impact on bus use (Rasca & Saeed, 2022). Rasca and Saeed (2022) found that travellers living within a comfortable walking distance (e.g., five minutes or less) of bus stops are more willing and likely to use the bus. The only current international sustainable urban development standard, the ISO Standard No. 37120:2018 Sustainable Cities and Communities—Indicators for City Services and Quality of Life specified a benchmark of the "percentage of population living within 0.5 km of public transit running at least every 20 minutes during peak periods" for public transport provision (International Organization for Standardization, 2018, p. 70). Yao et al. (2021) found that the quality of bus services has a significantly positive impact on bus use. Balcombe et al. (2004), Ha et al. (2020), and Kawabata (2009) have all produced evidence to show that very long travel times have a negative impact on public transport use. By comparing bus travellers making journeys of different travel times, Rasca and Saeed (2022) found that people are more likely to use buses when the travel time is between 15 minutes and 60 minutes; when the travel time is more than 60 minutes, people are least likely to make their journeys by bus. Hagenauer and Helbich (2017) claimed that travel distance is the most significant variable in determining travel mode use. Rasca and Saeed (2022) found that bus use increases with travel distance, which is in line with the findings from Chng et al.'s (2016) research. By exploring 24 experimental cases in Norway, Brechan (2017) found that both reducing prices and increasing the frequency of services can have positive effects on public transport use. Numerous other studies have also confirmed this finding (Ha et al., 2020; Paulley et al., 2006; Rasca & Saeed, 2022).

It is worth noting that existing studies have largely focused on global large cities and metropolises; only Rasca and Saeed (2022) targeted small cities and towns in Norway as case studies. However, Rasca and Saeed (2022) did not consider the effects of other transport modes (e.g., walking and cycling) on bus use. In this study, data on travelling by bus, car, active travel, and electric bicycle, in Heze, a medium-sized city in China, is used in an attempt to fill the existing research gap.

2.2. Car Dependency and the Shift to Sustainable Travel Modes

Nordfjærn et al. (2014) found that there is a weak relationship between habitual car use and the intention to use public transport. Existing research has demonstrated that a high rate of car ownership leads to a reduction in active travel and public transport use (Balcombe et al., 2004; Chng et al., 2016; Paulley et al., 2006). Car ownership influences both car use (Van et al., 2014) and bus use (Ding et al., 2018). Rasca and Saeed (2022) produced evidence to show that car ownership has a negative impact on bus use. Car owners rarely use public transport, and bus use is primarily driven by the absence of cars (Chakrabarti, 2017). Some studies have shed light on the relationships between the quality of bus services, bus use, car ownership, and car use. On the one hand, a higher quality of bus services has a significantly negative effect on car ownership (Fairhurst, 1975; Goodwin, 1993; Lee et al., 2003; Liu & Cirillo, 2015; Yao et al., 2021). On the other hand, a better quality of bus services leads to an increase in bus use, which in turn causes a reduction in car use (Eriksson et al., 2008; Lee et al., 2003; Liu & Cirillo, 2015; Yao et al., 2021). Furthermore, by surveying residents who commuted by car in Shanghai, Wang et al. (2013) found that enhancing the punctuality and comfort of public transport could reduce car use. In short, car ownership and car use decrease as bus use increases (Yao et al., 2021). However, the increase in car use caused by car ownership is much greater than the decrease in car use caused by improved bus services and the increase in bus use, which helps to explain why traffic congestion in China is so severe (Yao et al., 2021).

Several studies have investigated car users' subjective attitudes to explore how they could be persuaded to use cars less and buses more. Improving bus services may result in travellers developing a more negative attitude towards car use and/or perceiving bus travel in a more positive light (Cullinane, 2002; Eriksson et al., 2010; Kingham et al., 2001; Mackett, 2001). Fiorio and Percoco (2007) found that faster public transport services could encourage as many as 25.41% of car user respondents to use public transport. Similarly, Kingham et al. (2001) found that promoting greater reliability and convenience and better connections, as well as offering discounted tickets, could persuade 40% of car commuting respondents to switch to buses.

Kim and Kim (2004), Li et al. (2011), and Yao et al. (2021) pointed out that car ownership and car use usually increase in line with income. Conversely, those facing financial pressures are more likely to travel by bus (Yao et al., 2021). Ha et al. (2020) demonstrated that travel time could also give an indication of the competitiveness of public transport in relation to other travel modes. Public transport may be able to offer shorter travel times than cars during peak periods, but the reverse is true outside of peak periods (Guan et al., 2020; Ha et al., 2020). Collins and Chambers (2005) discovered that, when the travel time of a journey by public transport is 1.25 times as long or longer than that of travelling by car, people's preference for using public transport decreases significantly. Kawabata (2009) found that commuters travelling by car had a much higher rate of job accessibility for a 30-minute threshold than commuters travelling by public transport. Travel distance, as the most significant variable in determining travel mode use (Hagenauer & Helbich, 2017), has received widespread attention, but previous studies have produced differing results. Rasca and Saeed (2022) found that bus use tends to increase with travel distance; however, Yao et al. (2021) showed that bus use decreases while car use increases when the travel distance is more than 10 km. Scheiner (2010) also found that travellers are more likely to switch to using cars as travel distance increases. However, few empirical studies have investigated users' preferences for buses or cars for journeys of different travel times and distances. Therefore, by comparing the probabilities of travelling by bus or car for different travel times and distances, we explore whether bus travel can decrease car dependency. Our study provides new evidence that bus travel has the potential to replace car use when travel times and distances are taken into account, and thus contributes to addressing the research gap in the existing literature.

2.3. Summary

The existing literature has paid considerable attention to bus travel, primarily focusing on two aspects, as shown in Table 1: (a) factors affecting bus use and (b) the relationship between car ownership and bus use. The findings suggest that some socio-demographic factors (e.g., age, gender, education) and travel behaviour factors (e.g., access to the bus stop, travel time and distance, service frequency, and ticket prices) have a significant impact on bus use. In addition, an increase in bus use leads to a reduction in car ownership and car use; in turn, car ownership has a negative impact on bus use. Moreover,

Table 1. Summary of the existing literature.

Research topics	Key ideas	Key indicators	Key references	Key findings
Factors affecting bus use	1. Socio-demographic factors	Age	Coogan et al. (2018); Ding et al. (2017); Ha et al. (2020); Litman (2004); O'Fallon et al. (2004)	Younger (under 25) and older adults tend to be bigger users of public transport.
		Gender	Buehler (2011); Ng and Acker (2018)	Females tend to use public transport more than males.
		Education	Rachele et al. (2015)	Individuals with higher educational levels are more likely to use public transport.

Table 1. (Cont.) Summary of the existing literature.

Research topics	Key ideas	Key indicators	Key references	Key findings
Factors affecting bus use	2. Travel behaviour factors	Quality of bus services	Yao et al. (2021)	A higher quality of bus services has a significantly positive impact on bus use.
		Access to bus stops	Rasca and Saeed (2022)	A longer distance from home to the nearest bus stop has a negative impact on bus use.
			Ding et al. (2017); Rasca and Saeed (2022)	Higher levels of accessibility are positively related to public transport use.
		Travel time	Rasca and Saeed (2022)	Travellers who have a maximum travel time of one hour are more likely to use buses when the travel time is longer. When travel times are more than one hour, the probability of travellers using buses is lower than for journeys with a maximum travel time of one hour.
			Balcombe et al. (2004); Ha et al. (2020); Kawabata (2009)	Very long travel times have a negative impact on public transport use.
			Ha et al. (2020)	Travel time could give an indication of the competitiveness of public transport services compared with other transport modes.
		Travel distance	Chng et al. (2016); Rasca and Saeed (2022)	Bus use increases as travel distance increases.
		Service frequency and ticket prices	Balcombe et al. (2004); Brechan (2017); Ha et al. (2020); Paulley et al., (2006); Rasca and Saeed (2022)	Increasing the frequency of services and reducing prices can have positive effects on public transport use.
Car ownership and bus use		Car ownership	Balcombe et al. (2004); Chng et al. (2016); Paulley et al. (2006); Rasca and Saeed (2022)	Car ownership is negatively associated with public transport usage.
		Car use	Yao et al. (2021)	Bus use negatively affects car use.
		Bus services	Eriksson et al. (2008); Fairhurst (1975); Goodwin (1993); Kim and Kim (2004); Lee et al. (2003); Liu and Cirillo (2015); Wang et al. (2013); Yao et al. (2021)	High-quality bus services can reduce car ownership and car use.
			Cullinane (2002); Eriksson et al. (2010); Kingham et al. (2001); Mackett (2001)	Improving bus services may result in travellers showing more negative attitudes towards car use or more positive attitudes towards travelling by bus.
			Fiorio and Percoco (2007)	Faster public transport services could encourage as many as 25.41% of car users to use public transport.

Table 1. (Cont.) Summary of the existing literature.

Research topics	Key ideas	Key indicators	Key references	Key findings
Car ownership and bus use		Bus services	Kingham et al. (2001)	Promoting greater reliability and convenience and better connections, as well as offering discounted tickets, could persuade 40% of people who currently commute by car to switch to buses.
		Financial considerations	Yao et al. (2021)	Car ownership and car use increase as people's income increases. Travellers facing economic constraints are more likely to travel by bus.
		Travel time	Collins and Chambers (2005)	When the travel time of a journey by public transport is 1.25 times as long or longer than that of travelling by car, people have a significantly lower preference for public transport.
			Guan et al. (2020); Ha et al. (2020)	Public transport may be able to offer shorter travel times than cars during peak periods, but the reverse is true outside of peak periods.
			Kawabata (2009)	Commuters travelling by car have a much higher level of job accessibility for a 30-minute threshold than commuters travelling by public transport.
		Travel distance	Yao et al. (2021)	Car use increases and bus use decreases when the travel distance is more than 10 km.
			Scheiner (2010)	Travellers are more likely to switch to using cars as travel distance increases.

financial considerations, travel time, and distance may affect travellers' decisions about whether to travel by bus or car. However, current studies have mainly considered the effect of car use on buses and ignored the influence of other travel modes, such as walking and cycling. Additionally, previous studies have paid scant attention to investigating the likelihood of travelling by bus for different travel times or distances. Furthermore, existing studies have focused less on small or medium-sized cities. Therefore, to try to fill these gaps, this article investigates the feasibility of bus travel replacing car travel by comparing the possibility of using different travel modes for different travel times or distances, using Heze in China as a case study.

3. Case Study, Data, and Methodology

3.1. Case Study

The developing and medium-sized city of Heze, located in the southwest region of Shandong Province, was chosen as the case study city for this research. Three districts and seven counties comprise the entire administrative planning region of Heze, with a total land area of 12,239 km^2 and 8.8 million permanent residents in 2020. The data used in this study were obtained from the Heze local authority's Urban Residents' Travel Behaviour Survey (Heze Urban Planning and Design Institute, 2021). The survey was conducted from June to July 2021, mainly on weekdays. After data screening, 1,785 valid samples remained out of a total of 1,971. The Heze Urban Residents' Travel Behaviour Survey mainly focused on the downtown and urban fringe areas of the city, as shown in Figure 1, which we analyse and discuss in this article.

3.2. Logistic Regression Model

Logistic regression is one of the most popular methods used in transport studies, particularly to analyse individuals' travel behaviour and travel mode choices (Rasca & Saeed, 2022). The following studies have used binary logistic regression: Chakrabarti and Joh (2019), Collins and Chambers (2005), Ha et al. (2020), and Lanzendorf (2002), while other logistic regression models adopted in existing studies cited in Section 2 include: ordered logistic regression (Rasca & Saeed, 2022; Saghapour et al.,

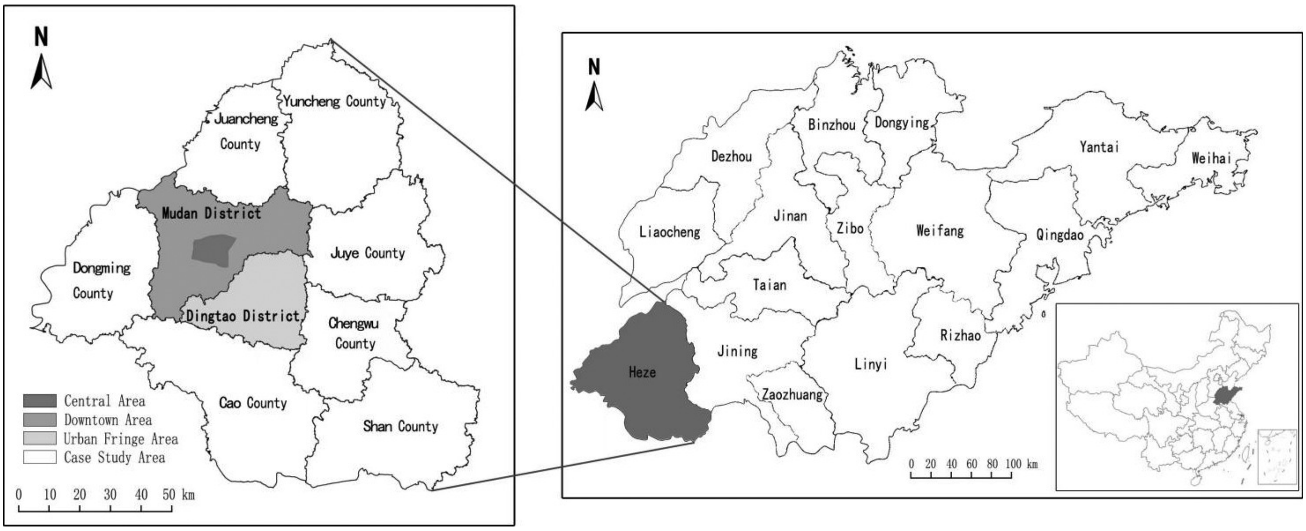

Figure 1. Case study map of Heze.

2016) and multinomial logistic regression (Chng et al., 2016; O'Fallon et al., 2004). Rasca and Saeed (2022) used logistic regression to explore the impacts of individual factors on bus use and investigate the probability of travelling by bus at different times and over different distances. In this study, we used binary logistic regression to analyse the relationship between individual factors and bus use and multinomial logistic regression to compare the probabilities of people using different travel modes to make journeys of different travel times and over different distances.

In the binary logistic regression model used in our study, the dependent variable 1 denotes the decision to *travel by bus* while 0 represents the decision to *not travel by bus*. A total of 11 independent variables relating to socio-demographics (gender, age, and employment status) and travel behaviour (travel time, travel distance, departure time, arrival time, departure area, arrival area, travel purpose, and number of travellers) were examined. More details can be found in Section 3.3.

Because this study aimed to explore how travel time and distance are associated with the choice of travel mode, we ran two multinomial logistic models. The dependent variable was the mode choice. Each of the multinomial logistic models contained 10 independent variables relating to socio-demographics and travel behaviour. Unlike the binary logistic regression model which included all 11 independent variables, one multinomial logistic model was run without the travel distance variable, while the other omitted the travel time variable, so as to avoid any effects resulting from the interrelationship between travel time and distance. More details are provided in the following sections.

3.3. Survey and Data Collection

All the information and data used in this study were taken from the Heze Urban Residents' Travel Behaviour Survey, which collected information on the following 13 categories from every respondent, as shown in Table 2:

1. Individual socio-demographic attributes: Gender, age, occupation, and employment status;
2. Travel time and travel distance: These were divided into two separate classifications for the respective quantitative analyses;
3. Departure/arrival time and departure/arrival area: Peak periods were defined as 5:00–9:00 and 17:00–19:00, and all other time periods were classified as off-peak;
4. Travel purpose: There were a total of 11 possible purposes, under the broader categories of commuting and leisure;
5. Number of travellers: Travelling alone or with others;
6. Travel mode: The following four kinds of primary travel mode choices were offered as options—active travel (walking and cycling), bus, car, and electric bicycle.

According to the 2020 Chinese census (Shandong Provincial Bureau of Statistics, 2021), males accounted for 50.78% of Heze's population, and females accounted for 49.22%. In our study, the respondents comprised 50.98% males and 49.02 females. Out of all the transport modes, the number of respondents who used active travel accounted for only around 7.79% of the total, while the proportion of respondents who travelled by bus was 25.15%, and 25.10% of respondents travelled by car. Respondents who travelled by electric bicycle accounted for the largest proportion of the total at 41.96%. Levy (2013) showed that some individual factors, such as financial, cultural, physical, locational, and gender-related factors, may affect people's choice of transport mode. A total of 27.28% of the respondents travelled for journeys lasting 20 to 30 minutes,

Table 2. Descriptive statistics (n = 1,785).

	Categories	Frequency	Percentage
Gender	Male	910	50.98%
	Female	875	49.02%
Age	<25	233	13.05%
	25–44	1,045	58.54%
	45–64	449	25.15%
	≥65	58	3.25%
Occupation	Managers, directors, and senior officials	127	7.11%
	Professional occupations	547	30.64%
	Skilled trades	434	24.31%
	Freelance or businessman/woman	352	19.72%
	Student	184	10.31%
	Retired/unemployed	141	7.90%
Employment status	Employed	1,460	81.79%
	Unemployed	325	18.21%
Travel time (min)	≤10	288	16.13%
	10–15	257	14.40%
	15–20	336	18.82%
	20–30	487	27.28%
	>30	417	23.36%
Travel distance (km)	≤3	447	25.04%
	3–6	556	31.15%
	6–9	278	15.57%
	9–12	218	12.21%
	>12	286	16.02%
Departure time	Peak period	1,223	68.52%
	Off-peak period	562	31.48%
Arrival time	Peak period	1,163	65.15%
	Off-peak period	622	34.85%
Departure area	Central area	1,196	67.00%
	Others	589	33.00%
Arrival area	Central area	1,220	68.35%
	Others	565	31.65%
Travel purpose	Commuting	955	53.50%
	Leisure	830	46.50%
Number of travellers	One	1,462	81.90%
	More than one	323	18.10%
Travel mode	Active travel	139	7.79%
	Bus	449	25.15%
	Car	448	25.10%
	Electric bicycle	749	41.96%

accounting for the largest proportion of the total. The most common travel distance was between 3 and 6 km, accounting for 31.15% of respondents' journeys.

Based on the descriptive statistics, the variables and corresponding measurements are shown in Table 3. These variables were regarded as the independent variables analysed in the binary logistic regression and multinomial logistic regression models. In the binary logistic regression model, the other variables were all binary variables, except age, which is a continuous variable. We ran multinomial logistic models to explore how travel time and distance influence the choice of transport mode. When we analysed the relationship between travel time and the choice of transport mode, we omitted travel

Table 3. Independent variables included in the models.

Category	Variable	Explanation and measurement
Socio-demographics	Gender	Binary variable (1 = *female*, 0 = *male*)
	Age	Continuous variables
	Employment status	Binary variable (1 = *employed*, 0 = *unemployed*)
Travel behaviour	Travel time	Binary variable (1 = *travel time > 30 mins*, 0 = *travel time ≤ 30 mins*)
	Travel distance	Binary variable (1 = *travel distance > 6 km*, 0 = *travel distance ≤ 6 km*)
	Departure time	Binary variable (1 = *departure in the peak period*, 0 = *departure in the off-peak period*)
	Arrival time	Binary variable (1 = *arrival in the peak period*, 0 = *arrival in the off-peak period)*
	Departure area	Binary variable (1 = *departure from the central area of Heze*, 0 = *others*)
	Arrival area	Binary variable (1 = *arrival in the central area of Heze*, 0 = *others*)
	Travel purpose	Binary variable (1 = *commuting*, 0 = *leisure*)
	Number of travellers	Binary variable (1 = *travelling alone*, 0 = *travelling with other people*)

distance from the independent variables, and travel time was regarded as a categorical variable containing five categories: (a) travel time ≤ 10mins, (b) 10 mins < travel time ≤ 15 mins, (c) 15 mins < travel time ≤ 20 mins, (d) 20 mins < travel time ≤ 30 mins, and (e) travel time > 30 mins. When we analysed the relationship between travel distance and the choice of transport mode, travel time was not included among the independent variables, and travel distance was regarded as a categorical variable containing the following five categories: (a) travel distance ≤ 3 km, (b) 3 km < travel distance ≤ 6 km, (c) 6 km < travel distance ≤ 9 km, (d) 9 km < travel distance ≤ 12 km, and (e) travel distance > 12 km.

4. Key Findings and Discussion

We used the binary logistic regression model to investigate how the socio-demographic and travel behaviour variables are associated with the choice of whether to travel by bus. The multinomial logistic regression model was then constructed to explore how travel time and distance are associated with the choice of travel mode.

4.1. Binary Logistic Regression

Table 4 shows the binary logistic regression results for how decisions about bus travel are associated with different variables. Age, employment status, travel time/distance, and departure/arrival area all had a significant influence on the intention to travel by bus ($p < 0.05$), while the other factors, namely gender, departure/arrival time, travel purpose, and number of travellers, did not significantly influence the intention to travel by bus ($p > 0.05$). First, we investigated whether demographic factors are associated with bus use. Residents were more likely to travel by bus as they got older. Our results are in line with several existing studies which found that older adults tend to be bigger users of public transport (Coogan et al., 2018; Ding et al., 2017; Ha et al., 2020; Litman, 2004; O'Fallon et al., 2004). Furthermore, according to our analysis, the relationship between gender and bus use is insignificant, contrary to the findings of studies by Buehler (2011) and Ng and Acker (2018). Second, unemployed residents were found to be more likely to travel by bus than employed residents. Yao et al. (2021) highlighted that people who were experiencing financial constraints were more likely to travel by bus. Third, residents whose points of departure/arrival were not located in the central area of the city were less likely to travel by bus, which means that, conversely, those whose points of departure/arrival were inside the city centre tended to be more frequent bus travellers. Regarding whether easy access to bus stops impacts bus use because there are fewer bus stops within the non-central area of the city than in the central area, travellers within the non-central area find it more difficult to access bus stops. In other words, residents whose points of departure/arrival were not in the central area had to walk a longer distance to bus stops. Correspondingly, Rasca and Saeed (2022) proved that long walking distances to bus stops were negatively related to public transport use. In turn, easier access to bus stops usually leads to higher levels of bus use (Ding et al., 2017; Rasca & Saeed, 2022); therefore, residents whose points of departure/arrival were located in the central area of the city were more likely to travel by bus. Finally, Table 4 shows that two further variables made residents less likely to travel by bus—if the travel time was less than or equal to 30 minutes or the travel distance was less than or equal to 6 km. In other words, residents making journeys of relatively longer travel times (>30 mins) or distances (>6 km) were more likely to travel by bus. Previous research found that travellers whose journey time lasted up to a maximum of one hour are more likely to use

Table 4. Results of the binary logistic regression (1 = *travelled by bus*, 0 = *otherwise*; *n* = 1,785).

					95% CI for Exp(*B*)	
Variable	*B*	Standard Error	Sig.	Exp(*B*)	Lower	Upper
Socio-demographics						
Male	−0.050	0.116	0.671	0.952	0.757	1.196
Age	**0.214**	0.083	**0.010***	1.238	1.053	1.456
Unemployed	**1.314**	0.147	**0.000****	3.720	2.788	4.963
Travel behaviour						
Travel time ≤ 30 mins	**−0.922**	0.138	**0.000****	0.398	0.304	0.521
Travel distance ≤ 6 km	**−0.380**	0.134	**0.004****	0.684	0.526	0.889
Departure in the off-peak period	0.134	0.229	0.557	1.144	0.731	1.790
Arrival in the off-peak period	0.162	0.230	0.480	1.176	0.750	1.845
Departure from the non-central area	**−0.278**	0.136	**0.040***	0.757	0.580	0.988
Arrival in the non-central area	**−0.377**	0.139	**0.007****	0.686	0.522	0.901
Leisure	0.196	0.130	0.130	1.217	0.944	1.569
Not travelling alone	0.207	0.149	0.166	1.230	0.918	1.648

Notes: Pseudo R^2 = 0.150; * *p*-value < 0.05, ** *p*-value < 0.01.

the bus (Rasca & Saeed, 2022), while very long travel times (i.e., more than one hour) have a negative impact on public transport use (Balcombe et al., 2004; Ha et al., 2020; Kawabata, 2009; Rasca & Saeed, 2022). Rasca and Saeed (2022) also found that bus use is positively associated with travel distance, which is in accordance with the research by Chng et al. (2016). However, Yao et al. (2021) pointed out that bus use decreases when the travel distance is more than 10 km, which is contrary to our results. In light of this finding, a further, more detailed classification of travel time and distance was used in the multinomial logistic model to explore how travel time and/or distance influences the choice of travel mode.

4.2. Multinomial Logistic Regression

Multinomial logistic regression was used to investigate how travel time and distance influence the choice of travel mode. The control group was comprised of those who travel by bus while people travelling by means of active travel, electric bicycles, and cars were the experimental groups. In order to achieve more accurate outcomes, travel time and distance were respectively treated as the independent variables. So as obtain the best results from the multinomial logistic regression, five different classifications of travel time and five different classifications of travel distance were used. Each classification was run through the multinomial logistic regression model and the best classifications for travel time and distance are shown in Table 5. After determining the best classifications for travel time and distance, four multinomial logistic regression analyses were conducted—two analyses each for travel time and distance, respectively. As shown in Table 5, the travel time analyses treated "≤10 mins" and ">30 mins" separately as the control groups, while in the travel distance analyses, "≤3 km" and ">12 km" were each treated as the control groups.

By comparing the coefficient *B* for different categories of travel time and distance, we were able to compare the probability of travelling by different transport modes for different travel times and distances (Rasca & Saeed, 2022). For example, with regard to car travel, when we treated ">30 mins" as the control group, the *p*-values for the other intervals of travel time were less than 0.05; therefore, we could compare the probability of travelling by car for different travel times by comparing the coefficient *B* of each of these travel time intervals. As shown in Table 5, we ascertained that residents are most likely to travel by active modes of travel such as walking, cycling, and electric bicycle, when the travel time is ≤10 mins or the travel distance is ≤3 km; residents are most likely to travel by car when the travel time is between 10 and 15 minutes or the travel distance is between 9 and 12 km. The following section shows the probability of using different travel modes for different travel times and distances in ranking order.

4.3. Comparison of Different Transport Modes

According to the results obtained from the multinomial logistic regression, the probabilities of making journeys by active travel, electric bicycle, and car for different time periods and over different distances are shown in Table 5. In addition, to determine the probability of people travelling by bus for different time periods and over different distances, another binary logistic regression was run, in which travel time and distance were treated as continuous variables and corresponded to the classifications of

Table 5. Results of the multinomial logistic regression (n = 1,785).

Categories		Active travel			Electric bicycle			Car		
		B	Sig.	Exp(*B*)	*B*	Sig.	Exp(*B*)	*B*	Sig.	Exp(*B*)
Travel time (min)	≤10	Control group								
	10 < x ≤ 15	−1.058	**0.004*****	0.347	−0.184	0.477	0.832	0.605	0.053*	1.831
	15 < x ≤ 20	−1.122	**0.000*****	0.326	−0.761	**0.001*****	0.467	0.218	0.439	1.244
	20 < x ≤ 30	−1.589	**0.000*****	0.204	−1.191	**0.000*****	0.304	0.058	0.825	1.060
	>30	−2.186	**0.000*****	0.112	−1.858	**0.000*****	0.156	−0.632	**0.018****	0.531
	≤10	2.186	**0.000*****	8.896	1.858	**0.000*****	6.409	0.632	**0.018****	1.882
	10 < x ≤ 15	1.128	**0.003*****	3.089	1.674	**0.000*****	5.333	1.237	**0.000*****	3.446
	15 < x ≤ 20	1.064	**0.001*****	2.897	1.097	**0.000*****	2.995	0.851	**0.000*****	2.341
	20 < x ≤ 30	0.596	0.055*	1.815	0.667	**0.000*****	1.948	0.691	**0.000*****	1.995
	>30	Control group								
Pseudo R^2 = 0.158										
Travel distance (km)	≤3	Control group								
	3 < x ≤ 6	−1.675	**0.000*****	0.187	−0.567	**0.001*****	0.567	0.711	**0.004*****	2.036
	6 < x ≤ 9	−2.668	**0.000*****	0.069	−1.139	**0.000*****	0.320	0.626	**0.020****	1.870
	9 < x ≤ 12	−2.527	**0.000*****	0.080	−0.864	**0.000*****	0.421	1.275	**0.000*****	3.579
	>12	−5.181	**0.000*****	0.006	−1.902	**0.000*****	0.149	0.721	**0.008*****	2.056
	≤3	5.181	**0.000*****	177.929	1.902	**0.000*****	6.698	−0.721	**0.008*****	0.486
	3 < x ≤ 6	3.506	**0.001*****	33.311	1.335	**0.000*****	3.799	−0.010	0.963	0.990
	6 < x ≤ 9	2.514	**0.020****	12.353	0.763	**0.001*****	2.144	−0.095	0.678	0.910
	9 < x ≤ 12	2.654	**0.018****	14.214	1.038	**0.000*****	2.823	0.554	**0.026****	1.741
	>12	Control group								
Pseudo R^2 = 0.298										

Notes: * p-value < 0.1, ** p-value < 0.05, *** p-value < 0.01.

travel time and distance used in the multinomial logistic regression, as shown in Table 6. The coefficient *B* of travel time was 0.424 when $p = 0.000 < 0.05$, and the coefficient *B* of travel distance was 0.265 when $p = 0.000 < 0.05$. Therefore, compared with other travel modes, residents of Heze were more likely to travel by bus as travel time and/or distance increased. It is worth noting that several studies have found that very long travel times negatively affect public transport use (Balcombe et al., 2004; Ha et al., 2020; Kawabata, 2009). Our results confirm Rasca and Saeed's (2022) findings, namely that travellers with a longer travel distance have a higher probability of making their journeys by bus. The results obtained from this binary logistic regression were in line with those discussed in Section 4.1.

In order to make it easier to compare the probabilities of using different travel modes for different travel times and distances, we have included Table 7 and Figures 2 and 3, which are based on Tables 5 and 6. Figure 2 shows that residents are more likely to travel by car when the travel time is between 10 and 30 minutes and more likely to travel by bus when the travel time is more than 15 minutes. Figure 3 shows that residents are more likely to travel by car when the travel distance is between 3 km and 6 km or more than 9 km and more likely to make their journeys by bus when the

Table 6. Results of the binary logistic regression (1 = *travelled by bus*, 0 = *otherwise*; n = 1,785).

Variable	*B*	Standard Error	Sig.	Exp(*B*)	95% CI for Exp(*B*)	
					Lower	Upper
Travel time (continuous)	**0.424**	0.047	**0.000***	1.528	1.393	1.677
Travel distance (continuous)	**0.265**	0.045	**0.000***	1.304	1.193	1.425

Notes: * p-value < 0.01. This table only shows the results for travel time and travel distance; other indicators are omitted.

Table 7. The probability of using different travel modes for different travel times/distances.

Probability ranking	Active travel	Electric bicycle	Car	Bus
Travel time (min)				
1	≤10	≤10	10 < x ≤ 15	>30
2	10 < x ≤ 15	10 < x ≤ 15	15 < x ≤ 20	20 < x ≤ 30
3	15 < x ≤ 20	15 < x ≤ 20	20 < x ≤ 30	15 < x ≤ 20
4	20 < x ≤ 30	20 < x ≤ 30	≤10	10 < x ≤ 15
5	>30	>30	>30	≤10
Travel distance (km)				
1	≤3	≤3	9 < x ≤ 12	>12
2	3 < x ≤ 6	3 < x ≤ 6	> 12	9 < x ≤ 12
3	9 < x ≤ 12	9 < x ≤ 12	3 < x ≤ 6	6 < x ≤ 9
4	6 < x ≤ 9	6 < x ≤ 9	6 < x ≤ 9	3 < x ≤ 6
5	>12	>12	≤3	≤3

Notes: Binary logistic regression was used to produce the results for bus travel; multinomial logistic regression was used to produce the results for active travel, electric bicycles, and cars.

travel distance is more than 6 km. Therefore, it is possible for bus travel to replace car travel when the travel time is between 15 and 30 minutes or the travel distance is more than 9 km. Previous studies have discussed the impacts of travel time and travel distance on bus use and car use. Collins and Chambers (2005) determined that travellers' preference for public transport decreased significantly when the travel time of their journeys by public transport was 1.25 times as long or longer than that of travelling by car. Yao et al. (2021) found that bus use decreases while car use increases when the travel distance is more than 10 km. Similarly, Scheiner (2010) claimed that an increase in travel distance will make travellers more likely to switch to using cars. Although our findings are not entirely aligned with some previous studies, we complement them by producing empirical evidence to explain the impacts of travel time and distance on bus use and car use. Several existing studies have found that increasing bus use can have the effect of decreasing car use (Eriksson et al., 2008; Lee et al., 2003;

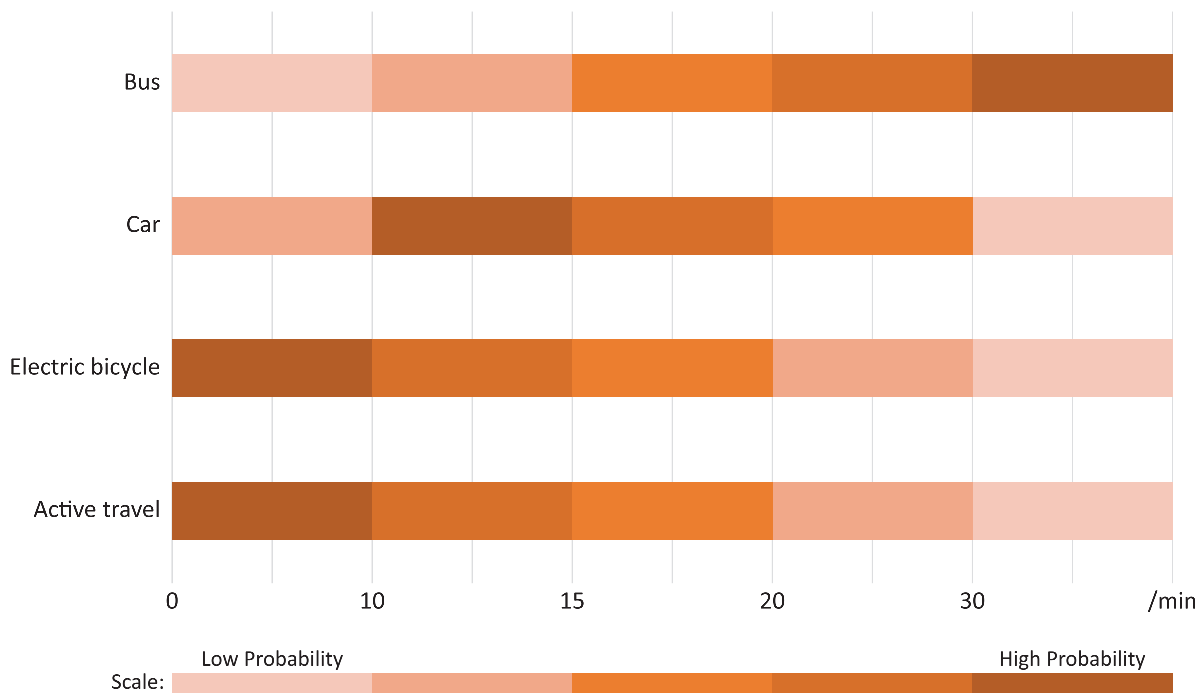

Figure 2. The probabilities of using different travel modes for different travel times.

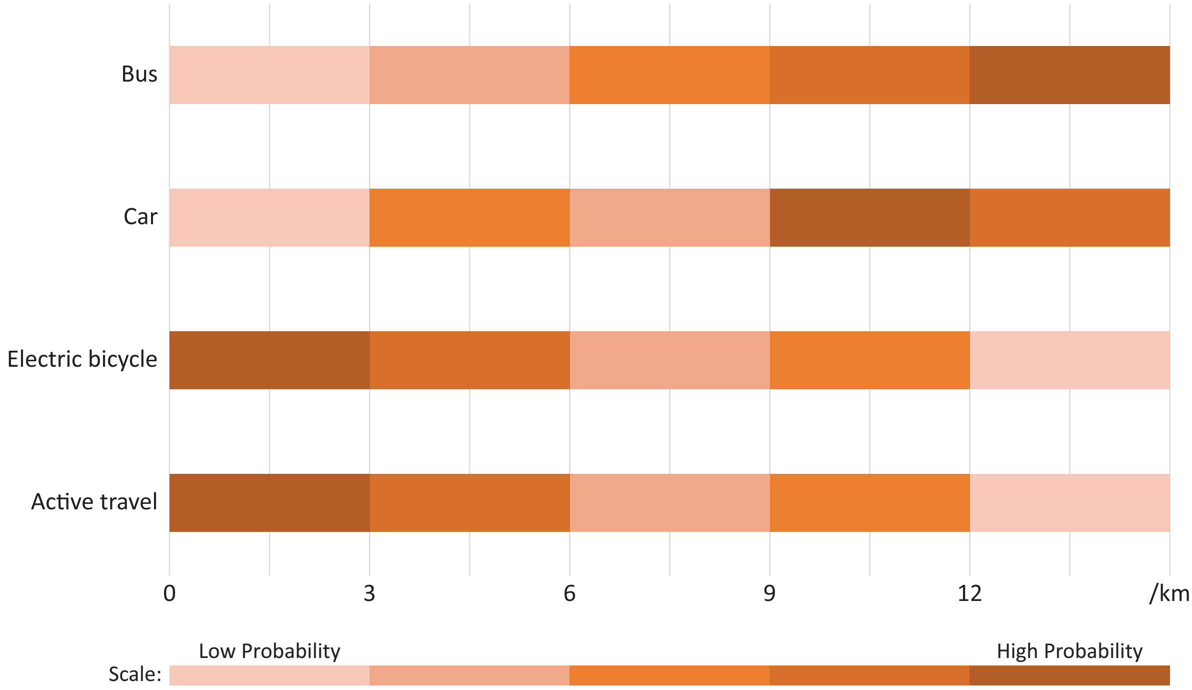

Figure 3. The probabilities of using different travel modes for different travel distances.

Liu & Cirillo, 2015; Yao et al., 2021). From the perspective of different travel times and distances, we discussed the likelihood of replacing car travel with bus travel.

5. Conclusions

In this study, we used data from the Heze Urban Residents' Travel Behaviour Survey comprising 1,785 valid samples and ran binary and multinomial logistic regressions to investigate the factors associated with bus use and explore the potential for bus travel to replace car travel.

Our study produced three key findings. First, we explored the relationship between individual/demographic factors and residents' daily bus use. Age, employment status, travel time/distance, and departure/arrival area all significantly affected whether people choose to travel by bus. Older and unemployed residents were more likely to travel by bus. Residents who have a relatively longer travel time (>30 mins) or longer travel distance (>6 km) were more likely to travel by bus. Furthermore, residents whose points of departure/arrival were located in the central area of the city were also more likely to travel by bus. Second, we investigated the likelihood of people travelling by different travel modes (bus, car, active travel, and electric bicycle) for different travel times and over different distances. Third, we discussed whether bus travel had the potential to replace car travel for various travel times and distances. It was found to be equally likely that people would travel by bus and car when the travel time was between 15 and 30 minutes or the travel distance was more than 9 km. In other words, there is the potential for bus travel to replace car travel to some extent in order to reduce car ownership and ease traffic congestion.

Our study makes two main contributions which attempt to fill previous research gaps. On the one hand, existing studies have mainly considered the effect of car use on bus travel and ignored the influence of other travel modes, such as walking and cycling (Yao et al., 2021); therefore, we analysed and discussed the possibility of using buses for different travel times or distances compared with other transport modes, including active travel, electric bicycles, and cars. On the other hand, only a few studies have investigated the possibility of travelling by bus at different travel times or over different distances (Rasca & Saeed, 2022), and rarely have they compared the likelihood of travelling by bus with other transport modes. We found that people had a similar probability of travelling by bus or car when the travel time was between 15 and 30 minutes or the travel distance was more than 9 km. In short, we provided empirical evidence for the potential of bus travel to replace car travel for journeys of these time and distance intervals, which could help to reduce car ownership and ease traffic congestion. Therefore, we identified the following relevant policy implications which could promote and improve bus transport in small and medium-sized Chinese cities. First, older adults are more likely to use public transport (Coogan et al., 2018; Ding et al., 2017; Ha et al., 2020; Litman, 2004; O'Fallon et al., 2004); thus, Heze's transport system should be developed with a focus on making bus travel more accessible for older adults. Second, given that unemployed residents are usually financially constrained, it would seem reasonable to reduce ticket prices for them as well, as offering discounted fares has been shown to positively affect public transport use (Brechan, 2017; Paulley et al., 2006; Rasca & Saeed, 2022). Third, given that easier access to bus stops tends to increase bus use (Ding et al., 2017; Rasca & Saeed, 2022), the government should address the problems caused by the inadequate bus infrastructure in the non-central area of Heze. Fourth, Redman et al. (2013) and Yao et al. (2021) provided evidence to show that enhancing the punctuality and reliability of buses can help to attract more travellers and increase bus use. Therefore, improving the punctuality and reliability of bus travel is another key area for the future development of bus services. Finally, the government should continue to prioritise buses alongside other policies aimed at reducing car use and ownership, as well as encouraging residents to opt for buses instead of cars when making medium- and long-distance journeys.

Because of the data set that we used, the results of our study are necessarily limited to Heze. Thus, the extent to which the findings of the research can be applied to other small and medium-sized Chinese cities is limited, because we used a single survey location. However, future research could seek to combine surveys and data from small and medium-sized cities in China to further develop the research findings and policy implications.

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Conflict of Interests

The authors declare no conflict of interests.

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Review

Driving Towards Car-Independent Neighborhoods in Europe: A Typology and Systematic Literature Review

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Abstract
Car-independent neighborhoods can be seen as a planning strategy for overcoming car dependency and achieving urban sustainability goals. This implies a structural and psychological car independency of people, which manifests itself into positive attitudes and perceptions towards sustainable mobility, acceptance of corresponding measures, and a shift from private cars to active transport, public transport, and sharing modes. Despite their relevance, knowledge regarding the actual implications of the various existing strategies remains scarce. This gap is addressed in this literature review, which aims to: (a) identify types of implemented car-independent neighborhood policies; (b) explore their rationales, main characteristics, and implications for mobility behavior, psychological factors, perceptions, and acceptance; and (c) investigate how they have been evaluated. Existing implementations in Europe can be divided into four types: car-independent central areas, residential developments, citywide implementations, and temporary interventions, which differ in their rationales and scope. Overall, little research was found on this topic, with most studies focusing on newly built residential developments, compared to the other types. There is evidence of positive impacts on sustainable mobility behavior in the relevant use cases. However, it is often unclear whether this is a causality or correlation due to the absence of comprehensive (longitudinal) evaluations. Less is known regarding the implications of implementations for psychological factors and perceptions and their interplay with mobility behavior. For future research, it is recommended to evaluate other types of car-independent interventions beyond newly built developments through long-term observation of attitudinal and behavioral changes.

Keywords
acceptance; attitudes; car dependency; car-free; car-independent; low-car; mobility behavior; perceptions; review; typology

Issue
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1. Introduction

The mass motorization, the modernist planning ideal of functional segregation, the consequent planning around cars, and values attributed to the car, such as freedom and flexibility, were each a catalyst in promoting car dependence in the last century, which Urry (2004, p. 27) called the “century of the car.” Early on, urban historians, such as Lewis Mumford, criticized the role that cars would have in destroying the complexity of existing urban fabrics (Ellis, 2005). This realization only grew post World War II, a time in which cities were being rebuilt in a way that allowed cars to flourish. As Jane Jacobs (1961/1992) later emphasized, the unrestricted integration of cars into cities would lead to the degradation of livable, multi-purpose streets and public spaces. Yet, despite critics’ insights, the movement of car dominance proceeded and remains palpable in the function and form of today’s cities as well as in society.

The car-free or car-reduced city can be considered a counter-model to the planning paradigm of the car-oriented city in order to tackle pressing issues such as pollution, climate change, public health, social injustice, or livability (Glazener & Khreis, 2019; Nieuwenhuijsen et al., 2019). This concept dates back to the 60s and 70s with the first wave of pedestrian zones in central parts of European cities (Nieuwenhuijsen et al., 2019; Orski, 1972). It is worth noting that most European historic centers were originally designed with a primary orientation towards walking, evident in their narrow streets and mixed, compact land uses, and that they had functioned without automobiles prior to the 20th century (Gehl, 2010). Since then, new initiatives such as car-free days and new car-free residential developments have emerged in planning practices, representing a diverse landscape of policies of different scopes, contexts, and intentions (Glazener & Khreis, 2019). Truly car-free cities have so far only existed in exceptional geographic and political contexts, such as Venice or Cuba (Melia et al., 2014). They have therefore remained more of a utopian planning idea, most famously envisioned by Crawford (2000). Current attempts are generally limited to neighborhoods, but can potentially be expanded to the wider city, as demonstrated by Barcelona's superblock concept. The strategy of a car-free or car-reduced neighborhood aims to create an urban setting in which private motorized transport plays a subordinate role. Car parking and access are restricted in combination with pull measures, such as the prioritization of public transport, walking and cycling infrastructure, high local accessibility to daily needs, or the design of streets as social multipurpose spaces. The car-free or car-reduced city or neighborhood concept thus shares common principles with historic planning ideas such as Clarence Perry's neighborhood units, as well as new urbanist concepts, such as transit-oriented development and, more recently, the 15-minute city.

A variety of terms have been used in literature to describe these interventions. The widely employed term car-free can generally be understood as the exclusion of motorized vehicles (in defined areas; Melia et al., 2010; Morris et al., 2009; Orski, 1972). Arguably, a certain level of motorized transport, including public transport, emergency and logistics vehicles, as well as private cars for mobility-impaired people, needs to be maintained, making the term somewhat misleading (Topp & Pharoah, 1994). To account for less restricting policies, various authors refer to car-reduced or low-car developments (Melia et al., 2010; Morris et al., 2009; Selzer & Lanzendorf, 2022). Whereas Delbosc and Currie (2012) label households with up to one car per household as low-car, Brown (2017) distinguishes between people who do not possess a car by choice (car-free) or involuntarily (car-less). These terms have also been used in an effort to classify the various manifestations into typologies based on their car restrictiveness (e.g., Melia et al., 2010; Morris et al., 2009). Wright (2005) proposed a car-free matrix that classified cases along two axes of spatial and temporal scale ranging from car-lite measures to large-scale car-free implementations.

To avoid these ambiguities, we adopt car independency as the umbrella term for this article and define it as follows: Car independency describes the ability to live without being reliant on private motorized transport ownership and use. Consequently, car-independent cities or neighborhoods are planned in such a manner that people mainly rely on sustainable mobility options to fulfill their mobility needs. This implies reversing the actual structural, as well as the perceived or psychological, car dependency of people (Lucas, 2009). While car-free or car-reduced developments structurally improve conditions for car-independent behavior, it can be argued that due to psychological factors, such as strong positive attitudes towards car use and ownership, these developments do not necessarily lead to the acceptance of the respective policies and the (immediate) adoption of sustainable mobility behavior. Moreover, people tend to choose a residence that matches their mobility preferences (so-called residential self-selection) or, if that is not possible, to live in their current neighborhood in dissonance with their attitudes (De Vos et al., 2012). Conversely, the residential neighborhood can change travel attitudes and behavior (De Vos et al., 2018). These general interactions between travel behavior and the built environment, residential self-selection, and psychological constructs, such as norms, preferences, and attitudes, have been covered extensively by mobility behavior studies (e.g., Cao et al., 2009; Ewing & Cervero, 2010; Handy et al., 2005; Steg, 2005). It nonetheless seemed of interest to examine whether real-world car-independent neighborhood interventions in specific have been analyzed in these regards to determine their potential for sustainable urban mobility. Furthermore, perceptions and acceptance are typically studied to measure the adoption of technological innovation into society (Huijts et al., 2012), which in this case can help to understand the success of car-independent policies. As Loo (2018, p. 7) argued, "the underlying perceptions and values of individual local residents are critical in understanding and sustaining the success of the car-free zone."

Thus far, substantial knowledge has been gathered on the potential environmental, social, and health benefits of car-independent cities (Nieuwenhuijsen & Khreis, 2016) as well as on the barriers and drivers of the transition (Nieuwenhuijsen et al., 2019). Melia et al. (2010) examined some of the early findings of the 2000s regarding the impact on mobility, social benefits, and issues of new car-reduced residential settlements. More recently, Sprei et al. (2020) reviewed the mobility effects of mainly Swedish housing projects as well as the evaluation quality of corresponding studies. Other types of car-reducing implementations, specifically those changing existing structures and temporary interventions, have not been adequately addressed by previous reviews. This review will expand on previous research by looking at all types of car-independent implementations beyond newly developed areas and adding the perspective of attitudes, perceptions, and acceptance beyond mobility behavior. Secondly, it will address both the methods and scientific rigor used in existing studies to derive recommendations and research directions for the evaluation of car-independent developments. Specifically, this article wants to shed light on the following research questions: Which types of car-independent city interventions have been implemented, and what are their rationales and main characteristics? How have they been evaluated in terms of mobility behavior, attitudes, perceptions, and acceptance? Our focus is on European cities as they are still the forerunner in implementing car-independent areas compared to the rest of the world (Bartzokas-Tsiompras, 2022) and literature is mainly available in this context. We further excluded historically car-free cities such as Venice to be able to address the change towards car-independent cities. Hereafter, Section 2 describes the methodology, and Section 3 reports the evidence found using the developed typology. In Section 4, conclusions on the findings are drawn and are followed by an outlook in Section 5.

2. Methodology

The methodology begins by conducting an initial screening to categorize various car-independent neighborhood interventions into four distinct types. For each type, the temporal and spatial scope, as well as the rationale and examples, are described. Afterward, a systematic literature review is conducted, using selected keywords concerning car independency, and each included study is assigned to a type for further analysis within each cluster.

2.1. Typology

As a preliminary step, we obtained an overview of implemented or planned car-independent developments in Europe based on Internet databases, related reviews, and snowball sampling. We deemed a classification necessary to review the wide range of interventions found. The typology developed was aimed to structure the study and relate the reported evidence to the characteristics of the defined types. We drew on the car-free matrix proposed by Wright (2005) and added the function or rationale of the different implementations in their urban settings, which we considered an essential criterion. Other aspects that might be of interest in other research contexts were intentionally left out of this typology (for a more general taxonomy, see Melia et al., 2014). Based on these reflections, we identified four distinct types, each with different rationales, scales, and temporal scope. These include car-independent central areas (Type I), residential developments (Type II), citywide implementations (Type III), and temporary interventions (Type IV), as seen in Table 1.

2.2. Systematic Literature Review

Thereafter, a systematic review of scholarly publications and, to a lesser extent, grey literature was conducted. Figure 1 describes the study selection process in detail. We limited our selection to publications and studies in English and German which examine policies for car-independent neighborhoods in Europe. On two databases, Scopus and Web of Science, we searched for articles with keywords to describe car independence,

Table 1. Typology of car-independent developments based on temporal scope, spatial scope, and rationale.

Type	Temporal scope	Spatial scope	Rationale	Examples
I. Central areas	Long-term	Mid-scale	Air quality, attractiveness, economic competitiveness of city center, and reclaiming “streets for people” (climate goals)	Bologna, Groningen, Nuremberg, York, Brussels, Oslo
II. Residential developments	Long-term	Small- to mid-scale	Car-independent living, community, and construction cost savings	Vauban (Freiburg), Lincoln (Darmstadt), Floridsdorf (Vienna), Hammarby Sjöstad (Stockholm)
III. Citywide implementations	Long-term (short-term pilots)	Large-scale	Climate goals, air quality, citywide modal shift, livability, and reclaiming “streets for people”	Low traffic neighborhoods (London), Superblocks (Barcelona), Kiezblocks (Berlin)
IV. Temporary interventions	Short-term	Small- to mid-scale	Pilot, awareness, car-free experience, reclaiming “streets for people,” sociability, and emergency response	Piazze Aperte (Milan), Leefstraat (Ghent), Summer Streets (Malmö, Gothenburg, Munich); car-free days (worldwide)

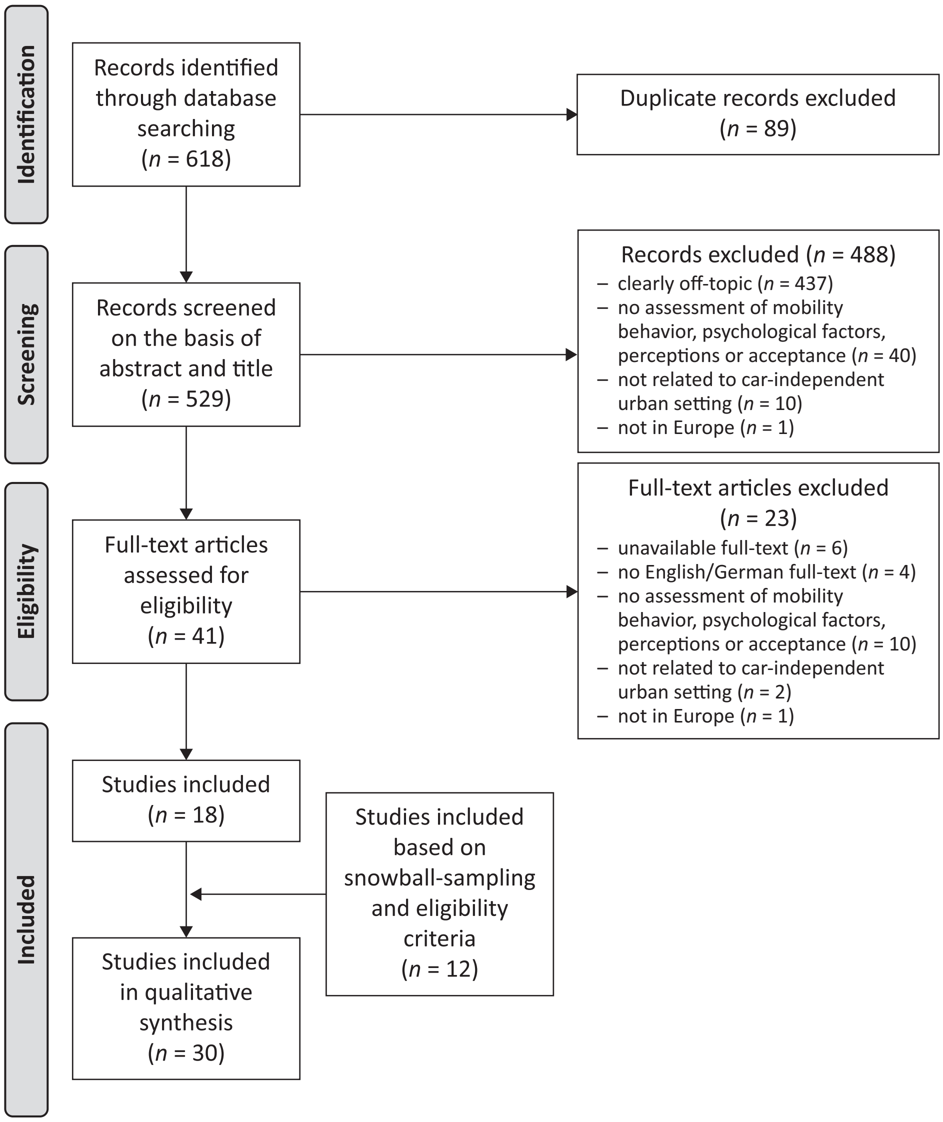

Figure 1. Flow chart of the study selection process.

such as "car-free," "car-reduce," "car ban," "*autofrei*," in combination with the spatial scope, such as "area," "neighborhood," "development," "city." In the Web of Science database, the search was additionally limited to the fields of transportation, environmental sciences, sustainability science, climate change, social psychology, and human geography. This resulted in 618 potential records. After removing duplicates (89), titles and abstracts were screened, resulting in the exclusion of 488 records which did not meet the inclusion criteria (see Figure 1). After the full-text screening, 18 studies were included that were related to car-independent urban settings and addressed residents' mobility behavior, psychological factors, perceptions, or acceptance of car-independent interventions. We found that some implementations were missing as not all use the identified keywords to describe car-independent interventions. Based on our expertise and through backward and forward snowballing, we complemented the search and included twelve additional sources. Nonetheless, we are aware that with this keyword search, we are examining only a small subset of mobility behavior research that addresses a particular type of intervention that is labeled car-free or similar. Supplementary sources were used to provide context but were not further defined as primary sources of the review.

3. Results

3.1. Summary and Quality of Studies

Table 2 provides an overview of the included studies, their methodology where present, and whether they addressed mobility behaviors (mob.), psychological factors (psy.), perceptions (per.), and acceptance (acc.). It proved difficult to distinguish between the different concepts because of the variety of methodologies, ontologies, and wording in the studies. Table 3, moreover, displays the evaluation criteria that we considered for the corresponding categories, as mentioned in the included studies.

Table 2. Overview of the studies included.

Reference	Case studies	Methods	Mob.	Psy.	Per.	Acc.
Type I. Central areas						
Bromley et al. (2007)	Bristol, Swansea, Birmingham, Cardiff	Secondary research: Analysis of census data (from 1991 and 2001) and household surveys in two cases (primary data, *n* = 541)	x[d]	x[i]		
Gundlach et al. (2018)	Berlin	Discrete choice experiment: Survey with students (*n* = 334), logit models				x[t,q]
Hagen and Tennøy (2021)	Oslo	Longitudinal study: Surveys with users and employees in the city center (*n* = 4,270 to *n* = 6,768)	x[b]		x[n,o]	
Nederveen et al. (1999)	Delft, Utrecht, Maastricht, Alkmaar, Groningen, Leeuwarden	Qualitative study: Informal interviews with residents (not stated) and interviews with representatives from resident groups (*n* = 10), document analysis				x[q]
Rydningen et al. (2017)	Nuremberg, Freiburg, Strasbourg	Secondary research and expert interviews during site visits (*n* = 6)	x[f]			x[q]
te Boveldt et al. (2022a)	Brussels	Longitudinal quantitative study: Survey with residents (*n* = 1,007), employees (*n* = 824), and visitors (*n* = 1,470)	x[b,h]		x[n]	x[s,q]
te Boveldt et al. (2022b)	Brussels	Longitudinal quantitative study: Survey with residents (*n* = 1,007), employees (*n* = 824), and visitors (*n* = 1,470), ordinal logistic regression analysis	x[h]			x[s,q]
Topp and Pharoah (1994)	Bologna, Lübeck, Aachen, York	Secondary research	x[a,e,h]			x[q]
Type II. Residential developments						
Baehler and Rérat (2020)	Burgunder in Bern, FAB-A in Biel/Bienne, Giesserei in Winterthur, Oberfeld in Ostermundigen, Sihlbogen in Zurich, Klein Borstel and Saarlandstraße in Hamburg, Stellwerk60 in Cologne, Weißenburg in Münster	Cross-sectional mixed methods study: Household survey (*n* = 571) and interviews (*n* = 50)	x[c]	x[j,k]		
Broaddus (2010)	Vauban and Rieselfeld, Freiburg	Secondary research, incl. official surveys and Nobis (2003)	x[c,d]			

Table 2. (Cont.) Overview of the studies included.

Reference	Case studies	Methods	Mob.	Psy.	Per.	Acc.
Type II. Residential developments (cont.)						
Foletta and Henderson (2016)	GWL-Terrein in Amsterdam, Vauban in Freiburg, Hammarby Sjöstad in Stockholm, Västra Hamnen in Malmö, Greenwich Millenium Village in London	Secondary research	x[d]			
Kirschner and Lanzendorf (2020)	Bornheim, Frankfurt	Cross-sectional quantitative study: Survey with residents (n = 1,027)	x[h]			x[q,u]
Melia (2014) and Melia et al. (2010)	Groningen, Vauban in Freiburg, GWL Terrein in Amsterdam, Saarlandstraße in Hamburg, Kornweg in Hamburg, Stellwerk 60 in Cologne	Secondary research, study visits, observations, and interviews	x[d]			x[r]
Morris et al. (2009)	European and UK residential developments	Secondary research	x[a,b]			x[r,q]
Nobis (2003)	Vauban, Freiburg	Cross-sectional study: Household survey (n = 247) and individual questionnaire (n = 438)	x[c,d]			x[r,v]
Ornetzeder et al. (2008)	Floridsdorf, Vienna	Cross-sectional mixed methods study: Survey in case study (n = 42) and in reference settlement (n = 46) and interviews (n = 9)	x[d,e]	x[j,k]	x[p]	
Scheurer (2001)	Torup in Hundested, Bo90, Skotteparken and Hyldespjældet in Copenhagen, Floridsdorf in Vienna, GWL Terrein in Amsterdam, Slateford Green in Edinburgh, Stadthaus Schlump and Saarlandstraße in Hamburg	Cross-sectional quantitative study: Survey with residents in nine case studies (n = 326)	x[c,d,e]	x[i]		
Selzer and Lanzendorf (2022)	Lincoln and K6-Kranichstein, Darmstadt	Qualitative study: Interviews with residents (n = 22), thematic qualitative text analysis in combination with a type-building text analysis	x[c]	x[j,k,l]	x[p]	
Selzer (2021)	Lincoln and K6-Kranichstein, Darmstadt	Qualitative study: Expert interviews (n = 15) and interviews with residents (n = 22), type-building text analysis	x[c]	x[l,m]	x[p]	x[r]
Sprei et al. (2020)	Settlements in Europe, focus on Sweden	Literature review, stakeholder interviews	x[c,b,d]			
Stubbs (2002)	Inner-urban London	Quantitative study: Survey (n = 47)				x[t,r]

Table 2. (Cont.) Overview of the studies included.

Reference	Case studies	Methods	Mob.	Psy.	Per.	Acc.
Type III. Citywide implementations						
Aldred et al. (2019)	Enfield, Waltham Forest and Kingston, Outer London (Mini-Holland program)	Longitudinal quantitative study: Surveys with intervention and control sample (n = 1,722), linear regression analyses	x[b,f]		x[o]	x[u]
Aldred and Goodman (2020)	Enfield, Waltham Forest and Kingston, Outer London (Mini-Holland and Low Traffic Neighbourhood program)	Longitudinal quantitative study: Surveys with intervention and control sample (n = 1,722), linear regression analyses	x[b,f]			
Scudellari et al. (2020)	Poblenou, Barcelona (Superblock program)	Qualitative study: Systematic document review, stakeholder interviews (n = 8), field interviews with users (n = 30)				x[q]
Type IV. Temporary interventions						
Bertolini (2020)	Street experiments worldwide	Systematic literature review	x[g]		x[n]	
Burton (2003)	European "in town without my car" car-free day	Secondary data	x[g]			x[q]
Marcheschi et al. (2022)	Summer streets, Gothenburg and Malmö	Cross-sectional mixed methods study: Environmental audit (n = 5), observations (n = 73), and interviews (n = 90); residents survey (n = 1,049), hierarchical regression analysis	x[h]			x[q]
Nello-Deakin (2022)	Eleven pandemic-related street interventions in Eixample, Barcelona	Longitudinal quantitative study: GIS-based evaluation of traffic count data on intervention and control streets	x[a]			
Reutter (2003)	Johannesplatz, Halle (Saale)	Triangulated quantitative study: Observations, traffic counts, and household surveys	x[a,b]		x[n]	x[r]

Table 3. Evaluation criteria by category in included studies.

Category	Evaluation criteria
Mobility behavior	[a] Traffic counts before and after, [b] change in mode use or ownership before and after, [c] self-reported change in mode use or ownership, [d] comparison of modal split or mode ownership with reference area, [e] comparison of kilometers (km) traveled by mode with reference area, [f] change in travel duration by mode, [g] shift in mode use or traffic volume (method unspecified), and [h] main mode or access to mode as an explanatory variable
Psychological factors	[i] Attitudes or motivations towards the residence, [j] attitudes towards modes, [k] pro-environmental or social values, [l] social norms or control, and [m] change of attitudes towards mode use
Perceptions	[n] Change in value or perceptions of public space or neighborhood, [o] change in perceived quality or accessibility of mode, and [p] perception of the physical or social environment
Acceptance	[q] Support towards implemented or future car-independent policies, [r] satisfaction with implemented or planned intervention, [s] change in support before and after, [t] preferences for different pull-and push-measures, [u] support for investment in active-mobility infrastructure, and [v] compliance with parking policies

Of the 30 studies included, the majority consisted of Type II (residential developments) with 14 studies, followed by Type I (central areas) with eight, Type IV (temporary interventions) with five, and Type III (citywide implementations) with three. The oldest studies date back to the 1990s and early 2000s, although the renewed interest in this topic in the last five years (14 studies) highlights the timeliness of this topic. Nine studies relied on secondary data from official statistics and other studies, often supplemented by qualitative observations or informal interviews. Two studies were systematic literature reviews (Bertolini, 2020; Sprei et al., 2020), providing an overview of specific types of implementations (Type II and Type IV) and access to results that were not available in English or not captured by our search strategy. The other 19 studies used primary data, of which 11 analyzed quantitative data (e.g., surveys and traffic counts), four analyzed qualitative data (interviews and document analysis), and three used mixed methods (e.g., surveys and interviews). In older studies, the description of data collection and analysis methods or original sources was overall lacking, especially those using secondary data.

Evidence of more sustainable mobility behavior in car-independent areas was examined in 24 of the 30 studies. In four studies, traffic counts before and after the intervention were used as an indication of a mobility behavior change. This can be problematic as it could also be related to a citywide modal shift, a shift in routes, or a change in the number of visitors to the area. Only one study compared intervention streets with control streets (Nello-Deakin, 2022). The surveys' designs were mostly cross-sectional studies that captured changes in mobility behavior based on reported changes (e.g., Baehler & Rérat, 2020; Nobis, 2003) or compared modal splits and ownership in car-independent intervention areas with reference areas (e.g., Foletta & Henderson, 2016). The bias of retrospective self-reports of changes, the frequent lack of matching control groups, and the limited comparability of different data sources compromise the methodological soundness of most studies. Recent studies often used longitudinal study designs to address changes in mobility behavior, which have the advantage of providing more reliable results on causality rather than correlation. However, three studies were not representative, and two of the studies did not include a baseline survey before the intervention (te Boveldt et al., 2022a, 2022b). Only two of them used a robust longitudinal design with control groups and regression analysis testing for significance (Aldred et al., 2019; Aldred & Goodman, 2020).

Five studies examined changes in perceptions in some way, while eight used perceptions and psychological factors to explain reasons for moving to car-independent areas, variations in acceptance, or mobility behavior. Only Selzer (2021) addressed changes in attitudes in their qualitative study. Acceptance was addressed by 17 studies.

3.2. Car-Independent Central Areas

From the late 60s on, pedestrian streets and car-free zones in city centers became a popular planning tool, especially in Europe (Orski, 1972). Since their role as employment and commercial centers typically predominates over their residential function, the primary intention of the early car bans or restrictions in central areas was to increase their attractiveness and boost the local economy (Orski, 1972). With growing awareness of the car's negative health effects on humans, lowering local air pollution and accidents has been a priority (Orski, 1972; Rydningen et al., 2017). Recently, there has been a renewed interest in enlarged car-free city centers. Cities like Brussels, Oslo, and Madrid announced or have already implemented their plans to further reduce car traffic in their centers (te Boveldt et al., 2022b). Narratives of these implementations shifted to GHG reductions and tackling car dominance towards "streets for people" (Hagen & Tennøy, 2021; te Boveldt et al., 2022b).

Overall, reviewed literature shows high acceptance rates among residents and users for both older and newer implementations (Gundlach et al., 2018; te Boveldt et al., 2022b; Topp & Pharoah, 1994). This combination, along with pull measures, was found to benefit acceptance rates for car restrictions (Gundlach et al., 2018). The evaluation of Brussels' recent extension of its central car-free area demonstrated that support had grown since its introduction (te Boveldt et al., 2022b). They found that among car drivers, there was a greater degree of disapproval, while cyclists and pedestrians, young individuals, and residents residing in close proximity exhibited greater levels of support (te Boveldt et al., 2022b). Contrary to the high approval of citizens, car bans in inner-city commercial areas typically face initial resistance from retailers who fear lost sales (Rydningen et al., 2017; Topp & Pharoah, 1994). In the case of Oslo, this resulted in a modified implementation approach (Cathcart-Keays, 2017). Spill-over effects in adjacent neighborhoods, i.e., higher parking pressure and increased traffic volumes, can result in dissatisfaction among affected residents and negative perceptions of the car-restricting policies (Nederveen et al., 1999).

While Topp and Pharoah (1994) identified a decrease in car use for trips to centers and an increase in the use of pedestrians, bicyclists, and public transportation, the results in Brussels were not as conclusive. There was a shift to sustainable modes for trips to the pedestrian zone by visitors and residents, however car use increased among people working in the center (te Boveldt et al., 2022a). Perceived safety was found to be low and decreased after the introduction (te Boveldt et al., 2022a), which potentially impacts walkability. The authors concluded that the causal relationship between the car-free intervention and mode shift remained unclear (te Boveldt et al., 2022b). This is consistent with the survey results from Hagen and Tennøy (2021) who found no clear change in mode choice among commuters and users of Oslo's city center before and after the introduction of street allocation measures. Still, with the improvement of cycling and walking conditions, perceived comfort and accessibility by those modes increased. It was found that while on-street parking was massively reduced, the percentage of businesses offering off-street parking to their employees increased. This provided a possible explanation for the slight increase in car driving (Hagen & Tennøy, 2021). Several authors suggested that due to its limited scope, there is little to no effect on the overall behavior or traffic volume (Orski, 1972; Topp & Pharoah, 1994). In the case of Oslo, the restrictions on motorized traffic on central streets were preceded by infrastructural changes and the tunneling of the city center and therefore had little impact on overall traffic volumes (Hagen & Tennøy, 2021). Moreover, trips to and within the center were already predominately done by sustainable modes of transport, leaving little potential for further reductions in car use (Hagen & Tennøy, 2021; Rydningen et al., 2017).

In the long-term, car-reduced city centers appear to attract new residents with low car ownership who value walkable distances to work and amenities (Bromley et al., 2007). However, this can lead to gentrification, as in the case of the British cities studied by Bromley et al. (2007), where highly educated young men with higher incomes were the main beneficiaries.

3.3. Car-Independent Residential Developments

The idea of residential developments with limited access and parking for cars to promote car-independent lifestyles and provide a healthy environment emerged in Europe during the 1990s (Baehler & Rérat, 2020; Scheurer, 2001). They range from "visually car-free" with no on-street parking but an abundant supply of off-street parking, "car-reduced" with lower parking provisions than standard, or (almost) completely "car-free" with the most stringent restrictions on car access and ownership (Morris et al., 2009). From the perspective of land developers, innovative mobility concepts are often introduced to reduce minimum parking requirements and thus construction costs (Seemann & Knöchel, 2018). Unlike pedestrianized city centers which are typically retrofitted, all permanent car-independent settlements found in this research were greenfield or brownfield developments where new residents had moved in after completion.

Car ownership and use were predominantly compared to the corresponding figures for the whole city and to other comparable contexts which proved to be lower in the majority of cases (Broaddus, 2010; Foletta & Henderson, 2016; Nobis, 2003; Sprei et al., 2020). Respectively, the share of sustainable modes was found to be substantially higher, also among car-owning households in the car-independent settlements (Nobis, 2003). Comparison to similar settings with conventional car policies pointed to the importance of financial, contractual, and spatial disincentives for parking to effectively reduce car dependency (Broaddus, 2010; Ornetzeder et al., 2008). The evaluation of nine case study developments by Scheurer (2001) showed a high ambiguity in terms of car use and ownership. Car ownership ranged from 8% in Floridsdorf, Vienna, where car ownership is prohibited by contract, to approximately 75% in Stadthaus Schlump, Hamburg, exceeding the city average. Notably, most of the developments studied by Scheurer (2001) were quite small and confined to only one block or house, indicating that the capacity to reduce car dependency without strict constraints on ownership is limited. The importance of scale was also discussed by Morris et al. (2009), who suggested that larger neighborhood-level mobility policies are needed rather than small-scale car-free housing which cannot provide benefits such as nearby amenities or low-emission and safe environments. In two studies, residents were asked to report any change in mobility behavior and car ownership since moving. They found a considerable effect of the new residents on reducing car ownership and the tendency to use sustainable modes more often (Baehler & Rérat, 2020; Nobis, 2003). Several studies showed that the mobility behavior of people is already more likely to be oriented toward sustainable modes of transport and many had already lived car-free before moving (Baehler & Rérat, 2020; Nobis, 2003; Selzer, 2021; Selzer & Lanzendorf, 2022). The reinforcing effect on existing sustainable mobility patterns is thus more pronounced than an actual shift from car-dependent to car-independent mobility choices (Selzer, 2021), whereby the relocation itself often provides the final impetus to abandon the private car.

Higher environmental awareness and negative attitudes towards cars, as well as the social context, were found to be connected with lower car use and ownership (Baehler & Rérat, 2020; Ornetzeder et al., 2008; Scheurer, 2001). Because people self-selected themselves towards car-reduced settlements, acceptance and satisfaction were typically high for this type (Nobis, 2003). Yet, several studies found that car owners frequently disregarded or circumvented parking rules (Nobis, 2003; Scheurer, 2001; Selzer, 2021). Acceptance and (partial) demotorization eventually grow with increased duration of residency in car-reduced neighborhoods according to Selzer (2021). Although there is a lack of documented and evaluated retrofitted car-independent residential areas, two of the found studies explored the potential of car-restricting policies in existing neighborhoods. In a central urban neighborhood of Frankfurt, study participants declared an overall high acceptance for all types of on-street parking policies (Kirschner & Lanzendorf, 2020). Interestingly, Kirschner and Lanzendorf (2020) found that car-owning residents with the intention to reduce their car use rated car-restricting policies similar to already car-free households in contrast to frequent car drivers. This speaks to the importance of psychological factors that anticipate actual change. In an earlier study, Stubbs (2002) found that homeowners in urban London were still opposed to the idea of car-free living.

The systemic context in which these developments exist seems to be the most limiting factor for car-independent lifestyles. In rural settings, constraints in accessibility and limited mobility options can lead to long-distance trips by motorized transport and even growth in car ownership despite pro-ecological attitudes and sustainability efforts within the settlement (Scheurer, 2001). Selzer and Lanzendorf (2022) found that people often still own or use a car to reach car-dependent areas in the outskirts for leisure and commuting trips. It was also the most often mentioned restraint for car-free households in Vauban (Nobis, 2003). This demonstrates the interlock of the car with lifestyle decisions and traditional urban planning, often separating functions of working, living, and recreation. The association of the car with more freedom, greater flexibility, and faster trips, as well as positive experiences and emotions developed over the years, still persist among many residents in car-reduced neighborhoods and hinder a modal shift (Selzer & Lanzendorf, 2022).

3.4. Car-Independent Citywide Implementations

Citywide policies aim to change the city's mobility system as a whole. Typically, rationales behind citywide car-independent strategies focus on climate change mitigation, modal shift, and livability goals including freeing space from the car for other uses and greenery. Although rare, some cities are in the process of implementing citywide strategies to significantly reduce their car traffic. A well-known example is Barcelona's superblocks or *superilles* which inspired similar movements in other European cities such as the *supermanzanas* in Vitoria-Gasteiz, *Superbüttel* in Hamburg, *Kiezblocks* in Berlin, or *Supergrätzl* in Vienna. They propose an organization of the city into neighborhood units, removing traffic and parking from the inner streets of communities and prioritizing active mobility and stationary uses (Scudellari et al., 2020).

To date, only three superblocks have been realized as part of Barcelona's comprehensive plan to redesign the city. In 2020, the city of Barcelona deviated from its original plan, introducing the concept of "green corridors" as a means to address public resistance (Nello-Deakin, 2022). Similarly, acceptance of the first pilot superblock in Poblenou was divided, with protests often coming from residents who did not have the benefits of living in the interior (Scudellari et al., 2020). In particular, the non-existent bike lanes and the traffic routing on the outer roads, which were foreseen to be adapted in the theoretical concept, led to dissatisfaction among users, but also the use of short-term means was less accepted than constructive improvements (Scudellari et al., 2020). Overall, it also revealed a problem of inequity between those who will benefit and those who will not.

London's scheme of Low Traffic Neighbourhoods and Mini-Holland program can also be considered a citywide strategy fostering car independency by introducing modal filters to inhibit through traffic in its neighborhoods and improving active mobility infrastructure. Its first implementations in Enfield, Waltham Forest and Kingston in Outer London have been thoroughly investigated (e.g., Aldred et al., 2019; Aldred & Goodman, 2020). By comparing intervention groups with control groups, Aldred et al. (2019) displayed that, especially in areas most affected by the interventions, active mobility trips and duration significantly increased as well as the perception of local cycling infrastructure improved. The impact on car use and ownership in low traffic neighborhoods was positively trending with statistical significance only in later waves (Aldred & Goodman, 2020). Although acceptance was not directly measured, the percentage of people who believed that too little was invested in cycling increased after introducing the measures (Aldred et al., 2019). Simultaneously, more people felt that too much money was spent, indicating a growing divide between those who were satisfied and dissatisfied with the interventions.

3.5. Car-Independent Temporary Interventions

Temporary interventions, also known as tactical urbanism or street experiments, are short-term measures ranging from the repurposing of parking spaces to the redesign of whole streets (Bertolini, 2020). They can be either recurring events, such as car-free days, play and summer streets, or one-time interventions over a period of several weeks, months, or even years, such as the Piazze Aperte program in Milan. Typically, they act as demonstration projects to raise awareness and allow citizens to experience a car-free environment (Nieuwenhuijsen et al., 2019) or as a pilot to learn in an iterative approach for later permanent implementation or upscaling (Lydon & Garcia, 2015). In research, they have been understood as niche experiments, acting in the car system or regime aiming for systemic change through incremental changes away from "streets for traffic" towards "streets for people" (Bertolini, 2020, p. 2).

According to Burton (2003), car-free days in Spain gained widespread acceptance, reduced automobile use, and increased the use of public transportation during the event. Yet, the interventions were claimed to have no lasting effect on traffic levels (Burton, 2003). Similarly, Bertolini (2020) found strong evidence in their review of street experiments for positive social impacts and increased physical activity, especially for play streets and open streets or *cyclovía* events, but no exploration of the experiments' ability to induce transformational change. Notably, Nello-Deakin (2022) demonstrated the effect of traffic evaporation in pandemic-related interventions in Barcelona, suggesting the potential for prolonged experimentation to induce modal shift or other adjustments in the form of destination shift. However, the three-year trial of a car-reduced neighborhood in Halle showed only a shift in traffic from car-restricted streets to main roads (Reutter, 2003). Car ownership even increased, which was attributed to a shift in the demographic of residents towards households with higher incomes.

As a result of a heated participation process, the Halle project had to adjust from a more radical car-free solution to a car-reduced solution (Reutter, 2003). After adjusting, the overall acceptance of the measures increased and perceptions of the quality of the neighborhood improved. It is noteworthy that the measures were not made permanent after the trial. Marcheschi et al. (2022) found that the acceptance of summer streets in Stockholm and Malmö was influenced by the attitudes and perceptions of users. Not surprisingly, individuals who identified as drivers and owned a car had lower acceptance rates. Individuals with longer residency and positive perceptions of quality of place also had lower levels of support for the measures, perceiving them as a disturbance. The authors recommended focusing on creating sociable places to increase acceptance.

4. Discussion

This review divided existing measures in Europe into car-independent central areas, residential areas, citywide measures, and temporary measures. This distinction by reason and scale synthesized the current state of research on car-independent developments regarding mobility behavior (change), psychological factors, perceptions, and acceptance. As such, a broader overview of car-independent neighborhood strategies was obtained than was previously done by Sprei et al. (2020) and Melia et al. (2010), who limited their review to new-built residential developments.

Earlier initiatives to car-free central areas (Type I) focused on the economic success of city centers and local emission reductions, while current projects also target climate goals, i.e., modal shift, and tackling car dominance in public spaces. The impact on people's mobility behavior, however, is generally limited to a few trip purposes and remains ambiguous. Evaluation of acceptance rates commonly displayed high overall support among users but strong (initial) opposition of businesses. Matching their primary motive of enabling car independent living, more sustainable mobility patterns were observed among residents of settlements of Type II compared to control areas or their city context. However, it is often unclear whether this is a causal relationship with the settlement design or—in the absence of a comprehensive (longitudinal) evaluation—a consequence of self-selection. The raised assumption of self-selection is consistent with studies showing that people with positive experiences and attitudes towards certain modes of transportation are more likely to live in areas that support their transportation preferences (e.g., Cao et al., 2009; De Vos et al., 2018). To achieve citywide car-independent environments, it is important to implement and evaluate practices beyond new developments and city centers. Rather little is known about transforming existing residential neighborhoods into car-independent areas (Types III and IV). This can be primarily attributed to the fact that there has been limited experience with citywide implementations (Type III) and little evaluation of temporary interventions (Type IV). The two examples found of citywide strategies, Low Traffic Neighbourhoods in London and superblocks in Barcelona, have only been partially implemented and evaluated in their pilots. Therefore, the question remains open regarding how existing structures can be changed on a large-scale that challenges the political, cultural, social, and functional lock-ins of the automobile regime, and what impact this would have on a city scale. Not surprisingly, there appears to be a greater polarization in terms of perceptions and acceptance among people in Types III (citywide implementations) and IV (temporary interventions) than in Types I (central areas) and II (residential developments). Experimentation has often been the starting point to incrementally initiate citywide implementation, Type III and IV are, therefore, strongly interrelated.

The results showed that (regardless of the type of car-free development) travel behavior, psychological factors, perceptions, and acceptance are interrelated (Marcheschi et al., 2022; Selzer & Lanzendorf, 2022; te Boveldt et al., 2022b). In the context of other research, it has been identified that attitudes have a strong influence on mobility behavior and that changing attitudes through improvements to the urban environment can contribute significantly to sustainable mobility behavior (De Vos et al., 2018). Yet, this has not been reflected in the focus of the found studies. Although not the focus of this research, several studies suggested that people value car-independent environments for their sociability (Bertolini, 2020; Ornetzeder et al., 2008; Scheurer, 2001). Conversely, they may perceive them as a threat to their usual environment (Marcheschi et al., 2022) or as reinforcing social inequalities (Nederveen et al., 1999; Scudellari et al., 2020). Practitioners and researchers are therefore advised to pay particular attention to the social impacts (and perceptions thereof) of car-independent neighborhood interventions which may foster or impede acceptance and positive experiences of car-independent mobility.

5. Conclusions

This article aimed to provide a typology of car-independent developments and a comprehensive literature review of their implications, enabling people to live without being reliant on private motorized transport ownership and use. To link characteristics, behavioral, and psychological implications, the car-independent developments were grouped into four types: car-independent central areas, residential developments, citywide implementations, and temporary interventions. Most studies focus on residential developments, more specifically, newly built housing developments.

While some knowledge is available regarding the potential environmental, social, and health benefits of car-independent cities, as well as barriers and drivers of the transition, few research papers discuss the actual behavioral and psychological implications. When impacts are assessed, a focus is often on mobility behavior, which changes depending on the measures implemented. In general, changing the environment in existing neighborhoods is much more challenging. The review shows a lack of knowledge on attitudes, perceptions, and acceptance among people affected by car-independent developments. It could be argued that actual impact is achieved through behavioral change only. However, the psychological factors should not be underestimated, as they provide the basis for a change in travel behavior. In terms of evaluation, the methods employed in many studies do not enable a complete and comprehensive understanding of causes and effects. Overall, there is a lack of reliable evaluations, but this has improved in more recent studies. While earlier studies primarily focused on mobility behavior, often using traffic counts as a proxy, perception has increasingly been included as one of the variables to be examined, while psychological factors such as attitudes remain scarcely studied in car-independent neighborhood interventions.

Future studies should focus on (a) other types of car-independent developments beyond newly built housing; (b) dedicated assessments of changes in psychological factors, perceptions, and acceptance; and (c) increased long-term observation of changes in behavior and mindset. Additional insights and knowledge on the impacts of car-independent developments, including the underlying causes, will help to derive recommendations for practical implementations and support the transformation of cities towards car independency.

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Conflict of Interests

The authors declare no conflict of interests.

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Article

Enhancing the Modal Split in Paramaribo Through Design-Driven Participatory Action Research Fuelled by Urban Tactics

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Abstract
There appears to be no "one-size-fits-all" strategy for evolving from a car-dependent urban environment towards a well-balanced modal split. The search for a suitable mobility strategy for a particular setting can be framed as seeking a suitable governance strategy. This article explores the opportunities of design-driven participatory action research (DD-PAR) as a governance strategy for improving mobility within a context of weak governance by investigating a single case study conducted in Paramaribo North, Suriname. Despite available plans, designs, and policy proposals, Surinamese public authorities are struggling to improve mobility. Notwithstanding many efforts, clientelism and patronage are weakening the power of the government, resulting in unimplemented public initiatives. Moreover, there are few civil society organisations to advocate for this weak public power. This creates a context in which neither the government nor civil society is sufficiently equipped to realise the modal shift in Paramaribo. Governance strategies depending on strong government or proactive civil society (e.g., actor-based strategies) are thus not suitable. In contrast, DD-PAR appears to have potential as a governance strategy, as it uses research and academics as forces to create societal enthusiasm, establish actor networks, and generate action. The current case study identifies key actors and preconditions for building a network of actors. It also provides tentative insights into urban tactics for increasing pressure on the government to provide adequate infrastructure and policy to accommodate newly developed action that supports a more diverse modal split.

Keywords
car dependency; civic engagement; design driven; participatory action research; urban tactics; weak governance

Issue
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1. Introduction

Achieving a more sustainable urban future with lower carbon emissions will require a well-balanced modal split. International organisations (e.g., the UN) promote sustainable urban policy carried out by a strong public sector, combined with civic participation and even co-creation (United Nations, 2016). Unfortunately, several urban environments that currently suffer from car dependency are unable to count on public support to improve their modal split, for a variety of reasons. This is problematic, as popular initiatives, policy strategies, and actions aimed at decreasing car dependency (e.g., increasing public transportation, providing sufficient and safe sidewalks and bicycle lanes, increasing parking rates, developing parks and rides on the fringes of cities, promoting the use of bicycles for functional transportation) often rely on networks that include a capable public sector or a strong civil society. In addition, it is difficult to autonomously create an actor-network to function within a context of weak governance without strong policymakers, a skilled professional public sector, or an existing actor-network, and one that is affected by adverse governance mechanisms. Such contexts call for alternative governance strategies, such as those using external professionals to locate key actors in order to establish an actor-network and identify feasible actions.

This article explores the opportunities offered by design-driven participatory action research (DD-PAR) as an alternative governance approach aimed at improving mobility within an urban environment that is affected by obstructive public actors and a weak civil society. More specifically, this article assumes that urban tactics (as a part of DD-PAR) can stimulate civic organisation and civic actions to improve mobility in specific cases (Lydon et al., 2015). Previous applications of DD-PAR have included an initiative in Milan to advocate for an improved modal split by organising a Massa Marmocchi (Massa Marmocchi Milano, 2023). Another example involved a self-governance approach that resulted in the redesign of several blocks in the Cerda grid in Barcelona to realise pedestrian-friendly and bike-friendly "super blocks" (Rueda, 2019).

To test this assumption, this article elaborates on how an environment of weak governance can benefit from urban tactics and DD-PAR. The following sections provide a description and analysis of the experiences and preliminary results of a two-month DD-PAR field project focusing on mobility in Paramaribo. In this project, researchers built on the hopeful practices and field experiences of the research unit known as the Interdisciplinary Studio for Territories in Transition (ISTT) of the University of Antwerp (UA) and the Anton de Kom University of Suriname (AdeKUS). These experiences are used to set the stage for developing an actor-network to engage in a DD-PAR process involving urban tactics. Finally, some preliminary conclusions are formulated with regard to the potential of and preconditions for urban tactics to enhance civic organisation, including how these tactics relate to public policy and private initiatives, as well as how they contribute to improving the modal split in Paramaribo North.

2. Urban Tactics as Part of Design-Driven Participatory Action Research

2.1. Design-Driven Participatory Action Research

DD-PAR is a specific form of PAR, a methodology that aims to identify capable actors, bring them together within a network, and finally, assess the potential of self-organisation in the attempt to set up actions within a specific context. The research method has been applied in a broad variety of disciplines. As defined by Kindon et al. (2007, p.1), PAR is "an umbrella term covering a variety of participatory approaches to action-oriented research. Defined most simply, PAR involves researchers and participants working together to examine a problematic situation or action to change it for the better." Each of the many variants of PAR differs in the manner and extent of involvement on the part of the practitioner or community, as well as in the expected outcomes and the way in which the research is conducted (Bilandzic & Venable, 2011). Despite the wide variation in existing forms of the method, Gaventa and Cornwall (2006) identify three common principles common to any PAR project: (a) it should develop an alternative form of knowledge that contributes to empowerment and social change; (b) it should encourage mobilisation and action; and (c) it should encourage reflection, learning, and individual critical consciousness. As aptly stipulated by Nakamura (2015), PAR should also be related to urban and community issues, in addition to providing a methodology for carrying out research with communities and aiming to achieve participation, empowerment, change, and power transfer. Close community involvement in PAR results in capacity-building and helps to empower communities to continue engaging in decision-making processes over the long term. In DD-PAR, research by design and design are used to assess specific situations, as well as to encourage or prepare specific civic action. The addition of a DD dimension to the characteristics of PAR thus often ensures that the outcomes are more tangible (Goethals et al., 2022).

2.2. Urban Tactics

Lydon et al. (2015, p.7) define tactical urban planning (or emerging urbanism) as "[a] strategy of action-based research focused on short-term intervention, through creative and low-cost ideas, at a local, punctual and controlled level. Its goal is to condition public space for those who live in it: citizens."

Tactical urbanism is a form of planning that is complementary to the formal urban-planning process. It offers a solution to the slow, cumbersome nature that characterises urban planning. However innovative and promising they may be, large-scale urban projects take a long time, cost a lot of money, and are often delayed. Tactical urbanism can allow action to emerge in a very short term. As noted by Lydon et al. (2015, p.2), Merriam-Webster defines "tactics" as small-scale actions that serve a larger purpose. They further elaborate this definition to describe urban tactics as small-scale, temporary interventions in space for the mental and physical transition by and for local people. Urban tactics are thus characterised by four properties: (a) small-scale interventions on specific and most crucial locations in the city where something can or should change spatially; (b) temporary actions that are not major infrastructural, physically invasive works and that often involve working with loose, mobile components to test out situations; (c) actions that support a mental transition; and (d) actions that have a very strong social component through an open, participatory, and iterative design process (Lydon et al., 2015). They thus provide a quick, accessible manner of initiating positive change. These characteristics sustain the interest of civil society and state actors. Citizen participation in urban tactics creates a sense of ownership and investment, and the creativity and innovation of such tactics can capture the imagination of the public, thereby generating excitement and interest in the longer term. Several case studies and toolkits relating to urban tactics are available on the internet, thus allowing the tactical-urbanism movement to spread around the world.

The relationship between DD-PAR and tactical urbanism is based on the fact that they both prioritise collaboration with and engagement of community members in the design and implementation of urban interventions. While DD-PAR emphasises more general co-creation and co-design, tactical urbanism focuses on executable citizen-led initiatives and on-the-spot experimentation.

3. Case Study: Design-Driven Participatory Action Research and Urban Tactics in Paramaribo North

Paramaribo, the capital of Suriname, is a sprawling Caribbean city that suffers from traffic congestion, poor public transportation, and an unattractive public domain for pedestrians and cyclists (Claes & Debaene, 2009; Heirman, 2019; Heirman et al., 2007). This adverse mobility situation has emerged in the last four decades. Paramaribo was originally a planned tropical city with a well-balanced modal split (see Figure 1). Since the 1980s, however, cars have been displacing bicycles, and pedestrian zones have become unattractive due to parked cars and the absence of shade, owing to the disappearance of trees (Dikland, 2004; PHI for Inter-American Development Bank, 2005; Verrest, 2010). Public transportation has currently been reduced to a network of minibuses that no longer covers the entire area, combined with small private jetties to cross the river. Public jetties and light rail services are no longer available. As a result, private cars have become the dominant mode of transportation, thereby leading to a steep increase in private car ownership. As of 2019, car use had more than doubled relative to 2005 (Inter-American Development Bank, 2019).

As demonstrated by several policy plans and academic studies, it is theoretically possible to improve the modal split in and around Paramaribo. These plans and studies have produced ideas for reinstating the public jetties and light rail services, as well as for creating a new public transportation infrastructure and redesigning streets to make them more amenable to pedestrians and cyclists. Some of these ideas have been elaborated into detailed construction plans or operational policies. Unfortunately, however, these mobility plans and projects have been discontinued, and the government has changed very little concerning mobility. Although some of the public domain has been reconstructed, this has been done with little regard to the needs of pedestrians and cyclists (Inter-American Development Bank, 2019; Jankipersadsingh et al., 1993; Ministry of Public Works, 2010; Ministry of Public Works et al., 1992; NEA Transport Research et al., 2011; Neyt et al., 2020; Rymenants & Struyf, 2022).

Figure 1. Gravestraat, Paramaribo in 1949 (photo by De Spaarnestad).

Problems of obstructive policy implementation and unrealised projects are not limited to the domains of mobility and urban planning. Several scholars have identified similar situations in a variety of policy domains and have linked these issues to weak governance in Suriname. Although it is a middle-income country, Suriname is characterised by a high level of inequality, and it is suffering from a financial crisis. The country's per-capita GDP in US dollars has decreased by half, from 9,199.2 in 2014 to 4,869.1 in 2021 (World Bank, 2023). Moreover, the inflation rate surged to 70% in 2021 (IMF, 2021). As a result, more than half of all inhabitants in the interior of Suriname are living in poverty. Since gaining its independence in 1975, the Surinamese government has struggled to provide adequate public services and develop policies to create living conditions of acceptable quality. Its post-colonial governance has been characterised by deeply rooted mechanisms of patronage and clientelism. Hout (2007) describes Suriname as a prime example of a rentier state. The public institutions involved in the administration of land allocation, public works, spatial planning, regional development, and mobility are highly politicized. Adverse path-dependent institutional arrangements have created a situation in which few planning initiatives are developed and even fewer are successfully implemented (Heirman, 2019).

3.1. Action Research and Urban Tactics by Interdisciplinary Studio for Territories in Transition

Since 2005, the UA and the AdeKUS have collaborated in research, educational strengthening, and civil service projects (Adams & Heirman, 2012). The first years of the collaboration focused on large-scale urban renewal plans and policy improvement, with the close involvement of public institutions. Despite considerable enthusiasm and lively discussions on sustainable urban development in Suriname, none of the policy recommendations or projects was implemented. To embody a new collaborative approach with a greater focus on civic engagement, the two academic institutes joined forces in a research unit: the ISTT. Since 2016, the ISTT has focused on DD-PAR at several research sites in Suriname (ISTT, 2022). In these projects, UA staff and master students of architecture, urbanism-spatial planning, and heritage studies have worked with the staff of the AdeKUS to perform DD-PAR research with bachelor students of infrastructure and civil engineering. Whenever possible, they try to engage citizens, civil society organisations, and/or representatives of local public offices. Students and local supervisors carry out the research, with the UA supervisors guiding the students together with the local supervisors during online meetings. In most cases, the UA supervisors join the teams for several days during the two-month fieldwork period, in addition to participating in the overarching, multilateral actor workshops. The focus of the research ranges from integrated planning processes on specific neighbourhoods to more thematic research focusing on such topics as housing, heritage, or mobility. This article focuses only on the DD-PAR action regarding mobility in Paramaribo North.

3.2. Momentum for Urban Tactics Regarding Bicycle Mobility in Paramaribo North

The financial crisis and global rise in fuel prices have made the use of private cars less affordable for the citizens of Paramaribo. The reliability of public transportation decreased during the Covid-19 crisis when many private bus drivers stopped driving. In response, more citizens resumed walking and cycling, thus creating opportunities for increased attention to pedestrian and bicycle mobility. Alongside the effects of these crises, several fragile, yet hopeful practices have emerged in Paramaribo North with regard to a more diverse modal split. In Paramaribo North, many facilities (e.g., markets, supermarkets, and schools) are located within walking or cycling distance (Peleman, 2020). Furthermore, this part of the city has relatively more economically strong residents. This provides greater capacity for mobilising resources to support a mobility transformation. In addition, this group of citizens has more time for recreation, as they are not merely struggling to survive. As indicated by Strava data, observations and testimonials, recreational exercise (e.g., jogging and cycling) is relatively more prominent in Paramaribo North than it is in the rest of Paramaribo (Inter-American Development Bank, 2019; Peleman, 2020; Rymenants & Struyf, 2022). The increasing number of bicycles on the streets has lowered barriers for other citizens, as it has helped to break down the general stigma perceived by many Surinamese that cycling is a mode of transportation for the urban poor. This development could provide a stepping stone to cycling for functional purposes. In addition to local and spontaneous individual exercise, three organisations have established biking tours that regularly pass through this area. Finally, Paramaribo North is situated between the historic centre of Paramaribo and the plantation heritage area in North Commewijne, which is accessible by the private jetties at Leonsberg. Tourists often pass through Paramaribo North on their way to the jetties. The area thus has the potential to serve as a link between the two hotspots, thereby accommodating a good connection. In this way, a positive environment, strong individual actors, and several hopeful practices are creating positive preconditions for identifying key actors, bringing them together within an emerging network and establishing joint actions at the neighbourhood scale or as a part of temporary improvements in the modal split in the neighbourhood. Based on these aspects, Paramaribo North was selected for a DD-PAR project fuelled by urban tactics.

3.3. Shaping an Actor Network in Paramaribo North

Very little public investment for cycling infrastructure exists in Paramaribo. In 2017 and 2019, no public funding was allocated to this end, and investments in 2018, 2020, and 2021 amounted to only 750,000 USD. These figures suggest that a diverse modal split is low on the policy agenda. Pedestrian and bicycle mobility is perceived as dangerous due to the lack of infrastructure, in addition to image problems relating to their perception as mobility options for the urban poor. An actor-network is therefore needed to create a critical consciousness regarding the need for more pedestrian and bicycle mobility, while also demanding public investment in proper infrastructure. After a positive consciousness has been created, supporting actions and improved infrastructure could jointly promote a mental transition, in which more people are convinced to use their bicycles or walk. No such coherent, jointly cooperating actor network was available at the start of the DD-PAR fieldwork (Rymenants & Struyf, 2022).

The DD-PAR fieldwork in Paramaribo North aimed to bring together individual actors and to start building an actor-network that would encourage mobilisation and claim ownership over jointly developed activities. The network was also expected to identify bicycle ambassadors to convince other citizens in their areas to cycle as well. The researchers tried to encourage the development of this network by engaging as many citizens as possible. An iterative process of observations and informal and formal conversations (both individual and in groups) was conducted to explore the following question: "Which actors could we involve in establishing a network that could stimulate bicycle mobility from the bottom up?" The researchers talked to cyclists on the streets, and contacted cycling clubs, bicycle stores, rental agencies, businesses, voluntary organisations, journalists, and schools, in addition to participating in local events. During conversations and interviews with these actors, the researchers talked about past research and future goals, while listening to the stories, concerns, and suggestions of the actors regarding road safety and bicycle mobility in Suriname. As mentioned previously, safety and status are major concerns, although climatic conditions play a role as well.

To achieve a well-balanced network, the researchers tried to include public authorities by organising presentations at their offices to advocate the benefits of urban bicycle mobility to the Ministry of Public Works and police departments (see Figure 3). The goal was to act as a voice for cyclists and vulnerable road users, as well as to draw attention to its importance in terms of benefits relating to health, climate, and other aspects. In addition, the researchers tried to assess the extent to which these public actors were willing to engage in the network and to work towards the realisation of a mobility transition. At the end of the DD-PAR fieldwork in Paramaribo, the researchers organised an evening for all stakeholders to share ideas and experiences concerning cycling in Paramaribo (see Figure 2). During this evening, the capable actors came together, began to identify themselves as a network and even joined forces through an online

Figure 2. Discussion evening with involved actors in Paramaribo North. Source: Rymenants and Struyf (2022, p. 59X).

platform on which all actors could discuss bicycle mobility and promote activities. Two key actors expressed willingness to take the lead in continuing the dynamics and network that had been created during the DD-PAR fieldwork. They also expressed the ambition to establish an official bicycle council to act as an advisory organ for government agencies and to organise activities and urban tactics in the future (Rymenants & Struyf, 2022). One of the key actors collaborated with a government official and several actors in the network to submit a proposal to the Bloomberg Initiative for Cycling Infrastructure.

3.4. Urban Tactic 1: Bicycle Routes in Paramaribo North

To stimulate the identification of key actors and to support the establishment of an actor-network, the DD-PAR fieldwork also developed two urban tactics. More specifically, the researchers used small-scale, punctual actions in Paramaribo North to influence the discussion with the actors involved, as well as with citizens and organisations that had not yet been involved in the fieldwork. For the first action, the researchers focused on raising awareness concerning the problematic nature

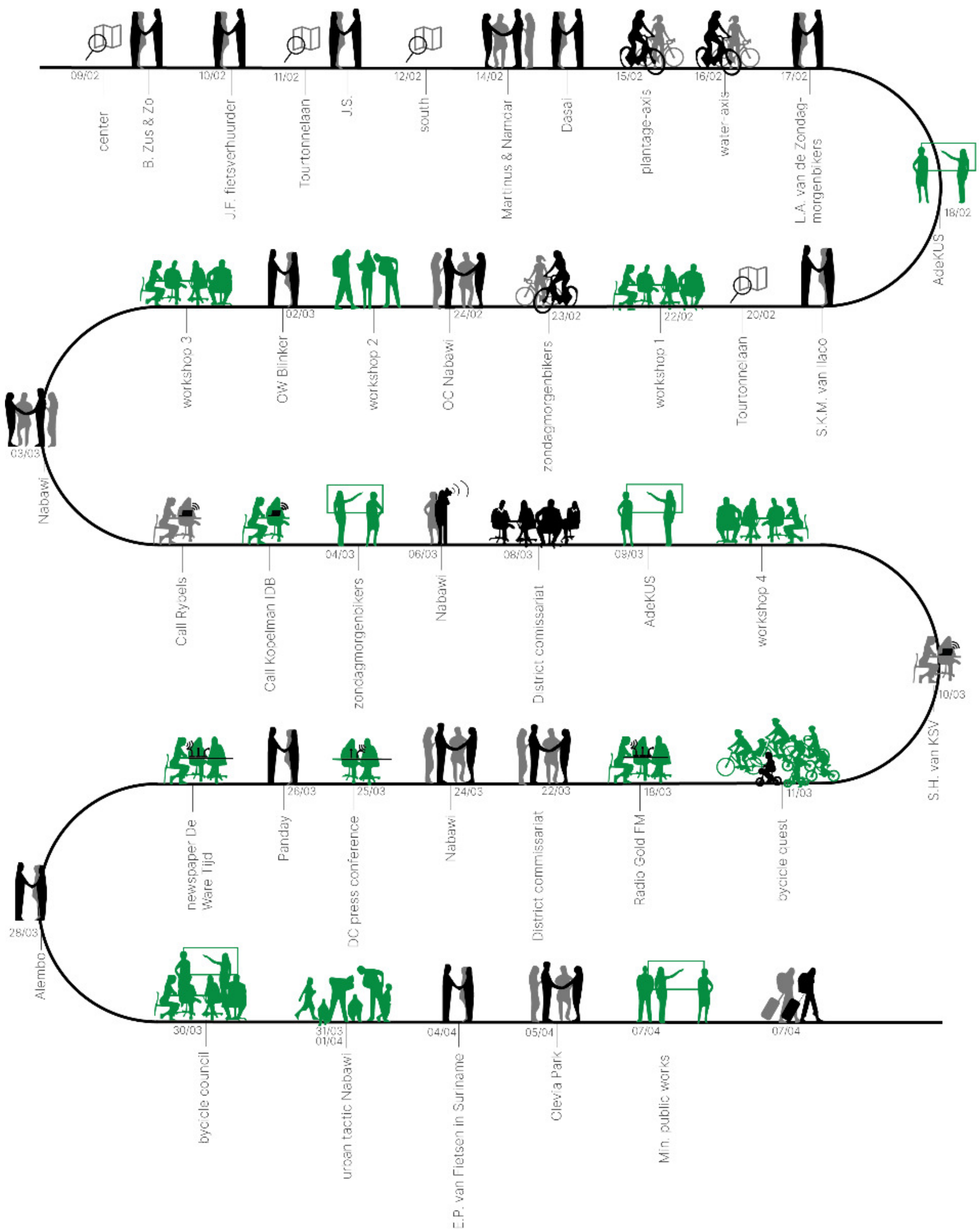

Figure 3. Conceptual timeline for establishing a local actor network for pedestrian and bicycle mobility in Paramaribo North during the DD-PAR fieldwork. Source: Rymenants and Struyf (2022, p. 42).

of the absence of bicycle infrastructure in Paramaribo North. To raise awareness and initiate modest infrastructure adaptations in favour of bicycle mobility, tentative bicycle routes were created between the historic centre of Paramaribo and Leonsberg by spray painting bicycle signs on the roads (see Figure 4). This first urban tactic was intended to convince the government to integrate the improvement of bicycle mobility into its policy priorities. Through bottom-up testing of physical intervention, the researchers tried to demonstrate the benefits of bicycle infrastructure.

The urban tactic of using spray paint and stencils to mark bicycle lanes on roads has been applied all over the world. The markings were primarily intended to exert a visual influence and make road users aware of the co-use of cyclists on the lane. It creates space for cyclists and makes car drivers aware of it. This was done in the hope that local authorities would notice them, which was often the case. The realisation of the action explicitly drew the attention of approximately 12 passers-by. Several cars stopped and asked what was going on. Most reactions to the unusual action were positive, albeit suspicious. Several cyclists also passed by, smiling and giving a thumbs-up sign. The few, but positive reactions received during the realisation suggest that the implementation of the intervention had a limited but positive influence on passers-by. Given that the researchers returned to Belgium shortly after applying the symbols to the road, however, additional follow-up research is needed in order to study the impact of the symbols in a more structural manner.

Although the initiative could be described as an initial physical improvement, it primarily served as a small-scale, low-cost action that encouraged a mental transition for passers-by, as well as for public and private actors within an emerging network. Although this act of tactical urbanism was performed solely by the researchers, with no other actors involved, it was discussed with relevant actors by showing pictures and talking about the example of tactical urbanism. The discussion also served to alert residents to the possibility of taking individual action in favour of directing greater attention towards sustainable transport modes. Although the discussions were interesting, they did not result in any local actors taking ownership of this urban tactic.

The Ministry of Public Works and the district commissariat of Paramaribo North East were enthusiastic about the research and the proposed urban tactics. The financial engagement proved difficult, however, as no budget was available for this type of project. For these officials, the most important question appeared to concern how to create a safer traffic situation through small-scale, preferably bottom-up projects. The researchers introduced them to urban tactics (e.g., focusing on bicycle routes and activities), demonstrating that they could be used to take the first steps towards a more exercise-friendly Paramaribo. Immediately after the meeting, the head of the district proposed to submit an application for a permit to spray paint bicycle symbols on the road. Once the application had been submitted, approval would be sought from the police stations and the Ministry of Public Works. Although the

Figure 4. Cycling symbols were applied with spray paint to the roads in Paramaribo North. Source: Rymenants and Struyf (2022, p. 72).

police stations granted approval shortly thereafter, the researchers did not receive any news from the ministry. Several weeks later, we received word that the application had been rejected, due to the absence of a road classification, which the ministry was then in the process of preparing. No further explanation was given.

Contrary to expectations, the procedure seemed to go smoothly at first. Unfortunately, it eventually became lost within the maze of the Surinamese bureaucracy and the associated power struggles among political figures. We can therefore conclude that, despite the interest and support demonstrated by local agencies, it is quite difficult to obtain approval for such actions, given that it is not a standard procedure. It thus requires a great deal of time to create a network that includes engaged public officials who are willing to allow or even engage in short-term, low-budget interventions to improve mobility. Given that the public officials were unwilling to cooperate in issuing a permit, they are unlikely to be willing to engage in urban tactics aimed at contributing to the mental transition towards structural changes in mobility policy and road design. Research by design is therefore needed to consider and prepare future locations for urban tactics in this regard. Because the public actors rejected the project and no other local actors were involved in the realisation of the urban tactic, there was no ownership of this action on the part of any actors in the emerging network. The events that were held in conjunction with the action nevertheless contributed to a positive discussion, thereby fuelling the emerging network.

3.5. Urban Tactic 2: Bike-Friendly School Environments in Paramaribo North

To further explore the possibility of creating a local actor-network with regard to enhancing bicycle mobility, making temporary improvements to the local situation temporary, and contributing to a mental transition towards a better modal split, the researchers collaborated with an elementary school in Paramaribo North to develop a second urban tactic. As demonstrated in the literature on action research, schools offer considerable potential to act as hubs within a network of slow-mobility options. Previous student research in Paramaribo has included educational institutions in the development of a proposed ideal bicycle route. As public facilities that must be accessible to the majority of the population (Neyt et al., 2020), schools have a major impact on society. Given their age and learning ability, students constitute a target audience with considerable potential. In addition, collaboration with a school offers several interesting advantages: the possibility of addressing a broad group of participants who are following a learning process within a fixed organisational structure, easy accessibility to the facilities and buildings of the school for the organisation of actions and urban tactics, and easy connection to the educational character of a school environment. Moreover, the target audience reached through collaboration with a school extends beyond the children to include teachers, principals, and parents. The joint creation of urban tactics with actors in the emerging network also increases the probability that the local actors involved will take ownership of the action.

As illustrated by the empty bike racks and ideas for drive-through parking lots, private cars were the dominant mobility option at the Nabawi School. The school's concern for the safety of children was evidenced by its support for the installation of speed bumps. Observation of traffic and infrastructure in the school's seemingly quiet surroundings confirmed these concerns. Everyone consulted by the researchers appeared to have the ambition to enhance traffic safety around the school and during after-school activities with children. To this end, a walk-bike quest was organised, primarily as a means of addressing the mental transition and contributing to the social component of generating support for positive change.

The walk-bike quest set a lot in motion: children discovered the joy of walking and cycling, parents came out of their comfort zone to walk and cycle, and passers-by were amazed at the large group of pedestrians and cyclists on the streets. Interestingly, the reactions of motorists toward cyclists were remarkably different from their reactions to pedestrians. Due to the institutionalisation of several "walkathons" in Paramaribo, drivers are used to slowing down for pedestrians. In contrast, cycling is still uncommon, and motorists are not accustomed to slowing down for cyclists. Some motorists even intentionally displayed inappropriate driving behaviour. The mental process of accepting pedestrians as acknowledged users of the public domain was thus further advanced than that of accepting cyclists, who continue to be marginalised and unacknowledged.

Participation in a cycling event provided the opportunity to renew acquaintances with cycling, to consider the benefits of bicycle use, and to fuel enthusiasm and demand for bicycle facilities. Several participants expressed a desire to do this more often. One student at the AdeKUS who had participated in the event as a facilitator had prepared his bicycle for the activity. Although it had been neglected for years, the bike was now back in sight and ready to use. As a result, his sister also wanted to start cycling again. The organisation of recreational events sparked a mental process, and positive change might advance functional bicycle use in the long run. Repeating such recreational events regularly and expanding them to other schools and organisations could expand the reach and likelihood of increased bicycle use.

After the walk-bike quest, enthusiasm for tactical urbanism grew, along with the hope for a safer school environment. This encouraged further mobilisation for action, and a spatial intervention in the school environment soon followed. Most of the children at the Nabawi School are transported to and from school in their parent's cars. This creates heavy congestion on the school's street during peak school hours, and children must walk between and around the manoeuvring vehicles. The situation is dangerous, and it does not enhance the motivation to walk or cycle to school. Together with students, the researchers created a painting on the surface of the street in front of the school gate (see Figure 5). The goal was to make the drop-off/pick-up process smoother and safer while creating additional room for slow-moving traffic. The project was also intended to narrow the lane and slow down motorised traffic.

The urban tactic received positive feedback from both teachers and parents. In addition, the children immediately started using the extra space to play while waiting. The change obviously requires further explanation, however, as such urban tactics cannot work for drivers without clear communication. The intervention provided enjoyment for children and it made parents think.

Additional small-scale actions could increase the short-term impact of the urban tactic of the painting. For example, old car tires could be used to make the area of the painting inaccessible to motorised vehicles. Temporary actions could be organised as well. For example, closing the street in front of the school and moving the playground to the street for a day could highlight the possibilities of using the public road as a place for children to skate, bike, or draw with chalk. At the same time, such activities would require a different organisation of motorised traffic when dropping off and picking up the children. If repeated regularly, this could eventually result in a permanent monthly event. In the longer term, an application to redesign the street for one-way traffic could be combined with softening one lane, thereby improving the infiltration of stormwater for the surrounding area and reducing the intensity of common roadway flooding.

Through research by design, the team also developed a follow-up plan for realising more functional bicycle traffic: a manual for establishing a "bicycle bus" to encourage cycling to school in groups. Although such an initiative would make cycling safer, it would be impossible without demand for it. Design research is being conducted to explore how actions in school environments in Paramaribo could be continued and expanded. Unfortunately, the bike bus has not yet been organised.

4. Discussion

Despite the limited number of actions and the brief time span for the field research in situ, the project has yielded some preliminary insights regarding the effects of positive preconditions, identification of capable actors, bringing the actors together in a network, and establishing actions. The results also illustrate the effects of collaboration between researchers and local actors to address a problematic situation through small-scale actions. The careful selection of the research area, in which hopeful practices were already present, made it possible to draw connections with local actors, build on

Figure 5. Painting on the streets in front of the Nabawi School. Source: Rymenants and Struyf (2022, p. 93).

their initiatives, and set the stage for the development of an actor-network within a short time span. The researchers were also able to build on the existing ISTT network that has been growing over the years. The renewed energy that accompanies a new group of students each year helps to activate local interest and community participation. These aspects illustrate the strength of the research process adopted by the ISTT.

Given that the researchers were not able to draw on an existing actor-network, a strong civil society organisation or well-functioning public offices, the DD-PAR fieldwork in Paramaribo North was not expected to have much effect on encouraging parents and children to walk or cycle to school in the short term. It may take years to transform entrenched habits. Additional actions are needed over a longer period, thereby allowing for incremental change of habits. Critical consciousness is also needed with regard to a more balanced modal split amongst the other road users. Over time, it will be necessary for motorists to adapt their behaviour in the presence of cyclists, given the importance of safety on the streets on the way to school. The research processes of the ISTT employ DD-PAR and urban tactics to provide a stepping stone to bottom-up change so that local actors can continue the process and achieve long-term goals once the researchers have left. Ambitions call for engaged local actors to pick up the thread themselves to initiate further changes. The role of the researchers is to activate these actors and show what is possible by initiating such urban tactics. This objective appears to be overly ambitious, however, as the networks are too fragile. Over time, the groups and organisations that are now emerging could grow into accountable civil society organisations. At present, however, they are not sufficiently institutionalised to assume the leading role played by the researchers during their DD-PAR fieldwork.

The formation of a network that reflects on current situations focuses on the empowerment of pedestrians and cyclists, and works towards social change that could improve the modal split in Paramaribo is a slow process of trial and error. Successful results help to sustain the interests of these actors, as well as regular follow-up by new students. The DD-PAR projects described in this article have activated a network that is willing to continue the work. For example, the principals and the parents' committee became more willing to engage in urban tactics after the walk-bike quest. As indicated by contacts with the school and cycling clubs, the path towards functional bicycle traffic will be slow and phased, with deliberate detours into the recreational sphere.

The methodology of DD-PAR using urban tactics played a leading role in this project, and its various elements all proved crucial. In addition to working in steps and small, punctual actions, local actors are essential to keeping the efforts feasible and affordable. The proposal to work with schools was one of the ideas conceived to encourage bicycle traffic. The existing organisational structure of the parents' committee (with its wide reach) appears to have been a key factor in the preliminary success of the actions. Moreover, schools can help to manage tension existing between government-driven and independent organisations. As a target group and a collection of actors to co-direct the actions, the Nabawi School constituted a vulnerable link within the project. The students of a secondary school would have been a better choice as, unlike the children of the Nabawi School, they are old enough to travel independently to school through the streets of Paramaribo. They might have been more solicitous than the members of the parents' committee, who must now take on the leading role for their children. The greatest challenge is now to ensure that the members of the parents' committee will continue the work voluntarily, without the researchers acting as a driving force. To this end, efforts are being made to fill the gap between research groups by organising a bicycle-stakeholder meeting to connect local actors who are already active within the field.

Although they should ultimately occur from the bottom up, urban tactics and the public discussion regarding pedestrian and bicycle mobility should not be completely separated from the government. The connection with the government in this regard is necessary, as civic actions aimed at altering the critical consciousness to generate a modal shift and change the mobility behaviour of citizens must be accommodated through the production of infrastructure. The relationship with the government appears to be fragile, however, and enthusiasm during a meeting does not necessarily imply cooperation for the implementation of the urban tactics. Instead of ensuring that sustainable mobility has a place on the agenda, long procedures with copious paperwork and persistent study apparently serve to keep it off the agenda, due to a lack of attention, political support, and a sense of urgency.

The DD-PAR fieldwork in Paramaribo North confirmed the existence of weak governance in the region. During the project, it was possible to identify key actors within public offices, involve them in our discussions, and spark their interest in urban tactics. The fieldwork period was nevertheless too short to develop a mature, robust relationship between actors in the private, societal, and public sectors or to involve the public sector in co-production. The dialogue has started, however, and fragile connections have been made, which can be built upon by future research groups.

Despite the limited success achieved with the public actors during the DD-PAR fieldwork, it was possible to stimulate the critical consciousness of several other actors. The most valuable outcomes of this research, however, are the testimonies of partners from the Nabawi School and the students of the AdeKUS concerning how their attitudes about bicycle use changed during the project:

> The researchers' actions led to tangible changes in the effective use of space at the Nabawi School. Through

the application of urban tactics, they have been able to influence the traffic behaviour of and the use of the street by the parents and students of the school, resulting in an improved pick-up and drop-off of students during peak school hours. (Marciano Dasai)

We, as Surinamese students who participated in the study, feel that the direct contact of the researchers with the Surinamese people was of added value. Thanks to this approach, the results are better suited to the context. This has an impact on the sustainability of the results and encourages the implementation of more urban tactics. (Priscilla Alendy and Wiedesh Ramcharan)

As highlighted by the theory of transition thinking (Geels, 2002), small-scale, bottom-up initiatives can ultimately become the roots of long-term system change. Building an actor-network is crucial to niche expansion to gain wider acceptance and support for new ways of thinking. Urban tactics or other small initiatives can strengthen the belief of individual actors in their ability and responsibility.

5. Conclusion

Achieving a sustainable future with significantly lower carbon emissions will not be possible without a sustainable mobility policy and a well-balanced modal split. Globally, many mobility strategies and good practices are available that could inspire urban environments to move towards an improved modal split. Most of these strategies require capable government, well-functioning public offices, and a strong civil society to advocate for better mobility policies and projects. Regretfully, not all urban environments are situated within a context of strong governance. Some are exposed to adverse governance mechanisms that make it difficult to implement such strategies successfully. In this article, we consider whether DD-PAR fuelled by urban tactics could serve as an alternative governance strategy for raising awareness and establishing actions to improve mobility in urban environments within contexts of weak governance.

When using DD-PAR, researchers work with real-life problematic situations, in which they try to identify capable actors, bring them together within a network, and establish actions driven by design. Such research generates multiple outcomes, including generating insight into specific situations, encouraging empowerment, and mobilisation, creating critical consciousness and stimulating civic action. Urban tactics can be described as specific types of action in which researchers focus on creative, low-cost interventions focusing on small-scale actions that initiate a mental transition and create positive change.

In a single case study conducted in Paramaribo North, a research team from the ISST used DD-PAR with urban tactics to improve the modal split. In a previous study on mobility at a larger scale in Paramaribo, ISTT researchers identified pedestrian and bicycle mobility as a critical problem, due to the absence of safe road infrastructure and a lack of awareness of the necessity of demanding a safe traffic environment for the various groups of road users in Paramaribo. In the same study, the researchers also identified Paramaribo North as an interesting environment where hopeful practices were emerging (e.g., recreational walking and cycling). The neighbourhood also has a substantial number of strong citizens who are not merely struggling to survive and who have the capabilities that they need to organise. A second group of researchers, therefore, returned to Paramaribo North to conduct DD-PAR with urban tactics. These researchers were able to identify capable actors and start a community dialogue. With regard to public actors, several interesting discussions occurred between the ISST team and public offices at the local and central levels, but the actual involvement of these offices (i.e., issuing permits to set up the actions) ultimately failed. Although the team was able to set up two urban tactics, only one was realised with local actors. The other action was performed solely by the research team. A fruitful collaboration with the local primary school was achieved, in which the ISTT researchers, students, teachers, and the school council were able to organise a successful walk-bike quest, followed by an intervention on the road in front of the school's entrance. The project thus generated enthusiasm, sparked reflection on current school mobility, and provided the initial stimulus for civic action aimed at improving mobility. Unfortunately, the objective to achieve actual change in the modal split in Paramaribo proved overly ambitious.

More time is needed in order to transform enthusiasm into an actual change in mobility habits. To this end, follow-up action research is necessary. Additional time will also be required in order to build a stronger relationship with the government and to involve it in urban tactics or to open a structural debate on changing mobility policy and including pedestrian and cycling facilities in the redesign of streets. To explore the opportunities identified within this project and to address the weaknesses of the DD-PAR fieldwork, further research is necessary. It is also important to explore ways of creating more continuity between the research periods of student groups. To this end, the ISTT should schedule follow-up research and improve the processes of DD-PAR.

Conflict of Interests

The authors declare no conflict of interests.

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Article

Mobility Hubs: A Way Out of Car Dependency Through a New Multifunctional Housing Development?

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Abstract
Today's urban design of new quarters in the fringes of German metropolises shows a renaissance of the garage building as a cluster for car parking. In contrast to the past, parking garages are planned as multifunctional "mobility hubs." Planners enrich them with new mobility and sharing options and incorporate sports or social infrastructure facilities on the roof and the ground floor, thus contributing to vibrant neighborhoods. In contrast to the internationally renowned example of Nordhavn (Copenhagen), we observe a decentralization in the mainstreaming of the approach: Mobility hubs are to become constitutive parts of small subcenters. In this respect, they can be seen as a common leitmotiv for urban design in Germany's metropolises. The hubs form a new model of local mobility, guaranteeing a certain flow of pedestrians and freeing the adjacent streets of car traffic. Integrated into a system of alternative modes of transportation and nearby mass transit, those infrastructural and mobility clusters might contribute to a change in mobility habits and ultimately reduce car dependence. If their underlying mobility policies can be implemented and if they are ultimately more successful than traditional parking garages or even create an incentive not to use private cars at all remains open to further investigation. For this purpose, the article will trace the emergence of mobility hubs in the discourse and practice of urban design with a particular focus on major new developments at the periphery of German cities. It analyzes urban design competitions and the formal planning and implementation following them.

Keywords
car dependency; Germany; housing; mobility hubs; parking; suburbanism

Issue
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1. Introduction

The following article analyzes the debates around and the planning of decentralized "mobility hubs" in the context of urban development on the periphery of German metropolitan areas. In this context, mobility hubs are essentially understood as a spatial link between overground parking garages, facilities for non-motorized modes of transportation, and other neighborhood-related services. Interestingly they evolve around renewed models of overground parking garages despite the negative experiences that have been made with them in recent decades (McDonald & Sanders, 2007). Mobility hubs, instead, are considered attractive options for organizing neighborhood-related traffic as they combine regulatory, design, and functional elements of development that promise to make a user-friendly and significant contribution to reducing car dependency in suburbs.

Our disciplinary perspective is urban design from a governance point of view. We do not elaborate, from a transport planning perspective, which modes under which conditions can be shared by whom (Bell, 2019; Rongen et al., 2022; see also CoMoUK, n.d.-a) or which consequences this might have for the modal mix—ideally, fewer cars than before (Czarnetzki & Siek, 2022;

Deffner et al., 2014; Frehn et al., 2019). Certainly, in Germany, especially in its metropolises, we have strong public transport in a global comparison, which serves as a prerequisite for all Germany-centered discourses from a global perspective.

Multimodality and the reorganization of local traffic are playing an increasing role in a desired comprehensive change in mobility behavior (Guth et al., 2012; Libbe et al., 2010). Practice, therefore, strives to both attract public transport to the periphery and stronger regulation of parking (Kodransky & Hermann, 2011; Rammler & Schwedes, 2018). At the neighborhood level, this entails a reorganization of parking as such.

The article is to a part based on a literature review and interviews with housing actors from Berlin, Hamburg, and Frankfurt, of which seven of 14 interviews are used as direct sources in this article (I1–I7). These seven interviews with representatives from different housing institutions from Berlin, Hamburg, and Frankfurt, involved in development projects in the outskirts of their city and/or active members of the municipal housing discourses (e.g., as honorary members of local lobby organizations) were conducted in 2019–2020, anonymized for review, and randomly numbered as I1–I7. Interviewees are predominantly representatives of housing companies from Berlin, Hamburg, and Frankfurt, but also from public offices and/or work on behalf of the public. Additional background talks regularly happened since 2019 with (anonymous) public officers from Hamburg's district Bergedorf, Berlin's Senate of Housing and Urban Development, or Frankfurt's administration on the occasion of venues of the research project "New Suburbanism" and during on-site visits. This enables us to contextualize the perspective of housing actors into the current local urban development discourses of these three German cities with emerging and planned new neighborhoods in their outskirts. We emphasize that we cover by our selection three of the five metropolitan regions with a core of more than one million inhabitants; Frankfurt is accounted as the territorial entity of its common zoning plan area with 2.4 million inhabitants of the so-called Regionalverband. We skipped Munich and Cologne. As an additional case, we chose Freiburg to avoid a "metropolitan bias" and to gain knowledge about one of the many "mid-sized" big cities of polycentric Germany with a population between approximately 250,000 and 600,000 inhabitants (in a ranking by population these would be #6 and #30 of the German cities). We chose Freiburg because of its fame in terms of progressive urban development phases (see Section 3).

The interviewees of our three cases, Hamburg, Berlin, and Frankfurt, are either involved and/or close observers of the developments in their municipality. We consciously chose the housing perspective on mobility, because, eventually, it is up to them to implement planning by building something. Our selection derives from our research project "New Suburbanism" where we predominantly explore the role of real-estate actors within the overall governance schemes of development areas in the fringes of metropolitan areas. The focus on mobility has been one of several themes of our interviews in 2019–2021; nonetheless, we received sufficient information on mobility questions from this particular perspective.

Furthermore, we conduct a brief review of planning history of the approach to parking in suburban developments since the 1950s with the aim to embed case-based knowledge on German planning practice into a global international discourse. For lack of space, this review remains sketchy and we look exemplarily only into Vauban (Freiburg), then focus on two cases of emerging housing projects in Hamburg (Oberbillwerder) and Berlin (Buckower Felder; Frankfurt's developments are delayed for political reasons and shall start around 2024–2025). There we can demonstrate a significant change of approach to parking; ultimately aiming at a way out of car dependency. We thereby discuss mobility hubs not only functionally, but also as buildings with an infrastructural prominence.

2. The Organization of Stationary Traffic: A Retrospective View

The triumph of the automobile was a major driver of suburbanization in the 20th century (Buchanan, 1963; Fishman, 2008; Jackson, 1987; Kopecky & Suen, 2010; Newman & Kenworthy, 1999; Ward, 2002). In particular, mass motorization after the Second World War led to the ideals of urban modernism, not only becoming the program of suburban development to an extent not seen before. Rather, with parking spaces above and below ground, it inevitably changed not only everyday traffic but also the character and amenities of public and private open spaces. We will not retrace the well-known history of the enforcement of car dominance here. However, for the question of why today there is (again) an increased focus on a concentrated accommodation of passenger cars in overground parking garages, we will briefly discuss the decline of this model in the context of an increasingly critical assessment of urban modernism.

Whereas in more owner-occupied single-family and terraced house areas, the allocation of parking to private property can be realized in many places to this day without major questioning and is an everyday practice, in connection with considerations of cost- and space-saving construction and a reduction in individual traffic from the 1970s and especially the 1980s onwards, in many cases smaller parking lot systems and garage yards were initially conceived. These are intensively used because of their individual allocation of parking spaces to the user's unit and are indispensable for keeping private properties and residential paths free of parking traffic—often the goal of the respective urban development concept (Kirschner & Lanzendorf, 2020; Selzer, 2021; Selzer &

Lanzendorf, 2019). A stronger concentration of parking spaces in garages is not very well accepted due to their poor design (e.g., poor lighting and safety aspects).

Modern large housing estates in both parts of Germany from the 1960–1980s had in common that parking facilities—following modern models—were geared towards a functional separation between car traffic and other uses and between car traffic and pedestrian traffic. The usage intensity of public space was, therefore, less dependent on how they are spatially designed, but rather on purpose, they assumed for individual and social life and how intensively people spent time there accordingly. In particular, the enclosed parking garages offered few qualities in this regard (for the international debate, see McDonald & Sanders, 2007). In contrast, the garage yards in large East German housing estates, for example, represented an important place for private craft activities despite their limited space.

Criticism of urban-architectural modernism went along with a reduced number of social housing and the waning of the image of large housing estates. The urban planning debate of the late 20th century focused more on the use of already built-up areas as part of an increasing re-urbanization trend (Brake & Herfert, 2012). In this context, it was largely determined by three practical trends: the emergence of cautious urban renewal starting in the late 1970s, the retrofitting of large housing estates since the 1980s (West) and 1990s (East), and the restructuring of numerous conversion areas starting in the 1990s (Federal Institute on Building, Urban Affairs, and Spatial Development, 2021; Nelle, 2018). In many cases, neighborhood-wide traffic calming and attempts to make public and private open spaces more attractive and more amenable to an appropriation by citizens played a particular role. To the extent that new settlements originated in the suburbs, these in turn tended to be smaller than the previous ones. Overall, this created opportunities for reorganizing both moving and stationary traffic in residential neighborhoods, with a focus on inner-city spaces. One motivation for this was urban ecology concerns in planning, so the first car-free housing developments were also planned and implemented at the time.

Overall, a policy shift eventually occurred in major German cities to restrict private motorized transport by reducing the total number of available parking spaces on a project-by-project basis (Kodransky & Hermann, 2011). In the areas of cautious urban renewal, their high building density made a reorganization of stationary traffic advisable due to the very limited space of the street-grid dating back to the 19th century. Thus, there were better opportunities for completely new traffic concepts on inner-city conversion sites (Frehn et al., 2019). Innovative new quarters, especially in Southern Germany redefined the model of the European city in the spirit of re-urbanization. They attempted to realize a "city of short distances" (Feldtkeller, 2001; Gertz, 1998), which also included a series of traffic-calming measures within the project development. With a consistent separation of private and public open space and the dedication of private open space as quiet, unsealed retreat and recreation space, coupled with a high building density and the desire to keep the local streets free from stationary traffic, the question of accommodating cars inevitably arose. The perimeter block concepts inspired by the street grids and block structures of the b 19th-century city required structural integration and compact arrangement, which for cost reasons mostly resulted in overground garages. Hence, freestanding parking garages, as they were built in the large housing estates of the modern era, hardly ever appeared, not least because of their design problems.

3. Current Approaches and the Renaissance of the Neighborhood Garage

Since the turn of the millennium, planners and project developers in inner cities have in some cases gone even further in their parking space solutions. Even commercial project developers have revised their parking space ratios downward in corresponding re-densification projects. Decades ago, they assumed that a high-end condominium, for example, is "naturally" accompanied by the ownership of two cars, which needs space in an underground garage. However, today there are parking space ratios in projects in the inner city of 0.3 to 0.6 cars per residential unit (I1, I2, I7). On the denser outskirts of the city, 0.6 applies. Inner-city milieus are now also mobile in other ways than by car—They apparently make up the clientele of public transport as well as car-, bike-, and other ride-sharing services (including conventional cabs). It even no longer seems outlandish to offer the inner-city residential property without any parking space of one's own (I7).

Based on these experiences, it no longer seems very surprising that people would like to eliminate parking traffic from public spaces not only in inner cities but also on the outskirts, although the level of motorization is still much higher there (Huber-Erler, 2010). In addition, there are crucial real estate economic conditions. Underground parking is still the ordinary case (I1), but no longer a matter of course in times of careful evaluation of construction costs (I2, I3, I6). Thus, there are different reasons to organize parking in the neighborhood differently. Overground garages still seem to offer a perspective for this, especially against the background of recent experiences in neighborhoods on conversion sites.

At the same time, the approach to cluster parking in buildings promotes both the electrification of cars and the changed usage patterns (Vrhovac et al., 2021, p. 26). A garage building facilitates the necessary energy supply for charging as a collective infrastructure. Furthermore, at a location like this, it is more easily possible to provide sharing vehicles—cars and beyond (I2, I3, I4; skeptical: I6)—another incentive for the use of alternatives to the private car. Vehicles are then not only cars but possibly also (electrified) bicycles, cargo bikes, vans, scooters, etc. The yet unresolved question is how the operator models of the sharing providers and the calculation models of the real estate players should mesh (I5, I6; Coenegrachts et al., 2021). To get away from car dependency, another prerequisite is to link housing and mobility immanently on an institutional level.

Of the aforementioned precursors in conversion projects, Vauban (Freiburg), built as a partially car-free neighborhood in the 1990s, 2000s, appears particularly instructive (Broaddus, 2010; Gies et al., 2021; Growe & Freytag, 2019; Mahzouni, 2018; Späth & Ornetzeder, 2017). The central Vauban Avenue, half of which is designed as a pedestrian zone, and the adjacent residential streets are completely traffic-calmed. Two neighborhood garages (reserved for residents) are located at entry points to the neighborhood, and the third (public) neighborhood garage is located at one end of Vauban-Allee (Figure 1). For the majority of residents, pedestrian flows are either oriented from the residential building to the garage and the car or Vauban Avenue with public transport and local amenities. There were no considerations yet to spatially integrate parking into everyday situations, on the contrary: It should be inconspicuously pushed to the edge of the neighborhood. Parking should disappear from the central public spaces. From this point of view, Vauban has become a model for current urban development projects. Thus, what began 20 years ago as an ecological niche, is now becoming the standard in numerous large cities. Freiburg itself is particularly revealing in this regard: Where Vauban still managed with three neighborhood garages, contemporary Dietenbach has 12 neighborhood garages planned (mostly along a development ring). Compared to the older and smaller neighborhood of Vauban, the everyday mobility on foot raises to a higher level. This results in similar path lengths to the nearest neighborhood garage as in Vauban, but also smaller proximities to local supply facilities and streetcar stops.

Copenhagen serves as a different role model (Freudendal-Pedersen et al., 2020; Herrmann et al., 2021). The approach thereof combining a garage with playgrounds—and this with a rather extroverted architecture—attracted attention, even if the object is a unique piece and as such not easily scalable for housing development. The building itself, called Park'n'Play, is an ordinary parking garage in terms of its structural design but has a public play and sports area on the roof, which is accessible via a curtained staircase structure. In addition, an outstanding façade design ties in with the historic use of the harbor. Nevertheless, in Germany's new development areas, high-quality green spaces with sports and play facilities are provided anyway, so there is no need to resort to garage roofs for this purpose as in the cramped situation of the inner city. The inspiring moment of the design rather results, on the one hand, from its multifunctional usability and, on the other hand, from the horizontal linking with curtain wall uses, which

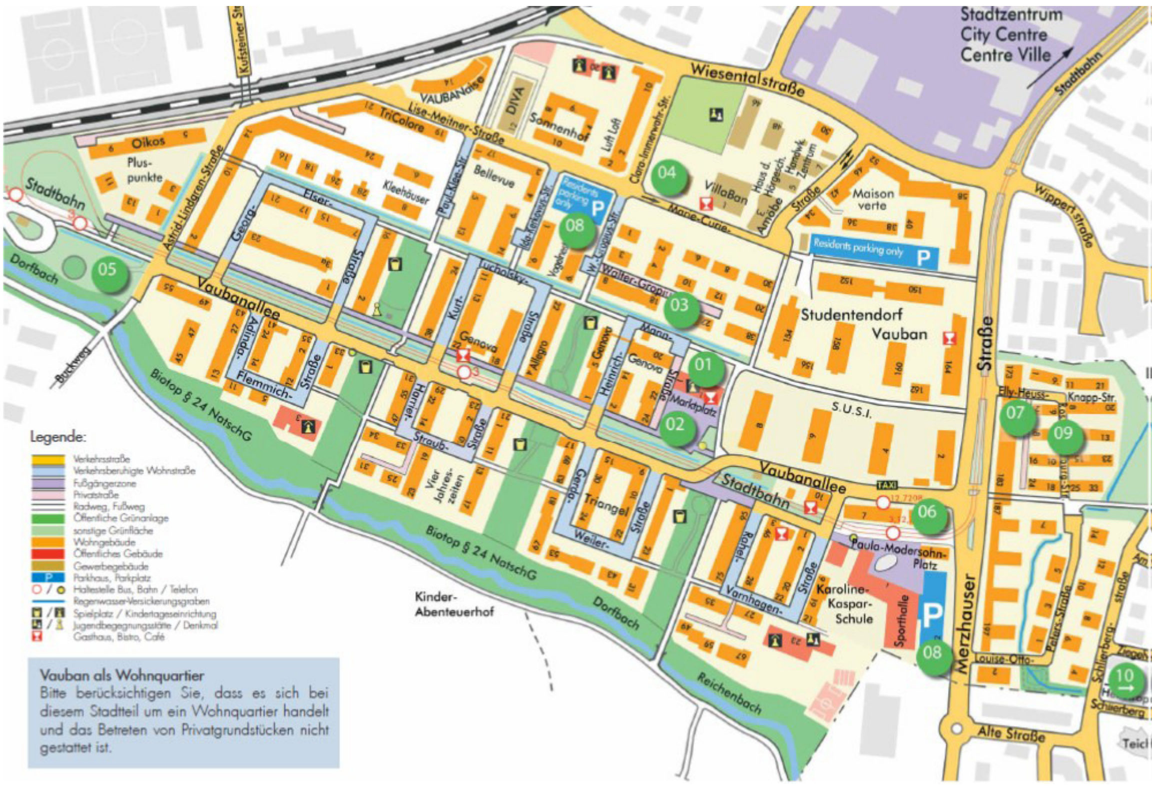

Figure 1. Vauban overview map. Source: Orientation map provided by the Freiburg Wirtschaft Touristik & Messe GmbH, situated in Freiburg, photographed by the author.

are accessible by an exterior staircase and show completely new possibilities for the integration of a parking garage into the urban environment in terms of design.

If the aim is not only to create parking more cost-effectively, however, a garage building must go beyond parking. In recent years, the term "mobility hub" has been increasingly used for this purpose, also in Germany (for further considerations and precursors, see Miramontes Villareal, 2018; see also Czarnetzki & Siek, 2022; Federal Institute on Building, Urban Affairs, and Spatial Development, 2015; Jansen et al., 2015; Miramontes Villareal et al., 2017; Suthold et al., 2015; for the unfolding international debate on the same term, especially in the US and the Netherlands, see Arseneault, 2022; Bell, 2019; Rongen et al., 2022).

Initially, the idea of a mobility hub continued to be primarily a parking space, which thus unreservedly follows the logic that the car is of relevant importance for the development of a neighborhood and must accordingly be stored, potentially in a garage to save space. Conventional car dependency is therefore not fundamentally restricted as such. However, it is made more "inconvenient" by not offering parking spaces everywhere.

Nevertheless, mobility hubs are often understood as means to promote alternative modes of transportation: "Mobility hubs bring together shared transport with public transport and active travel in spaces designed to improve the public realm for all" (CoMoUK, n.d.-a).

Those can go hand in hand with restrictions for parking individual cars. The idea is to concentrate on parking facilities within walking distance of apartments. This is legally accompanied by the renunciation of almost all on-street parking. This is enforceable, but always means a conflict for the housing company during the planning process (I3, I5). In this context, mobility hubs are complex facilities that combine regular parking garages with the promotion of alternative modes mentioned above by attaching sharing and other facilities to the garages:

> When reimagined as mobility hubs, car parks are no longer just places to store vehicles. Instead, they become positive places that offer co-located services such as electric vehicle…charging and shared mobility services. Mobility hubs also represent the next step in the evolution of park & ride services, which will become genuine interchanges where people can switch from private cars to buses, trains, cycles and walking. (Landor LINKS, 2023)

Interestingly, the planning of greenfield sites in Germany goes beyond this understanding. They promote an ever more complex idea of a mobility hub that aims at bringing transport functions together with central functions of a neighborhood and social amenities. Thereby, they try to make their alternative transport facilities more feasible, as a greater part of the local residents has strong incentives to use the hub for other purposes, too. Besides, they make use of the opportunity to encase the parking garage part of the hub with other, more pleasing amenities and uses in terms of urban design. In the following, we discuss those ideas in more detail.

4. Case Studies: Hamburg and Berlin

In the following, current planning cases from Hamburg and Berlin illustrate how planners incorporate mobility hubs into urban design. Hamburg, Berlin, and Frankfurt belong to the group of largest cities in Germany with high pressure on housing; thus, they do not only follow infill strategies, but erect new neighborhoods in their fringes (Altrock & Krüger, 2019). Our research focus is on those cities that do both. Therefore, our interviewees present real estate stakeholders from Berlin, Hamburg, and Frankfurt. Our general interest in talking with them is the proposed urban design of the newly planned areas, especially questions of density and mixture. Our interest in the real estate stakeholders' point of view derives from their upcoming role to implement the plans the municipalities make.

This interest results in certain aspects of urban design promoting a dense and mixed neighborhood, of which the aspects of active ground floor zones along streets and squares and a pedestrian-oriented public space are suitable to be discussed with a mobility focus in urban design discourses. We will pick up these aspects in Section 5 (together with the obvious question of how a building looks like). They have a considerable impact on the overall urban design of the respective neighborhoods and mark a significant step further in the concept of mobility hubs, as they are no longer just seen as complex and sophisticated infrastructural elements improving the transport system but are also seen as an integral part of attempts to increase vibrancy in peripheral neighborhoods.

Before, we go into the neighborhoods themselves. As Frankfurt's plans have not been specified yet enough to discuss them with interviewees in 2019–2020, we chose to focus on Hamburg and Berlin. Oberbillwerder, the largest new development currently planned in Hamburg with several thousand residential units, is to consist of five differently profiled quarters as well with high-density multistorey housing near the station and with terraced and single-family houses in the peripheries of Oberbillwerder (International Building Exhibition Hamburg, 2019). In all quarters, there will be one to three elevated garages (11 in total), each of which will be located at a small neighborhood square (see Figure 2). A street axis with a sequence of three squares from the metropolitan train station northwards forms the backbone of the future settlement.

The initial situation in Buckower Felder, a new development on the southern outskirts of Berlin, is quite different (see Figure 3). Situated in the far south, just at the municipal limit, and far away from any rail-transit connection, the area is located in a relatively dense, but in terms

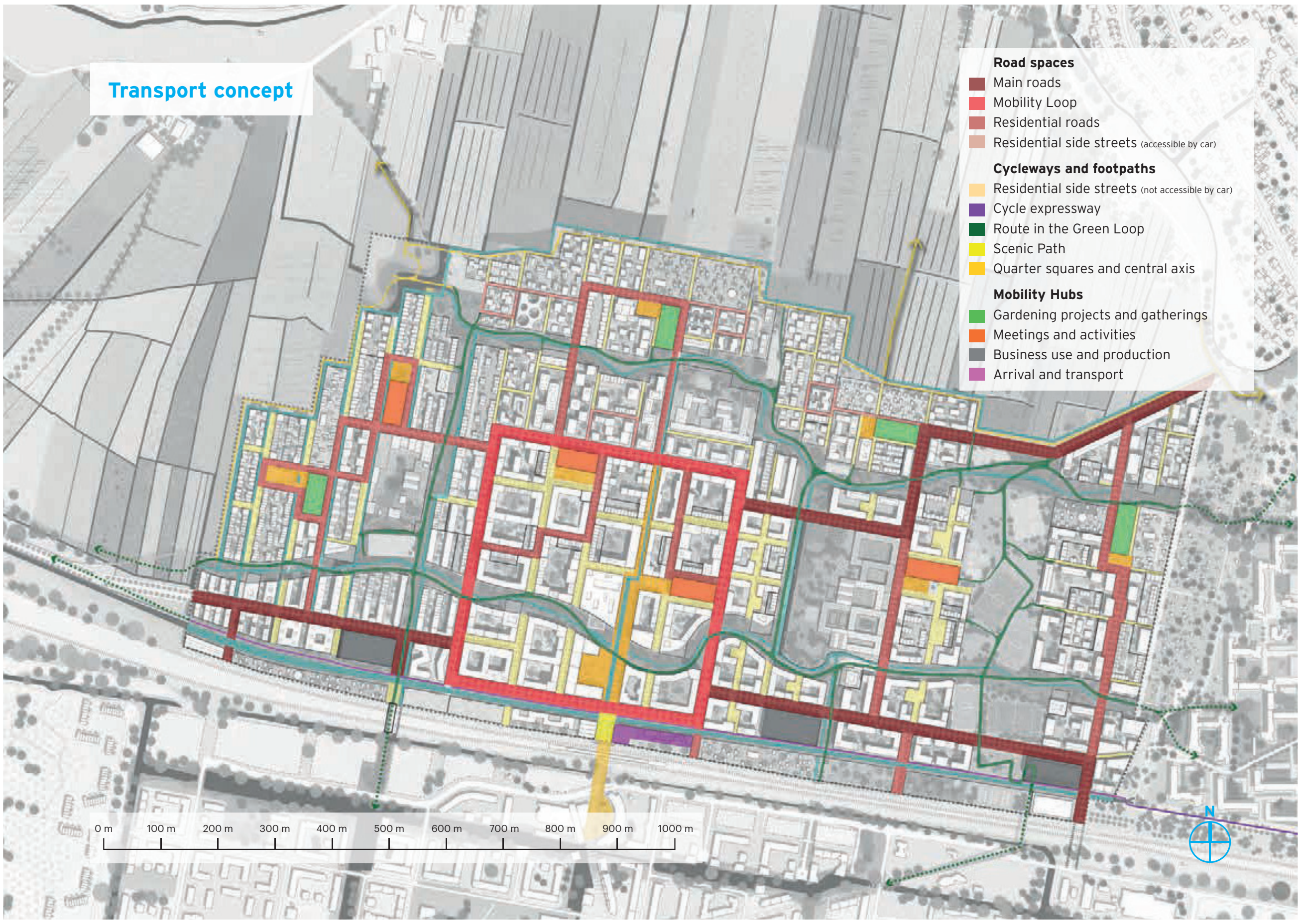

Figure 2. Transport concept for Oberbillwerder. Source: IBA Hamburg GmbH (2019, p. 61).

of urban design hardly structured heterogeneous suburban location between single-family houses and commercial and multi-story residential buildings from the 20th century (this results in the limited options of a walled West Berlin). Under the direction of the public company Stadt und Land, approximately 900 residential units emerge in dispersed apartment blocks in mostly four to five-storey buildings with a high proportion of affordable housing. Two garage buildings replenish them (I3).

One of the two garage buildings will also accommodate various shared mobility services as part of its multifunctionality. In addition, a kindergarten and youth club will be located next door, as well as the (already-built) school (diagonally across the street), and the first-floor zone of the garage itself will offer social infrastructure (counseling and meeting places). The upper floors of the other two buildings will be residential (I3). The three buildings enclose a square, which will form a hub for everyday mobility through their bundling of functions. Ideally, one can imagine a parent walking with his or her child from the apartment to the square in front of the kindergarten and "dropping off" the child not from the car, but on foot—as well as picking up a vehicle to commute to work afterwards. Although the different uses (daycare center, garage, residential) are combined in a building ensemble and not in an individual building, this still results in a small-scale functional bundling around the garage. The integration of a square situation in the center of the U-shaped building ensemble is also already an important further development compared to the role models presented above: the combination of open space and building. While the neighborhood is predominantly an experimental site for contemporary serial and affordable housing, it is likely to be as well an experimental model case in terms of a parking concept less car-dependent than before.

While the allocation of the garages became the starting point for considerations of decentralized neighborhood squares, similar to Buckower Felder, the complexity of the overall neighborhood in Oberbillwerder is much greater (International Building Exhibition Hamburg, 2019). Using Vauban as a model, garage buildings align with existing or planned main access roads according to previous designs (this also applies to Buckower Felder). In simple terms, the garages arrange along smaller access roads in such a way that this circumstance results in a kind of "automobile entrance situation" to the residential quarters, which minimizes car traffic in the latter and replaces it with footpaths between the home and the car.

However, the design approach in Oberbillwerder goes much further. A green loop as a central, ring-shaped

Figure 3. Buckower Felder. Courtesy of Stadt & Land Wohnbauten Gesellschaft mbH.

open space links the individual neighborhoods. A largely orthogonal system of streets and paths makes use of a few conventional streets with separate footpaths, along which most of the neighborhood garages are built. They arise at traffic-calmed neighborhood squares, whereby one building front of the neighborhood garage will always face the street (for the car access) and another the square. With the establishment of an "active" first-floor zone in the garage building facing the square and—in the majority of cases—in the other buildings adjacent to the square, a plaza situation is accomplished. Again, different everyday uses are bundled. Now and then, school and daycare buildings also adjoin these squares; school properties in particular then mediate spatially between the neighborhood square and the green loop (International Building Exhibition Hamburg, 2019). A possible typology of urban infrastructure emerges that can be arranged around such a square.

As already described in the case of Buckower Felder, it is the attempt to bundle spatially mobile footpaths in such a way that a corresponding liveliness of the public space is created at the node of bundling, without the covered distances in the neighborhood being perceived as a burden. The path combinations should be suitable for everyday use and possibly even facilitate everyday life. The approach, therefore, bases on the sectoral problem of accommodating stationary traffic, hence goes beyond the mere infrastructure sector of traffic, because it rather integrates overarching socio-infrastructural planning. Doing so, it uses infrastructural planning to integrate its needs into the urban figure of the neighborhood square, which in turn should shape the character of the settlement. The squares serve as a serial element. Admittedly, this approach only works if the sectoral problem of accommodating stationary traffic actually succeeds in this way, as outlined in the master plan (I6).

5. Design and Planning Elements of a Mobility Hub

Abstracting from the cases just mentioned, we will analyze relevant design and planning aspects to evaluate whether the mobility hubs acquire such a model quality and if they are more than just a new edition of the customary garage. For this purpose, we also include current debates taking place in the German planning context (Bergedorf District Office of the Free and Hanseatic City of Hamburg, 2021; International Building Exhibition Hamburg, 2021; Rehme et al., 2018; Senate Department for Urban Development and Housing Berlin, 2018b), not only from documents and publications but from insight views from interviews and background talk with the very actors. A changed approach is thus not only a means to get away from car dependency, but also a transformation of public space and functional mixed-use in suburbia (see Figure 4). The leitmotiv to allocate and equip these garage buildings also means that the spatial (re)configuration should have positive effects on public life at the neighborhood level. This links to the leitmotiv of transit-oriented development (Loukaitou-Sideris et al., 2017). We will discuss four aspects that have both a functional and a design dimension.

5.1. Active Ground Floor: Commercial

The novelty of the planned mobility hubs is the divergent use of its ground floor. As hubs, they represent traffic nodes of local pedestrian traffic (Deffner et al., 2014). This is because when everyone walks to their vehicle to the same location in the neighborhood, numerous pedestrian traffic flows intersect here. This should not be underestimated for turning around traffic on the urban fringe and creating revitalized places in the neighborhood: In many, especially suburban new development areas of whatever urban type, people have so far used their own vehicles (cars, bicycles) to travel directly from the property (above ground or coming from underground parking) to schools, supermarkets, leisure venues, etc. Besides sporadic walkers, only those who walk to the public transport system pass through the suburban neighborhood. It is, therefore, no wonder that pedestrians are rare in the suburban neighborhood.

The achievement is to make the pedestrian traffic numerous enough for a little centrality—i.e., to enable the proverbial corner shop. It is thus sensible to allocate the mobility hubs not only according to in- and outgoing traffic (as back in Vauban's 1990s) but simultaneously at neighborhood squares (as in Oberbillwerder and Buckower Felder). The planning aim as such is questioned by no one we interviewed or talked to, neither is it in the conclusions of the documents (e.g., Bergedorf District Office of the Free and Hanseatic City of Hamburg, 2021; Senate Department for Urban Development and Housing Berlin, 2018b). However, the path to that aim remains fuzzy, with one exception: There have to be

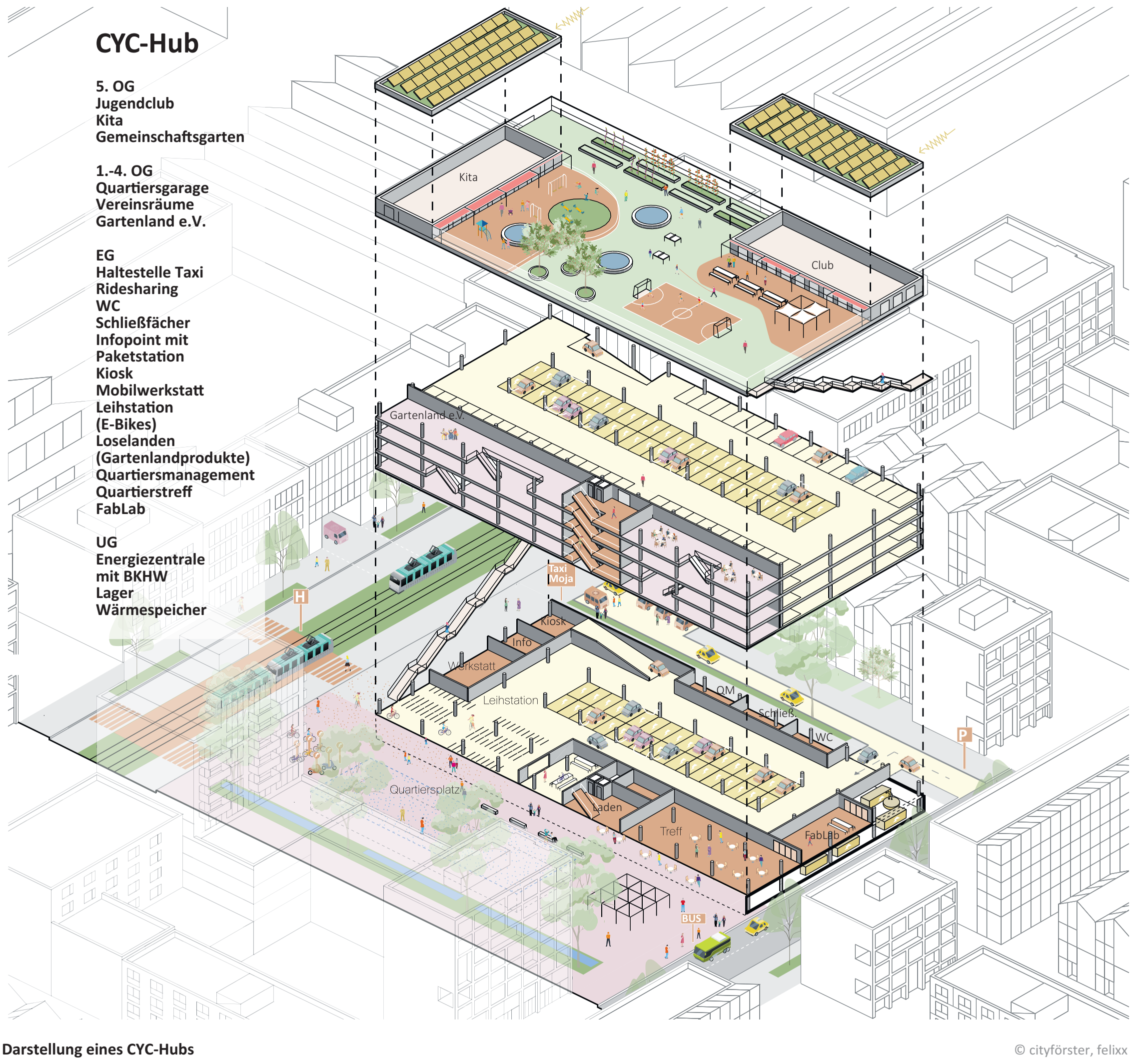

Figure 4. So-called "CYC study" on garage levels, commissioned by Senate of Berlin. "CYC" plays with the word "recycling" and denotes a concept that integrates a decentral CHP station, a multimodal mobility hub and a community center. Source: Senate Department for Urban Development and Housing Berlin (2020, p. 20).

people walking around and they have to be walking around for a reason. The different spatial patterns of parking and centrality locations need thinking together: Everyday walks for everyday errands inside the quarter and to get a vehicle away (and back) cross at the mobility hub square. Additionally, we can assume an emergence of specific offers in the context of new mobility such as, for example, bicycle repair workshops, service offices of sharing providers, back-office units for maintenance, or automatized delivery stations (I2, I3, I6). Interestingly, housing actors assume, they need mixed calculations to enable certain centrality offers to enable enough "pedestrian traffic" to contribute to the overarching aims of the development—which they shall, as the distribution of property by the public will take that into consideration. That is one particular reason the view of housing actors is crucial for the development of these areas.

In particular, potentials are conceivable for uses facing away from the street in ground floor zones. Courageous project developers are already thinking about offering co-working spaces, space for start-ups or something similar between these units. These are activities not necessarily dependent on the interactivity of the ground floor. However, their sheer presence—even behind windows—already contributes to a (re)vitalization of public space on these squares (I3). Ideally, all buildings on the square have corresponding ground floor zones—it is therefore of secondary importance what emerges in the garage building and what does in the building as long as the ground floor use faces the square.

5.2. Active Ground Floor Zone: Social Infrastructure

More likely is an economically stable lease to providers of social infrastructure. In the history of cautious urban renewal, we can trace back to storefronts increasingly used for social infrastructure since the 1970s and 1980s, especially due to the institutional condition with independent welfare providers (Krüger, 2022, p. 53). In this context, mobility hubs de facto represent social infrastructure buildings, because they not only serve the provision of general interest as a host of welfare. They also act "as social infrastructures when they have an established physical space where people can assemble" (Latham & Layton, 2019, p. 3). The combination of classic social infrastructure and public infrastructure for mobility can create an urban interaction.

However, the installation of social infrastructure within the garage building does not remain without consequences for the social infrastructure facilities that the public usually allocates as single-building structures, be it schools, kindergartens, or sociocultural centers (Grunze, 2017). It is expectable that smaller "welfare stores" like counseling or meeting places can be located in the ground floor structures of these mobility hub squares, too. However, if not there, we experience these kinds of facilities as "extra" uses on school campuses (Krüger, 2022). There was a particular task force inside Hamburg's public realm—bringing local and state staff together—to formulate requirements for allocation schemes in Oberbillwerder (Bergedorf District Office of the Free and Hanseatic City of Hamburg, 2021) with links between research (e.g., Altrock & Krüger, 2019; Grunze, 2017) and practice. In addition, more and more housing companies establish their own community spaces. Again, housing actors go beyond their provisional task to build apartments. A certain governance of allocation is necessary though, and we observe exactly this in both cases. The public domain and housing companies cooperate to devise allocation schemes for social infrastructure.

5.3. Pedestrian Node and Public Space

The garage building itself and the associated square situation are to be thought of together as lots for urban infrastructure to jointly achieve a little centrality in the suburban neighborhood—and thus to avoid motorized means of transit to a certain extent. To qualify the mobility hub and square as an infrastructural node within and beyond mobility is a challenge at first, but also offers new options for neighborhood life. Since the square becomes a crossing point for pedestrian traffic because of the mobility offers clustered, it transforms functionally into something like a station. Moreover, if it is comparable, the transit-oriented approach may operate—linking this planning approach to the efforts to reduce car dependency. In view of the pedestrian frequency ensured by the function of the hub, the question arises as to which offers in which design invite users of the neighborhood garage to stay in the square. Thus, it is of high relevance how many square meters of ground floor real estate and public space are projected. It is already noticeable in both cases that, compared to the squares built in the 1990s—back then often dimensioned along the dimensions of "classic" Central European squares—they will be much smaller. In the suburbs, their diversity of use remains smaller, too. This comes especially by request of the housing players (I2, I6) involved. Designing the little neighborhood squares remains a task for planners and architects, noteworthy is the governance to estimate its sizes. Both cases show a crucial involvement of possible or actual housing developers. In Buckower Felder, it was clear from the beginning, that a public housing company will develop the neighborhood; in Oberbillwerder, the developer is a public company allocating property to estate developers at a later point in time (International Building Exhibition Hamburg, 2021). The housing developers we interviewed are not only company operatives but as well "characters" in the political sphere of Hamburg or Berlin. They are not only investors, hence, part of a civic realm (e.g., International Building Exhibition Hamburg, 2021). Their interest in smaller squares might derive from the business calculation. Collaterally, the smaller squares may facilitate the appropriation by citizens (Tessin, 2011) more properly (see Figure 5). As scientific observers, we watch

Figure 5. Neighborhood square with mobility hub: Visualization for Oberbillwerder. Source: Adept & Karres en Brands & IBA Hamburg GmbH (2019).

a concordance of interests between design and mobility demands.

5.4. Cubature and Façade

Finally, in view of the negative experiences with the design of traditional parking garages, the attractiveness of mobility hubs raises the question of the architecture of a garage building. The Copenhagen example is a showcase example of the architectural integration of a parking garage into an urban settlement context. However, we safely assume that a scalable approach on garages with all the complexity of governance in terms of socio-infrastructural use and building calculation the garages in Oberbillwerder, Buckower Felder, and similar places elsewhere tend to have a simple cuboid cubature and a plain façade (see Figure 6). This is because such an object cannot be financed easily, let alone with elaborate architecture (I1, I3). In the two case studies, public real estate actors are the motors of development and expectations regarding affordable housing are as well burdened on them. If the garages are cross-financed with residential uses in an overall settlement planning, their costs as well as other cost-relevant features (energy concept, parceling, economies of scale in construction, etc.) are included in an overall calculation and surely have an impact on rents or purchase prices. However, if housing policy caps rents to achieve more affordable and social housing, these costly features will have to be borne by a however defined general public. It could be the municipality, national funding, public real estate actors, or a mix of means, which we are not able to elaborate on in this context (yet). Anyway, there will be cost pressure on the structural substance of a garage in order to keep costs that cannot be refinanced by (affordable) rents within limits (I3, I4, I5, I6).

At first glance, this counteracts severely with outlandish design schemes, the Copenhagen example, but also

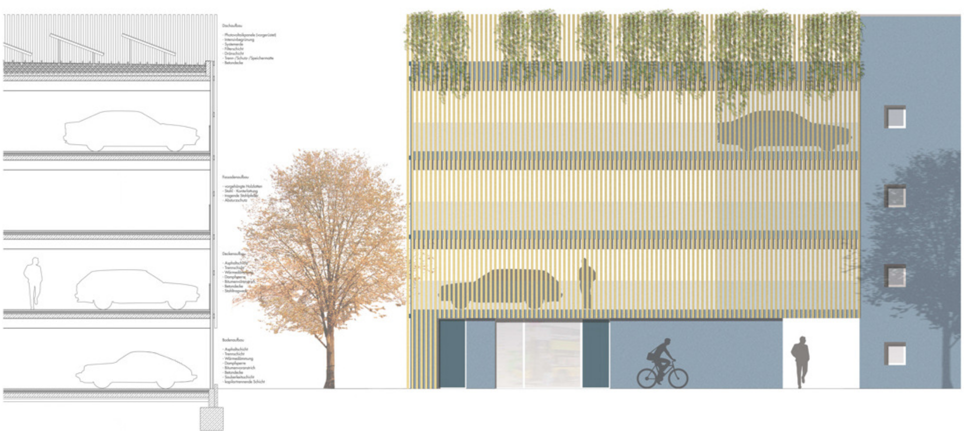

Figure 6. Garage building visualization for Buckower Felder in Berlin. Source: Stadt & Land (2018).

what visualizations inside the community (e.g., Senate Department for Urban Development and Housing Berlin, 2018b) stand for (see Figure 4). It remains to be seen what the 11 buildings in Oberbillwerder will look like, as the examples of Buckower Felder are presumably not for use in architectural publications. Hence, in contrast to Copenhagen, we do not need architectural highlights but scalable standards for a comprehensive transformation of mobility habits. Another challenge is the lighting and ventilation of the parking floors. If the façade is open, the parking decks are also visible from the outside, which reduces the attractiveness of the building in the urban environment. If other uses such as offices or storage spaces of commercial tenants "hide" the cars, the appearance inside the parking decks does not differ from an unattractive underground parking garage. As a result, the mobility hub is likely to face a difficult tension between cost pressures and design aspirations.

6. Conclusions

Mobility hubs are currently the talk of the town planning debate. As hardly ever before, they aim at combining three key challenges of "post-modern" urban development: (a) the creation of a system of public places in the urban neighborhood that are as vibrant as possible (Gertz, 1998); (b) the preference for non-motorized mobility and, in particular, the reduction of car dominance in the immediate residential environment (Growe & Freytag, 2019); and, finally, (c) the promotion of a mix of uses that goes beyond the coexistence of housing and residential follow-up facilities (Altrock & Krüger, 2019; Brake & Herfert, 2012; Federal Institute on Building, Urban Affairs, and Spatial Development, 2021). As such, this signals a new stage in the discussion of guiding principles in housing development, which clearly stands out from the earlier attempts to overcome urban architectural modernism in the 1990s (Senate Department for Urban Development and Housing Berlin, 2018a), which were often critically evaluated.

In addition to research projects and experimental preliminary considerations, which are being tested selectively as part of complex public transport transfer hubs and smart city initiatives, however, a noticeable qualitative leap is currently emerging. In the course of an alternative conception of systems for stationary traffic in new developments on the outskirts of cities, increasing efforts are being made to promote non-motorized traffic. They claim to take greater account of sustainability aspects. In return, car traffic is to be gradually pushed back in order to reduce the dependence of suburban living on the private automobile. To this end, the planners envisage a variety of measures in complex integrated urban district development concepts. Due to the ambivalent experiences with car-free neighborhoods and the difficulties of achieving significant reductions in car dependency by means of a significant improvement in public transport connections, the latter starts with a spatial and organizational reorganization of stationary traffic and its surroundings.

For the currently planned mobility hubs, this means concentrating parking in neighborhood garages and thus freeing public space from car dominance. Beyond attempting to thereby make settlements highly land-efficient while improving the quality of use and suitability of an appropriation of plazas, streets, and pathways in newly developed neighborhoods, the moderate concentration of parking aims to reduce the attractiveness of car use. It attempts at creating places where more sustainable transportation alternatives become available. Placement at neighborhood squares also aims to create synergies between alternative modes of transportation and community uses in the neighborhood. It is assumed that a comparatively high pedestrian frequency is secured at these squares, which makes stores and gastronomic and socio-cultural infrastructures viable to some extent. More ambitious attempts envisage these uses in a building with neighborhood garages so that their urban and architectural integration can succeed better than that of traditional elevated garages in large housing estates of the 20th century.

The cases from Hamburg and Berlin demonstrate that the significant costs created by an overground parking garage will have to be borne directly or indirectly by the residents. To make them feasible, management by housing companies or entities related to them seems appropriate but obviously requires severe restrictions on street parking from the outset. Although the related urban designs can make use of the reduced amount of parking space for other kinds of public space, the restrictions on car use and related reductions of attractiveness for car-owning households seem to limit the use to cities in which the housing shortages make people accept those. Nevertheless, the urban designs for both the small centers around the parking garages and the related public spaces at least in the Hamburg case show that the coordinated planning of housing areas, public spaces, the green loop, and the pedestrian and cycling infrastructures may allow for substantial change in the mobility patterns of the new neighborhood to take place. In the case of Berlin, the urban design solution and our interviews already show that the limited size of the new settlement seriously restricts the possibilities for the creation of vibrant sub-centers with a high concentration of additional facilities. Thus, we can conclude that the attractiveness of the approach towards reducing car dependency, building on a complex cluster of services attached to a parking garage and surrounded by dramatically car-reduced and strictly regulated public spaces, may only unfold its potential if integrated beforehand into a far-reaching and consequently implemented urban design strategy as in the case of Oberbillwerder in Hamburg.

So far, the planning and implementation of mobility hubs are still at an early stage, so it remains to be seen whether the ambitious goals associated with them can be achieved. In addition to acceptance by users and the attractiveness of the neighborhood locations to be created, unanswered questions also arise as to whether the mobility hubs and the uses attached to them can be operated economically. Nevertheless, a wide variety of design and functional solutions are being developed by architects, urban planners, and traffic planners in a whole series of urban planning competitions and design procedures. So far, there seems to be the will on the part of the planning authorities to implement these solutions consistently, especially in the important urban development measures of large cities. In view of the enormous difficulties in freeing peripheral residential neighborhoods from their dependence on cars, this approach seems appropriate and promising in this respect, even if it is still unclear how great their contribution to a sustainable change in traffic behavior on the urban periphery will really be.

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Conflict of Interests

The authors declare no conflict of interests.

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Review

Drivers' Perspectives of Car Dependence

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Abstract
The concept of car dependence includes both travel to destinations for which other modes than the car are not practical and preference for car travel even when other modes are available. While the concept has been a focus for transport analysts for some time, car ownership and use have continued to grow. This reflects the utility of the car for travel on roads where drivers do not experience excessive congestion and where there is parking at both ends of the journey. Local public transport and active travel only become generally attractive alternatives to the car in dense city centres where road space for car use is limited. Reduced car dependence is facilitated by city planning that encourages increased density, opportunities for which are constrained by the stability of the built environment. As well as utility for travel to achieve access to desired destinations, car ownership is also attractive on account of positive feelings, including pride, reflecting both self-esteem and social status. The positive feelings of the population at large towards car ownership are not consistent with the critical view of many analysts, a divergence in point of view that contrasts with the general acceptance of the need to respond to climate change, for which the purchase of electric vehicles is seen as an appropriate action. Rather than advocating measures explicitly aimed at reducing car dependence, a more effective policy approach would be to increase the availability of alternative modes while mitigating the detriments of car use.

Keywords
car dependence; car ownership; car pride; car utility

Issue
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1. Introduction

The concept of car dependence was first articulated in an editorial by Goodwin (1995), which arose from a substantial study (Goodwin et al., 1995). This was prompted by the observation that many people have built their way of life around their cars and depend on them for many regular and occasional journeys, despite the wide range of societal problems arising from growing car use. Goodwin noted the distinction between car-dependent people and car-dependent trips, suggesting that focus on the latter would be more likely to lead to changes in behaviour. Goodwin also recognised that car dependence is a process, not a state, such that those acquiring cars tend to rely on them more over time and pay less attention to alternatives.

The concept of car dependence has stimulated much academic research, notably the following contributions. Stradling (2007) extended Goodwin's typology, distinguishing between car dependent places, car dependent trips and car dependent persons. Mattioli et al. (2016) proposed an alternative three-fold distinction of car dependence as a function of scale—as an attribute of individuals, of societies, and of trips—employing time use data to identify trips involving carrying shopping, heavy goods and children as a contributing factor to car dependence. Lucas and Jones (2009), in a comprehensive study of the car in British society, reviewed the uses in the literature of terms associated with the concept of car dependence, identifying a spectrum of behaviours from reliance to pathological dependency or addiction. These authors recognised that purchase of a car made possible faster travel with greater access to, and more choice of, destinations, allowing more complex lifestyles. von Behren et al. (2018) developed a survey methodology encompassing both subjective and objective measures of car dependence that allowed the identification of differences between cities, as well as within the populations of individual cities.

Newman and Kenworthy (2015) analysed mobility in a large number of cities in both developed and developing economies, concluding that automobile dependence varied in a clear and systematic way with land use patterns, dependence increasing as population density decreased. Cullinane and Cullinane (2003) surveyed car owners in Hong Kong, a very high-density city where public transport is dominant and car ownership is very low, finding that once people acquire a car, they perceive it to be a necessary part of their lifestyle. Buehler et al. (2017) examined five major European cities where the car share of trips has fallen in recent years, and concluded that car dependence had been reduced by coordinated packages of mutually reinforcing transport and land-use policies that made car use slower, less convenient, and more costly. Mattioli et al. (2020) discussed the political-economic factors associated with car dependence, including cultures of car consumption.

The concept of car dependence has been taken up by those concerned with policy for transport, land use, and urban development. Cao and Hickman (2018) investigated the relationship between car dependence and housing affordability in outer London suburbs, where potential problems arise from a high proportion of travel to work by car, longer average journey distances to work, limited access to public transport, and high levels of housing unaffordability. Handy (2020) argued that while it is not realistic in the foreseeable future for most Californians to live without their cars, it is possible, and would be beneficial, to decrease car dependence. The intergovernmental International Transport Forum has reviewed the range of policies that can reverse car dependency by encouraging citizens to use alternatives to private cars (International Transport Forum, 2021a). In the context of its Transport Decarbonisation Plan, the UK Government wants walking, cycling or public transport to be the natural first choice for short journeys, and recognises that the planning system has an important role to play in encouraging development that promotes a shift towards sustainable transport networks (Department for Transport, 2021).

The current critique of car ownership and use, as embraced by the concept of car dependence, has a two-fold thrust: challenge to the existence of locations where the car is the only feasible means of access, particularly where other modes of travel might be provided; and challenge to car use in locations where other modes are available in the form of public transport and active travel. In this latter context, the term 'car dependence' has some resonance with other kinds of undesirable dependence, such as on alcohol or drugs.

Nevertheless, the impact of the critique of car dependence on observed travel behaviour has been at best quite limited. In Britain, for which relatively comprehensive travel statistics are available, the number of private cars licensed for use increased steadily from 2 million in 1950 to 30.5 million in 2019 (Department for Transport, 2019a, Table VEH0103). Car traffic increased with minimal interruption from 16 million vehicle-miles travelled in 1950 to 278 million VMT in 2019 (Department for Transport, 2019a, Table TRA0101). The estimated number of holders of driving licences also increased steadily to reach 36 million by 2020, with more than 80% of males and females between ages 30 and 70 being qualified to drive (Department for Transport, 2019b, Table 0201). On the other hand, while the proportion of households owning one or more cars increased from 14% in 1951 to reach 75% by around 2000, thereafter it remained unchanged through to 2019 (Department for Transport, 2019b, Table 0205). And the average distance travelled by car, driver and passenger, fell significantly, from 5,800 miles a year in 2002 to 5,000 miles in 2019 (Department for Transport, 2019b, Table 0303). More generally, evidence from a number of developed economies indicates that car use per capita grew until the beginning of the present century, after which growth ceased; whereas car mode share in some large cities has peaked and then declined (Metz, 2021a).

So, the question to be asked is why car dependence has generally persisted, despite analytical and policy orientations that favour its decline. In broad terms, the answer two-fold. First, the widespread deployment of the car over the past century has proceeded in parallel with the development of the built environment, within which are found the origins and destinations of nearly all trips. Expeditious door-to-door travel by car has made possible access to a wide range of people, services and destinations to which we have become habituated. As with path-dependent processes generally, reversal is difficult without loss of benefit. Second, car ownership is attractive to a large proportion of the population, and a large industry has come into being to satisfy this desire.

Car dependence is an impediment to decarbonisation of the surface transport sector, where many analysts and policy advisors take the view that technological change, largely by replacing the internal combustion engine by electric propulsion, would in itself be insufficient to achieve a trajectory to Net Zero by 2050 consistent with international agreements. Thus, the International Transport Forum argues that reducing reliance on cars in cities is pivotal to decarbonise urban mobility (International Transport Forum, 2021b). Yet the attractions of the car mitigate against such reduction. Hence to consider the scope for reducing car dependence, it is useful to address the perspective of drivers, who generally find the car of utility as a practical means of conveyance, as well as desirable for the wider benefits of ownership.

Accordingly, the purpose of this review is to summarise the main evidence relating to positive perceptions of car ownership and use, with the aim of helping policy makers, planners, analysts and practitioners make realistic judgements of the likely impact of interventions to reduce reliance on the car in the context of transport decarbonisation. In the course of the discussion, opportunities to advance understanding through research are identified. It is also the intention of the article to offer a counterbalance to a negative view of the behaviours denoted by the concept of car dependence, common within the disciplines of academic transport and urban studies and of transport planning practice. Arguably, there is too much wishful thinking about the scope for reducing car use though policy interventions, implicitly validated by reference to "car dependence," yet a reduction that seems likely in practice to be quite difficult to deliver.

To prepare this article, the TRID transport database was searched using the terms "car dependence" and "car dependency." Relevant sources were selected that illuminate the policy challenge implied by the concept of car dependence. A comprehensive literature review was not attempted since an extended itemisation of all citable papers would detract from the policy-relevance of the article that follows.

The article first addresses the utility of the car as a mean of travel, then other aspects of the attractiveness of car ownership, before discussing the implication for policy and practice.

2. Utility of the Car

The modern era of travel began in 1830 with the opening of the first passenger railway, between Liverpool and Manchester. Thereafter, the energy of coal fuelled the worldwide growth of railways in the nineteenth century, followed by oil that powered the internal combustion engines of road vehicles in the twentieth century. The benefits of travel at faster than walking pace took the form of increased access to people, places and services that enlarged opportunities and choices. The car, which permits door-to-door travel, has been central to the growth of access, even in cities such as Copenhagen, famous for its cycling, with excellent infrastructure and a strong cycling culture. Nevertheless, there is substantial car use in the city, only slightly less than in London, as shown in Table 1.

Aside from cycling, the other large difference is that public transport use in Copenhagen is half that London. This is consistent with the proposition that people can be attracted away from buses onto bicycles by good cycling facilities, since cycling is cheaper, healthier, environmentally benign, and no slower than the bus in congested traffic.

There is some evidence concerning the extent to which new cycling facilities attract users away from car travel. A study of the impact of new cycle schemes in eight UK cities found that only 5% of cyclists said they would have travelled by car if the scheme had not been built, although most users had cycled before implementation of the new schemes (Sloman et al., 2021, section 10.3). The UK Department for Transport's guidance for the appraisal of cycle investments, based on a review of evidence, stipulates a car-cycle diversion factor of 0.24, meaning that if there were to be 100 new cyclists, there would be 24 fewer people travelling by car (Department for Transport, 2022a, para. 3.7.3). The corollary is that 76% would switch from other modes, likely mostly from buses.

The car remains attractive even in Copenhagen, a small, flat city with excellent cycling facilities, where almost all drivers have experience of safe cycling. Some information on trip mode shares is available for other European cities. Kodukula et al. (2018) compiled data for thirteen cities. A wide range of travel patterns was found, reflecting historic city boundaries, population density, and public transport provision. There were also differences in the sources of data, whether from household surveys or from counts of traffic and passengers. The mode shares for Copenhagen and London were close to those shown in Table 1. Amsterdam was similar to Copenhagen with 32% cycling and 17% public transport. In contrast, Vienna, Zurich, and Madrid were similar to London with 38–40% public transport, although rather more cycling (6–8%). However, no city was found to have high levels of both cycling and public transport.

Kodukula et al. (2018) noted that car mode share varied widely, from 20% for Amsterdam to 65% for Rome (car mode share for Paris is stated to be 15.8%, but there is some uncertainty whether this predominantly reflects the high-density central area of the city). Buehler et al. (2017) found that the largest cities in Austria, Switzerland, and Germany had succeeded in reducing the car share of trips over the past 25 years: from 40% to 27% in Vienna, from 40% to 33% in Munich, from 35% to 30% in Berlin, from 39% to 30% in Zurich, and from 48% to 42% in Hamburg. Nevertheless, car use remains substantial, notwithstanding policies to reduce car dependence.

Table 1. Trip mode share 2018 (%), Copenhagen and London.

	Copenhagen	London
Cycling	28	2.5
Car	32	35
Public transport	19	36
Walking	21	25

Sources: City of Copenhagen (2018; data for trips to, from, and in the city of Copenhagen) and Transport for London (2019; data for all trips by residents and non-residents with origin and destination or both in the area of the Greater London Authority; motorcycle and taxi omitted).

So, why are cars widely used even in cities that encourage other modes of travel? The answer surely is that cars are useful for carrying people and goods, including child seats and other equipment that is regularly used, as well as for making trips longer than would be comfortable by bicycle. The car is well-suited for meeting needs for access to people and places, including for trips with a chain of destinations, for door-to-door travel where there is road space to drive without unacceptable congestion delays and the ability to park at both ends of the journey. Car travel generally requires less planning than trips by public transport, with digital navigation based on satnav devices a means of selecting the quickest route (Metz, 2022).

The car offers flexibility, comfort, privacy, and security, compared to public transport, particularly for people with mobility difficulties. The English National Travel Survey for 2019 (before the Covid-19 pandemic) found that the most common mode of travel for adult respondents with a mobility difficulty was by car, with on average 238 trips per person per year as drivers and 178 as passengers, compared to 123 walking trips, 39 bus trips and 7 rail trips (Department for Transport, 2019b, Table 0709).

Following lifting of restrictions on daily activities and travel during the Covid-19 pandemic, when public transport was less attractive on account of the perceived risk of infection, car use revived rapidly to close to pre-pandemic levels. In London, for instance, car use reached more than 90% of pre-pandemic levels by the summer of 2020, whereas public transport use was only at the 50% level. By the autumn of 2022, public transport use was back to 85% and car use to around 95% of pre-pandemic (Transport for London, 2022, section 2.2). National data show a similar picture (Department for Transport, 2022b).

Car travel may feel less costly than public transport, particularly with a full load of passengers. Car ownership requires a commitment to pay the costs of purchase, servicing and insurance, so trading off large one-off payments for low marginal costs at the time of use. Such sunk costs are largely disregarded when making a choice between car use, active travel and public transport for an intended trip. Thaler (1999), in his seminal paper on "mental accounting," observes that many urban car owners would be financially better of selling their car and using a combination of taxis and car rentals; yet paying $10 to take a taxi to the supermarket or a movie is both salient and linked to the consumption act, so seeming to raise the price of groceries and movies in a way that monthly car payments or a fully owned car do not. Moreover, even when public transport was made available free of charge for a group of state employees in Hesse, Germany, car use and availability did not decline (Busch-Geertsema et al., 2021), consistent with the proposition that low costs at the time of use are not a decisive consideration when commitment has been made to the costs of car ownership.

Importantly, the amount of travel that can be undertaken is limited by the time available, given the 24 hours of the day and all the activities that must be fitted in. For settled populations, average travel time amounts to about one hour a day (Metz, 2021b). Accordingly, faster travel allows greater access within the travel time available. Car travel is generally faster, door-to-door, than other modes over short to moderate distances, which increases people's access to desired destinations. Access increases approximately with the square of the speed of travel, so that urban car travel at, say, 30 km per hour allows four times the access than does cycling at 15 kph, and 25 times more than walking.

Consistent with this perspective, Smart and Klein (2020) found that in the US access to an automobile is strongly associated with employment, job retention, and earning more money over time. A meta-analysis of research studies demonstrated that car ownership significantly increases employment probabilities (Bastiaanssen et al., 2020).

The value of access to people, places and services, of the choices and opportunities that ensue, is the main reason for the popularity of the car for short-to-medium journeys where there is adequate road space, and for longer trips where the alternative modes, rail or air travel, may be less attractive. Yet the attractions of car ownership go beyond the utilitarian, as discussed next.

3. Attractions of Car Ownership

There is a growing literature on why the car is seen by many as attractive, quite apart from its utility for making journeys. Sheller (2004) argued that "car consumption" is never simply about rational economic choices, but is as much about aesthetic, emotional and sensory responses to driving, as well as patterns of kinship, sociability, habitation, and work. Steg (2005) noted motives for car ownership that included feelings of sensation, power, superiority, self-esteem, and social status. She carried out interviews with samples of drivers to demonstrate that symbolic and affective motives play an important role in explaining the level of car use, in particular for commuting, concluding that these motives may be a reason why attempts to influence car use have not been very successful. Gatersleben (2021) has summarised the extensive yet diverse literature on the symbolic and affective aspects of car ownership and use. Cars can be symbols of both social identity and status as well as of personal identity. Affective aspects refer to emotions that include pleasure and pride, freedom and being in control.

Studies commissioned by Transport for London identified a number of emotional benefits associated with car use, including status, self-expression, power, and independence; car ownership could also support relationships with family, neighbours, and work colleagues (Roads Task Force, 2013). Ikezoe et al. (2021) surveyed car owners in Tokyo, finding that symbolic and affective factors were twice as important than convenience for motivating car ownership. Ho et al. (2020) investigated the scope for introducing mobility-as-a-service in a region of the UK, concluding that for a large proportion of the population, nearly 50%, "the car will still be king," since car-lovers value the convenience of their own cars, so that mobility-as-a-service is better marketed as a substitute for a second household car.

Moody and Zhao (2019) developed a survey methodology, applied in two US cities, to measure "car pride"—related to the social status and self-esteem associated with driving a car. This was found to be positively predictive of car ownership, but not the reverse. The survey was extended to Shanghai (Zhao & Zhao, 2020) and to 51 countries via telephone interviews, finding a wide range of scores: developed countries ranked lower than developing countries, the USA having the highest score for a developed country and Japan the lowest. India and Kenya were the highest ranking of the developing economies (Massachusetts Institute of Technology, 2019, Section 3.4). The observation of an Indian journalist is to the point: "Cars remain deeply aspirational in India, and it's common for new buyers to offer prayers when a family adds a new vehicle. The upgrade from a two-wheeler to a four-wheeler is also a hugely important status symbol" (Kotoky, 2022). More generally, acquisition of a car in a low-income country represents a step towards modernity.

Moody et al. (2021) estimated the value of car ownership in four US metropolitan areas by means of discrete choice experiments. They found that the total value was at least as much as estimates of the average cost of private ownership, and that more than half the value was non-use value, beyond the use value of getting from A to B.

The fact that cars are generally parked for 95% of the time is an argument for the economic benefits of car sharing, which would make fuller use of a costly capital investment. Conversely, this also indicates the value of the car to individual owners, both for ready use when required, including at short notice, but also for the non-use benefits of ownership.

One indication of the non-use attractions of the car is the growth of sales of sports utility vehicles (SUVs), larger, heavier and more costly than the vehicles they replaced. In 2021, SUVs were expected to account for more than 45% of global car sales (Cozzi & Petropulos, 2021). While there may be some practical advantages, it seems likely that this growth reflects positive feelings about ownership of these vehicles.

The literature on the attractions of car ownership beyond utility in use is diverse and generally persuasive, but does not offer clear indications to action to reduce car dependence.

4. Discussion

The evidence outlined above indicates that car use is motivated by both utility and positive feelings. For travel between locations where there is no convenient alternative mode, utility is sufficient to account for travel behaviour. Where other modes are available, utility may still be the main motivation, on account of door-to-door speed and other convenience factors, although positive feelings may reinforce use of a car. Even when the car is the slower option, those with positive feelings about car ownership may prefer to drive.

From this perspective, there are a number of possible approaches to reducing car dependence that broadly fall into three categories: providing acceptable alternative modes of travel, making car use less attractive than the alternatives, and lessening the good feelings about car ownership and use.

4.1. Alternatives to Car Travel

Alternatives to car travel are receiving considerable attention in the context of transport decarbonisation. Investment in public transport is relevant, particularly rail that is fast and not impeded by road traffic congestion, but which generally requires public subsidy. Providing better cycling facilities is less costly, yet which attract people from public transport rather than out of their cars, as discussed earlier. Electric micro-mobility is likely to act in the same way. Provision of opportunities for car sharing, whether for short-term rental of vehicles from street locations or sharing journeys with others for longer trips, should help reduce personal car ownership and result in less car use overall.

Opportunities to offer such alternatives to car travel are greatest in high-density urban areas where traffic congestion impedes movement and parking opportunities are limited. Moreover, the economics of public transport provision are most favourable and catchment areas, whether of schools or supermarkets, are compact, facilitating access by active travel modes. Yet beyond dense urban areas—in suburbs, towns, villages, and rural locations—car use remains attractive.

There is particular concern when new housing on greenfield sites is planned without alternatives to use of the car. A question that arises is whether those who purchase these homes feel deprived on that account, or whether they choose to live in such locations because they are positive about driving and are pleased to have plenty of parking space for their cars. While there has been investigation into how attitudes, behaviours and residential choices influence choice of sustainable travel options in urban areas (Kant et al., 2015), empirical investigation is needed to understand to what extent a new greenfield housing development results in involuntary car dependence, with deprivation for those residents who do not have access to a car. Given that these developments are built to sell, it is possible that most purchasers are content with a car-based lifestyle.

The converse of car-dependent greenfield development is transit-oriented development where housing is constructed on sites within walking distance of new rail-based transit schemes. There is an extensive literature on the topic of transport-related residential self-selection—whether people choose to live in neighbourhoods that align with their travel preferences. A recent review highlights the complexity, heterogeneity and uncertainty of research findings (Guan et al., 2020).

While the planning of new settlements can and should include consideration of provision of alternative modes of travel to the car, the greater problem concerns the existing built environment that has developed over the period since the middle of the last century as car ownership has become widespread. The result has been low-density development where the car has facilitated access to people and places, allowing dispersion of opportunities for access to employment, housing, services, as well as to family and friends. In these circumstances, the scope for the planning system to reduce car dependence is very limited, particular since the vast share of property, both residential and commercial, is owned privately. Besides, home-owners value attractive neighbourhoods and could not afford the cost of rebuilding. Hence the ability to reduce car use through creation of "15-minute cities" or "20-minute neighbourhoods" is for the most part more of an aspiration that a reality in existing built environments. Conversely, car dependence in economically vibrant rural areas may be seen as a positive feature since, without the car, depopulation would be likely as people move to cities for employment opportunities.

4.2. Making the Car Less Attractive

To complement the availability of appealing alternatives to the car, there is scope for making car use less attractive—together amounting to a "carrot and stick" approach. Interventions may reduce distances travelled by car, but the larger effect is likely to be to change the mode of travel.

Urban car use is made less attractive by constraints on parking, including limiting parking at the kerbside to permit unloading of goods vehicles and setting down from taxis; likewise, reducing carriageway available for general traffic by conversion to bus and cycle lanes and pedestrian space. Low traffic neighbourhoods constitute area-wide efforts to reduce car use. Raising charges for parking also discourages car use, both on-street and off-street facilities controlled by local authorities. A Workplace Parking Levy, as implemented in Nottingham, UK, can discourage car-commuting while generating revenue to fund public transport (Dale et al., 2019).

Road user charging, also known as road pricing and congestion charging, deters car use, as implemented in London, Stockholm, and Singapore (Metz, 2018). Singapore, as a city-state without a rural hinterland, has always levied a high charge for entitlement to car ownership, to limit the number of vehicles to the capacity of the road network, so that car ownership is about 100 per thousand population, compared with more than four times that number in other developed countries. Some Chinese cities have also limited car ownership, whether by auction of entitlements, as in Singapore, or by lottery.

Road fuel taxation adds to the cost of motoring, with quite wide variations between countries. However, high taxation tends to encourage use of smaller vehicles, which while good for the environment, has limited impact on car dependence.

4.3. Lessening Good Feelings About Car Use

As noted above, feeling of pride in car ownership vary widely across countries for reasons that are not apparent, beyond the status associated with ownership in developing economies. Attitudes also vary within countries, with younger adults in developed economies making less use of cars, particularly when living, working, and studying in or near attractive city centres. More generally, concerns about the environmental detriments arising from car use prompt some to give up their cars, although it is difficult to predict how far such a movement might spread, particularly as the switch to electric vehicles reduces environmental anxieties.

Nevertheless, the marketing efforts of the highly competitive car industry will continue to identify motivations for the purchase and use of cars, while the engineering side will continue to innovate to develop more attractive products. The aim of these efforts to is instil positive feelings about car purchase and use, which tend to trump the countervailing efforts to reduce car dependence. The innovations associated with the current switch to electric propulsion yield vehicles attractive to drive, as well as receiving the endorsement of governments through financial incentives to purchase, including lower rates of taxation, and support for provision of electric charging facilities. More generally, the governments of countries in which car manufacturers and their supply chains are located are supportive of these businesses and their outputs, for reasons of both employment and industrial policy.

Attitudes to the car are part of a wider debate about the role of consumption in society, including whether current levels of consumption of goods are sustainable, the role of repair and recycling, and concepts such as the 'circular economy.' In this context, a better understanding is needed of how favourable behaviour change may be achieved, for instance within the COM-B framework, which posits that to change, an individual must have the capability, the opportunity and the motivation (Michie et al., 2011), and which has been widely used in the public health context (Public Health England, 2020). Behaviour change techniques have been applied with success to improving road safety (RAC Foundation, 2017). In contrast, a systematic review found no evidence of efficacy of behavioural interventions aimed at reducing car trips (Arnott et al., 2014). Nevertheless, the Scottish Government has stated that it has considered interventions to reduce car use in the context of the COM-B model of behaviour change, although no detail is provided (Transport Scotland, 2022, p. 21).

5. Conclusions

The car is one of the great inventions and is justly popular for the access it makes possible to people and places, family and friends, jobs and homes, opportunities and choices. In developed economies, more households own cars than have children. Car ownership is widely associated with positive feelings, of pride of achievement and of self-esteem. However, this popularity gives rise to the well understood detrimental aspects of car use—carbon emissions, air pollutants, traffic noise, deaths and injuries from crashes, road traffic congestion, severance of communities, and impeding use of streets as places for social and economic engagement. Moreover, widespread car use has permitted the evolution of a relatively low-density built environment that can leave those without access to a car at a disadvantage.

These concerns have stimulated interest in the concept of car dependence, in the expectation that reducing such dependence would be a direct way of reducing the detriments. Notably, reduction in car use is seen by many authorities as necessary to achieve net zero climate changes objectives. For instance, the Scottish Government aspires to achieve a 20% reduction in car kilometres by 2030 (Transport Scotland, 2022).

Yet, as argued above, a policy-led direct assault on car dependence is unlikely to succeed. Instead, it seems more productive to tackle the detrimental aspects of mass car use individually through evidence-based policies. Thus, the switch to electric propulsion that eliminates tailpipe emissions can be pursued independently of a pushback of urban car traffic in favour of active travel and place-based street activities. The need is to develop a range of policies covering both technological innovation and behavioural change, and to test these for public acceptability and impact. At present, new technologies seem to be more acceptable than behavioural changes that would reduce the access to which we have become accustomed and from which we benefit.

Nevertheless, human behaviour is mutable and it is possible that car dependence may be lessened through appropriate interventions, were there to be better understanding with supporting evidence. Accordingly, there is scope for further research that would illuminate opportunities to reduce car dependence, including investigation of the following:

- The factors that contribute to car use in locations like Copenhagen where cycling and public transport alternatives are good and where there is a strong cycling culture;
- A systematic comparison of the factors affecting car use in European cities, where its mode share varies very widely;
- The socio-economic determinants of car pride, both those attributed to self-esteem and to social status, and why these vary widely across countries;
- Why people choose the particular models of cars they purchase, especially SUVs, an aspect doubtless well understood by the car manufacturers but not by those outside the industry;
- Tracking car use by young adults as they grow older, start families and move to less dense suburbs;
- The effectiveness of interventions to effect behaviour change that would reduce urban car use, most of which seem to have had limited impact so far.

All in all, the concept of car dependence has proved to be less helpful for policy development than had originally been hoped, in part because it implies a judgement by planners and researchers that has not commanded popular support. This contrasts with climate change, where the attitudes of experts, the car industry and the public are broadly aligned in respect of the need to switch from oil fuels to electric propulsion. The evolution of policy and practice is most effective when it moves in line with prevalent public perceptions.

Conflict of Interests

The author declares no conflict of interests.

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Article

The Effects of Urban Polycentricity on Particulate Matter Emissions From Vehicles: Evidence From 102 Chinese Cities

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Abstract

This article analyzes the impact of the level of urban polycentricity (UP) on particulate matter emissions from vehicles (PMV) across 102 prefecture-level cities in China between 2011 and 2015. We adopt a spatial panel modeling approach to our measures of UP and PMV, controlling for (possible) intervening effects such as population density and economic output. We observe an inverted U-shaped relationship between both measures: When UP is low, an increase in polycentricity is associated with higher levels of PMV; however, when UP reaches a certain threshold, the increase in polycentricity is associated with a reduction in PMV. We find a similar relationship between economic output and PMV and demonstrate how the effects of population density on PMV consist of two opposite processes that likely offset each other. Nonetheless, jointly, population density and UP have a significant effect on PMV. We use our results to discuss policy implications and identify avenues for further research.

Keywords

China; pollution reduction; polycentricity; urban spatial structure; vehicle emissions

Issue

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1. Introduction

Since the onset of its gradual reform and opening-up policies, China’s urbanization rate has rapidly increased from 18% in 1978 to 64% in 2020 (National Bureau of Statistics of China, 2021). This fast-paced urbanization has gone hand in hand with a rising number of motor vehicles: There are now more than 370 million motor vehicles in China, many of which are used in or around cities. China is now the country with the largest number of motor vehicles in the world. This sharp increase implies that in 2020 more than 15 million tons of air pollutants were generated through exhaust emissions (Ministry of Ecology and Environment [MEE] of the People’s Republic of China, 2021), which has resulted in deteriorating air quality and economic losses equivalent to 4.3% of China’s total GDP (World Bank, 2007). In this article, we will focus on a specific category of these pollutants: small particulate matter from vehicle (PMV) emissions, defined as having an aerodynamic equivalent diameter ≤100 µ. It has been demonstrated that these PMV emissions constitute a significant threat to public health: PMV contains heavy metals which can be toxic to humans, such as cadmium, chromium, nickel, and lead (Mainka, 2021; Zhao & Zhao, 2012). PMV can be deposited in the human lungs after inhalation, and subsequently, enter other tissues through blood circulation; this then leads to lesions in organs and cellular DNA damage (Zhang et al., 2015), thus increasing the chances of developing diseases such as cancer (Kong et al., 2012).

Confronted with these problems, a variety of measures have been implemented to reduce vehicle emissions, such as completely replacing fossil fuel vehicles (FFVs) with electric vehicles (EVs). Because EVs do not emit exhaust gases, they only produce fairly limited amounts of PMV through tire-road friction and brake wear (Timmers & Achten, 2016). In recent years, EVs have gained popularity in China from both the government and the consumer side. For example, the Chinese government has introduced a subsidy policy to encourage the purchase of EVs, which contributed to China now being the world's largest EVs market (Lin & Wu, 2018). In addition to this transformation, there are also indirect solutions, for example, policies and interventions aimed at regulating the spatial structure of cities through macro-level policy instruments and mitigating PMV pollution through a polycentric urban structure (Wang & Zhang, 2020). Indeed, promoting urban polycentricity (UP) has become a normative territorial development goal (Y. Li et al., 2019) and includes narratives stressing its potential to alleviate environmental challenges (Wang et al., 2020). Since the release of the 13th Five-Year Plan (see Appendix A in the Supplementary File), a variety of policies aimed at building urban polycentric structures have been devised, such as the Beijing Urban Master Plan launched in 2017.

Analyzing UP is hampered by the fact that there is no universally accepted definition (Meijers & Sandberg, 2008). A straightforward interpretation is that a given area can be considered polycentric if its population or employment is dispersed across several centers of roughly equal importance (Rauhut, 2017). In China, UP has become a prominent feature of the urban-regional landscape (Y. Li & Derudder, 2022), with most Chinese regions being polycentric to some extent (Zhang et al., 2017). Most UP studies have focused on its putative economic contribution (Meijers & Burger, 2010; Zhang et al., 2017), but there has also been some research on the relationship between UP and environmental pollution (Burgalassi & Luzzati, 2015; Chen et al., 2021). It is to the latter literature we seek to contribute with this article.

To date, most of the studies on the relation between UP and environmental pollution have focused on what are arguably some of the most well-known pollutants: $PM_{2.5}$ and PM_{10}, representing particulate matter emissions with an aerodynamic diameter smaller than 2.5 μm and 10 μm, respectively. A specific focus on PMV is a worthwhile addition to these analyses for several complementary reasons. First, PMV has in part different sources than $PM_{2.5}$ and PM_{10}, with vehicle emissions being only one of several major sources of $PM_{2.5}$ and PM_{10}. In most Chinese cities, the primary sources of $PM_{2.5}$ and PM_{10} are fossil fuel emissions (MEE of the People's Republic of China, 2019) and soil dust, respectively (Wang et al., 2012). As a result, the conclusions drawn from research on the effects of UP on $PM_{2.5}$ and/or PM_{10} cannot directly inform our understanding of the effects of studies of UP on PMV. Second, the fact that there is only one major source of PMV allows for a clear and straightforward analytical framework and subsequent interpretation. By focusing primarily on how urban-spatial structure affects car use, it is possible to reasonably conjecture how and why UP can impact PMV. This advantage is not likely to exist in studies of the effects of UP on other pollutants.

Against this background, the purpose of this article is to extend earlier research on the environmental effects of urban-spatial structure by examining to what extent (changes in) PMV can be traced back to (changes in) UP across 102 prefecture-level Chinese cities. We investigate both the direct and indirect effects of UP on PMV and adopt an explicitly spatial perspective by exploring the role of population density and a range of other factors in mediating this association. The analysis of the nature and the degree of these effects is based on a stepping-stone framework: We begin by discussing the direct correlates of PMV (the number of cars and the demand for car use), followed by an analysis of how UP indirectly affects the direct correlates of PMV, and subsequently PMV itself. The remainder of this article is organized as follows. Section 2 takes stock of the literature that allows hypothesizing how and why UP may exert an influence on PMV. In Section 3, we describe the data, regression model, and methodology, after which the results are discussed in Section 4. Finally, Section 5 summarizes our main findings, suggests some policy recommendations, and puts forward some possible avenues for further research.

2. Literature Review

2.1. Definition and Construction of Urban Polycentricity

There are different interpretations and specifications of the nature of UP. For example, at the intra-urban scale, UP points to the balance of the distribution of population and economic activities among different areas within the city (Liu et al., 2018); at the inter-urban scale, it refers to the balanced interaction between multiple, proximately located cities within a region. The UP concept can even be extended to the continental scale, as shown by the European Spatial Development Perspective where polycentricity was put forward as a general development plan for promoting balanced and sustainable development in the EU. In addition to differentiation in spatial scales, UP can be approached from morphological and functional perspectives. Morphological UP focuses on the distribution and size (in terms of population, employment, etc.) of centers (Brezzi & Veneri, 2015). Accordingly, an area can be regarded as morphologically polycentric if its population/employment is mainly concentrated in two or more centers (Riguelle et al., 2007). Meanwhile, functional UP refers to the balance and the connections between the centers in a given area (Green, 2007).

This article focuses on the intra-urban scale, adopting a morphological perspective to UP: We envisage UP as the degree to which the "importance" of (sub)centers is evenly distributed (Y. Li & Liu, 2018), with the importance constituted by indicators such as population, employment, and gross domestic product (Green, 2007).

2.2. Impact of Urban Polycentricity on Pollutants

Research on the possible impact of UP on pollutants is inconclusive at best (Han et al., 2020), and different (possible) relationships have been put forward in the literature. Burgalassi and Luzzati (2015) found no evidence of UP impacting pollution in Italian NUTS-2 regions. Focusing on the case of Île-de-France, Etuman et al. (2021) argued that UP reduces transportation-related emissions by reducing commuting distance in the city, but increases the demand for cars outside the city and therefore entails more emissions. In the case of the US metropolitan areas, S. Lee and Lee (2014) showed a positive relationship between UP and transport-related pollution. In contrast, Castells-Quintana et al. (2021) found heterogeneous impacts of UP on pollutants in light of city size: they found that polycentric structures are associated with lower levels of CO_2 emissions per capita and $PM_{2.5}$ emissions per capita, but only in larger cities. Similar uneven results have been reported in the Chinese context. Y. Li et al. (2020) showed positive effects of UP on $PM_{2.5}$ concentrations, while UP was found to reduce $PM_{2.5}$ concentrations (Han et al., 2020; He et al., 2022) as well as other pollutants: UP has been shown to be associated with lower levels of CO_2 concentrations (Sun et al., 2020), as well as PM_{10} concentrations and SO_2 concentrations (Sha et al., 2020; She et al., 2017). More fine-grained empirical studies pointed out that UP can alleviate traffic congestion in high-population-density areas while increasing air pollution in low-population-density areas (Zhang et al., 2017). Importantly, Y. Li et al. (2019) and Chen et al. (2021) found that the relationship between UP and pollution is not monotonic: When the level of UP is low, UP helps reduce traffic congestion and therefore pollution; when the level is high, UP increases pollution.

2.3. Mechanisms of Urban Polycentricity's Influence on Matter Emissions From Vehicles

The above-mentioned studies do not directly address PMV. This is relevant given that the different nature of PMV's origins may influence the overall association. Because PMV comes mainly from vehicle emissions, the discussion can be recast into a related one: How and why can UP affect vehicle emissions? Previous research is less divided here: Despite using different methods and empirical settings, most studies of the (alleged) impact of UP on pollution reduction focus on the jobs-housing balance as a key explanatory mechanism (Castells-Quintana et al., 2021; Park et al., 2020; Sun et al., 2019; Tao et al., 2019; Wang et al., 2017). The term "jobs-housing balance" has multiple meanings, but in the UP literature, it is commonly interpreted as the spatial (mis-)match between the quantity of employment and housing across a specific region (Peng, 1997). The assumed mechanism at play is that higher levels of UP are associated with more sub-centers with a larger population, more housing options, and more job opportunities. Residents in those sub-centers are subsequently more likely to obtain jobs near where they live and/or labor finds housing near where they work, which means that a jobs-housing balance is broadly achieved. As a result, residents will have less demand for cross-center commuting, resulting in less car usage and lower PMV generation. In addition, the decline in commuting demand in sub-centers would also alleviate traffic congestion, hence reducing the commuting time (X. Li et al., 2018; Y. Li et al., 2019; Sun et al., 2013) and therefore PMV generation.

Finally, it should be noted that there is also an ancillary explanation for the mitigation of PMV through UP, based on the suggestion that more sub-centers lead to lower pollutant concentrations which are then more easily self-cleared (Wang & Zhang, 2020).

2.4. Intervening Socio-Economic Factors

The potential effects of UP on PMV are influenced by a range of intervening processes. For example, the level of vehicle ownership is likely a direct influencing factor of PMV. In addition, there are possibly opposing relationships between PMV and population density: Higher population densities are often related to more private vehicles, which brings more traffic congestion, extends the commute time, and results in more pollutants (Bechle et al., 2011). However, higher population densities may also go hand in hand with more job opportunities and smaller job-housing distances as well as better public transportation systems. As a result, residents who live in areas with a higher population density will have less need to travel by private car and will therefore produce less pollution (Duranton & Turner, 2018; Saeidizand et al., 2022).

In addition, previous studies also identified a range of other factors contributing directly or indirectly to (changes in) missions. For example, the level of economic development can have both a positive and a negative relationship with PMV. In cities with a larger GDP, residents tend to buy more private vehicles (Paulley et al., 2006) and may therefore be generating more PMV. On the other hand, larger levels of GDP also commonly entail more environmental investments, such as acquiring more air pollution control equipment that removes hazardous air pollutants (Y. Li et al., 2020; Lin et al., 2012). This may be construed as economic growth leading to higher preferences for environmental quality and therefore more attention being paid to pollution control and cleaning technology (Dasgupta et al., 2002). Although in China, GDP is closely correlated with foreign direct investment (FDI; Büthe & Milner, 2008), the latter can also affect PMV independently, and this is because local governments may adopt looser environment-related policies to facilitate FDI (Cole et al., 2006), while on the other hand, advanced pollution treatment technologies and equipment often arrive under the form of foreign investment (Markusen & Venables, 1997).

Furthermore, industry sector factors such as the proportion of manufacturing industry output in GDP are often found to be directly correlated with pollution (Lin & Zhu, 2018). However, given that PMV does not originate from factories it is hard to envisage a direct relation. Contrary to the other pollutants, PMV may be negatively related to industry sectors, since large levels of industrialization mean that factories or industrial areas will be more concentrated, which can be associated with better urban public transportation systems and transport accessibility, thus helping to reduce the people's commuting demand and decrease the average transportation distance of industrial products (Gordon et al., 1989) and therefore PMV.

2.5. Hypothesized Effects Based on Existing Studies

Figure 1 summarizes the hypothesized effects of UP and possible intervening processes on PMV. Vehicle ownership has a direct influence, while the other factors indirectly change PMV through one or more routes.

The figure also shows that three factors (population density, GDP, and FDI) may be hypothesized to have either a positive and/or a negative impact. As a result, a regression result that is not significant may be somewhat misleading in that can imply that positive and negative effects offset each other. Hence, drawing on earlier studies (e.g., Han et al., 2020), we will use regression models with interaction and quadratic terms to help better explore these factors. In the next section, we describe and operationalize these dimensions.

3. Analytical Framework

3.1. Empirical Setting

Our analysis focuses on 102 prefecture-level cities in China, with data spanning the period from 2011 to 2015.

Although there are 293 prefecture-level cities in China, only 109 of them, mainly located in the eastern and central regions of mainland China (see Appendix A in Supplementary File), have their PMV data observed and recorded by the MEE of the People's Republic of China (because of missing data on other socioeconomic factors, only 102 cities are studied in this article). Note that the selection is made by the ministry, and we were unable to identify exactly why and how the 109 cities were chosen. As a result, our sample is not random, and sampling biases cannot be excluded. However, this is the most comprehensive dataset to date, and we, therefore,

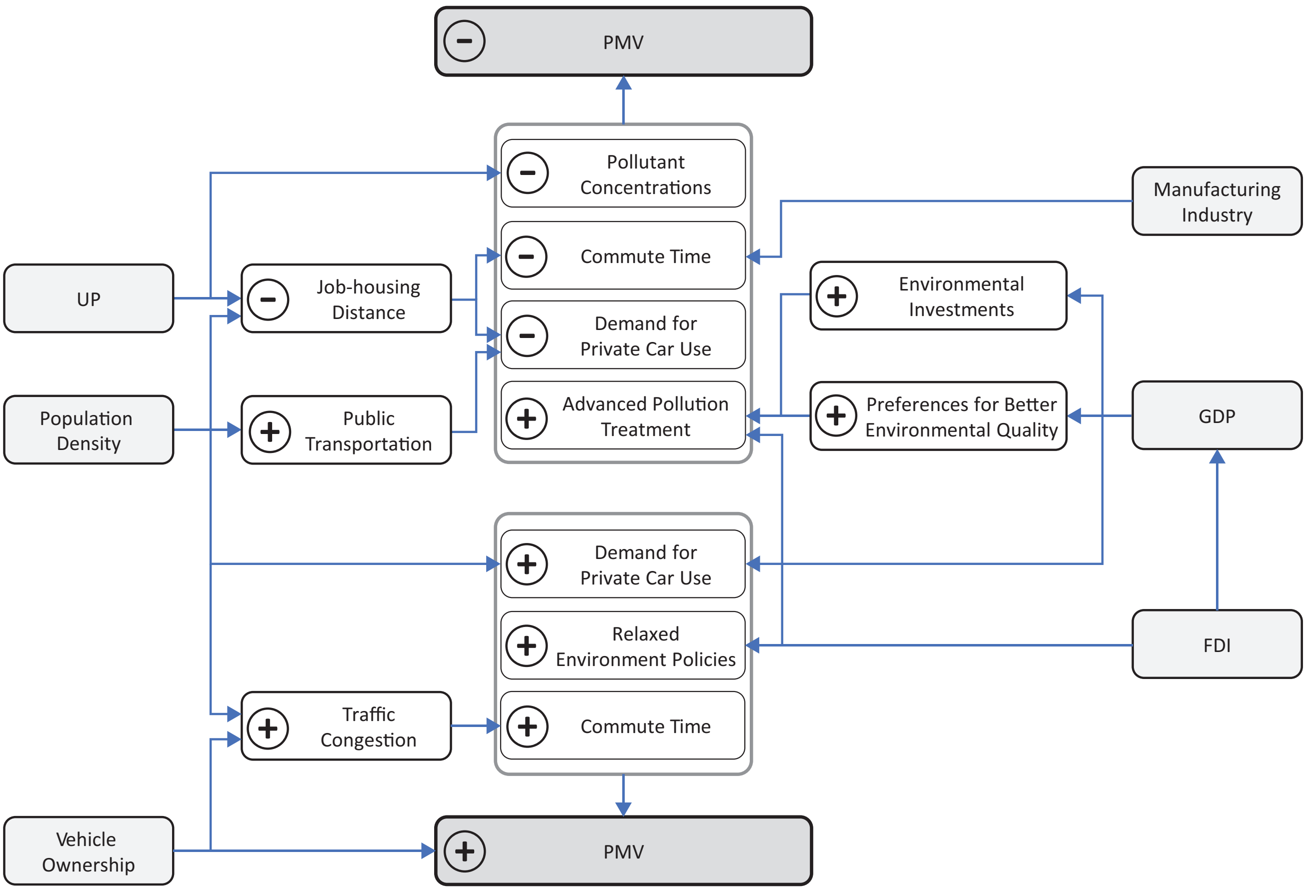

Figure 1. Hypothesized drivers of PMV.

proceed under the assumption that our analyses can inform our understanding of whether and how UP influences PMV.

Figure 2 shows that many cities are clustered, and interactions between those geographically clustered cities lead to the formation of urban agglomerations (Fang & Yu, 2017). Cities in these urban agglomerations become increasingly dependent on each other (Liu et al., 2016) and generate myriad economic and non-economic links, including trade, capital, information, and labor migration flows. As a result, the PMV of a city is likely to be influenced by its neighboring cities. This influence is known as the spatial spillover effect and should be considered in our models. In Section 3.5, we will therefore explicitly discuss how we capture this spatial spillover effect.

3.2. PMV Data

The PMV data are measured according to the *Technical Compilation Guide for Emissions of Atmospheric Pollutants from Road Motor Vehicles* (MEE of the People's Republic of China, 2014a). The guideline classifies vehicles according to their engine displacement, fuel consumption, and other relevant factors. In addition, it quantifies the number of vehicles in each category. Subsequently, the average annual distance traveled and the emissions per unit distance traveled for each type of vehicle are calculated. Finally, the PMV emission for each of the 109 cities can be estimated with the subsequent formula:

$$TPMV_i = \sum_j N_{i,j} \times EF_{i,j} \times VKT_{i,j}$$

$$\text{With: } EF_{i,j} = BEF_j \times \vartheta_i \times \rho_i \times \sigma_j \times \tau_j \quad (1)$$

Where $TPMV_i$ denotes the total amount of PMV emission of the city i, $N_{i,j}$ represents the number of type-j vehicles registered in city i. $EF_{i,j}$ is the amount of PMV emission generated per unit distance traveled for the type-j vehicle, and $VKT_{i,j}$ is the average annual distance traveled for type-j vehicles and BEF_j is the comprehensive reference emission factor, which is adjusted by the urban environmental correction factor (ϑ_i), the average speed correction factor (ρ_i), the degradation correction factor (σ_j), and the usage condition factor (τ_j) such as load coefficient and fuel quality.

Note that in this article we do not investigate the relationship between UP and the total amount of PMV emission. Rather, we examine PMV per capita. Because the total quantity of PMV emission is largely determined by urban dimension. As a result, research on this indicator would potentially obscure the impact of factors other than the urban dimension on PMV. Analyzing PMV per capita allows for a stronger association between PMV pollution and human commuting—one of the

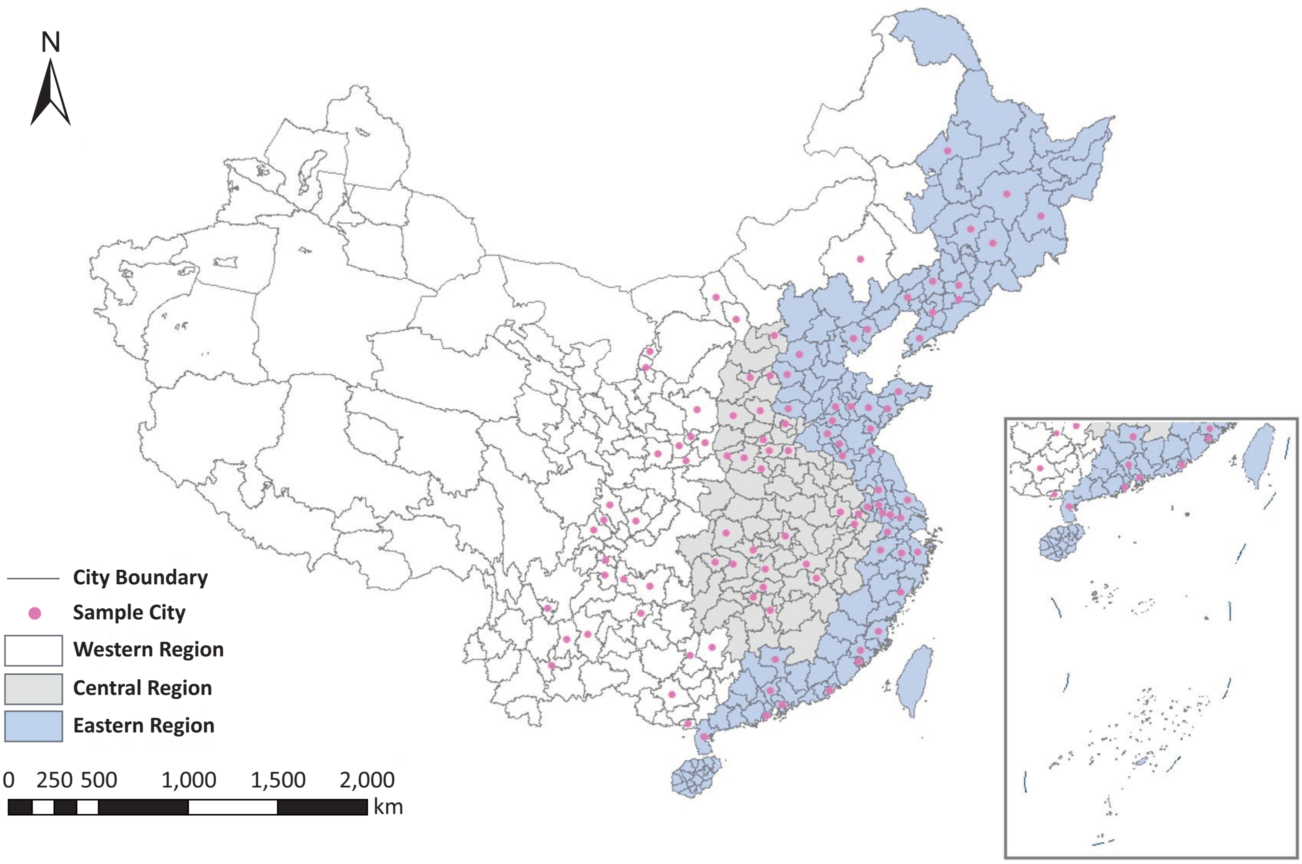

Figure 2. Research area.

key conduits connecting UP and PMV. And finally, this approach also aligns with the specification of the other socioeconomic factors in our study, such as GDP per capita and vehicle ownership per capita.

Figure 3 shows a decreasing trend of PMV over the five years, with the maximum value and mean value decreasing by 49.1% and 20.6%, respectively. Handan, Yan'an, Tangshan, Shenzhen, and Shijiazhuang had very high PMV values (>0.8) in 2011, while in 2015, only Handan's PMV value exceeded 0.8. The number of cities with PMV values below 0.1 went from seven in 2011 to 27 in 2015. The fastest decreases in PMV over the five years were found in Yan'an and Tangshan, with decreases of 0.864 and 0.411, respectively, while Dalian and Yinchuan witnessed the largest increases in PMV at 0.102 and 0.286.

3.3. Measuring Urban Polycentricity

To measure UP, it is first necessary to identify the population center(s). Drawing on Y. Li and Liu (2018), our first step is to identify potential population centers based on grid cells of approximately 1 km × 1 km in the LandScan population dataset. We use local Moran's I (Anselin, 1995) with an inverse distance weighting matrix to estimate the spatial autocorrelation pattern for each grid. The H-H grids (high-density grids surrounded by other high-density grids) are initially identified as potential population centers. Second, to filter out the smaller centers, we deleted potential population centers containing less than three grids or having a population that does not exceed 100,000 inhabitants. We calculate UP based on the thus-identified centers. Following B. Lee and Gordon (2007) and Y. Li et al. (2019), UP can be expressed as the proportion of the population of centers across the population of all centers:

$$UP = \frac{Pop_{sub}}{Pop_{main} + Pop_{sub}} \quad (2)$$

Where Pop_{main} denotes the population of the most populous center in the city, and Pop_{sub} represents the population of the sub-centers—the larger the population of the sub-centers relative to the main center, the higher the level of UP.

Figure 4 shows the changes in UP from 2011 to 2015. We can observe that the overall level of UP in China does not demonstrate a major increasing or decreasing trend over the five years. However, the bar chart reveals a weak rising in the UP trend in eastern China, increasing from 0.285 to 0.298 (+4.56%).

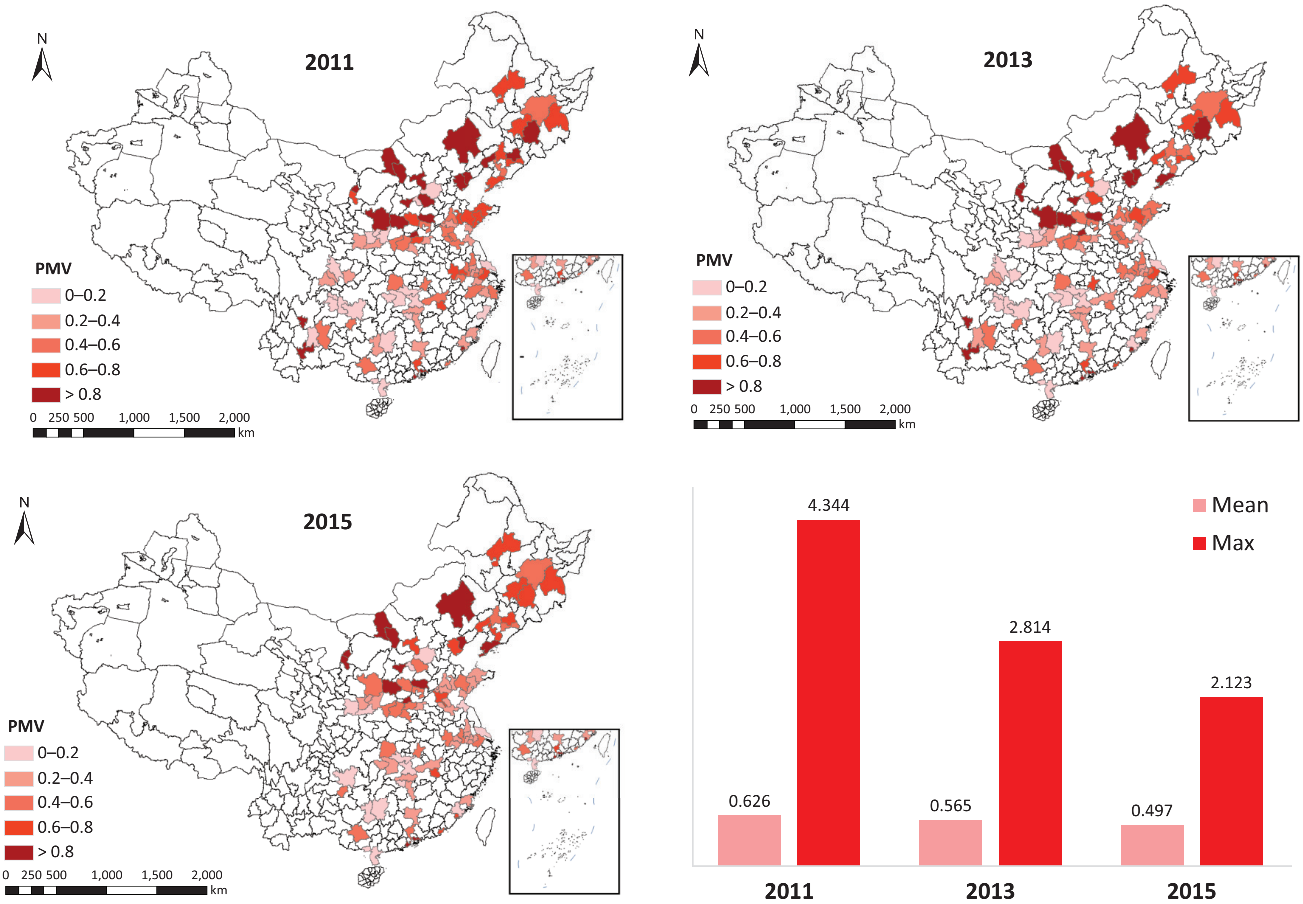

Figure 3. PMV between 2011 and 2015. Note: The unit of PMV is kilograms.

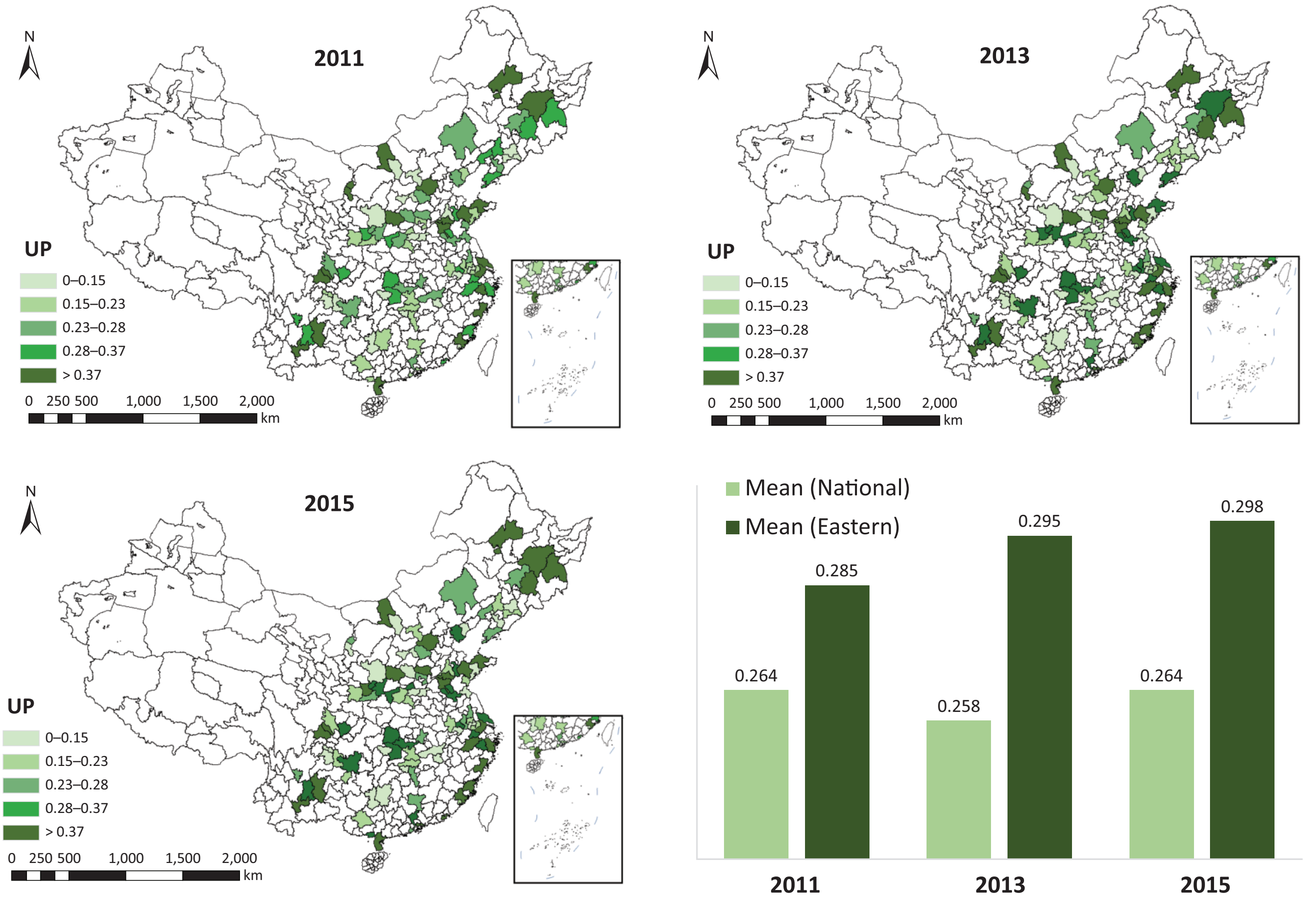

Figure 4. UP between 2011 and 2015.

3.4. Datasets

To analyze the impact of UP on PMV, we select five control variables, listed in Table 1 alongside the dependent variable (*PMV*) and the core independent variable (*UP*). In addition, for robustness checks, we consider another pollutant (*NOx*) that mainly emerges from vehicles alongside industrial emissions as the dependent variable.

Note that the minimum value of PMV equaling zero does not imply there are no PMV pollutants, but rather that the PMV density is too low to be measured by the gravimetric method. Meanwhile, a UP value of zero means that the city only has one population center. The variable *Car* contains both FFVs that emit PMVs and EVs that do not emit PMVs. Therefore, we cannot separate both types. However, the share of EVs was very small

Table 1. Descriptive statistics (number of observations = 510).

Variables	Mean	Standard deviation	Minimum	Maximum	Definition	Unit
PMV [a]	0.568	0.556	0	4.344	Particulate matter emissions from vehicles per capita	Kilogram
UP [b]	0.258	0.129	0	0.881	Urban polycentricity	No unit
GDP [c]	31536	15548	8074	91473	Gross regional product per capita, modified by GDP deflator based on 2000	Yuan
Density [c]	532.0	358.2	51.85	2648	Population density	Person/km^2
Industry [c]	52.03	8.700	24.3	75.9	The share of manufacturing output in GDP	%
FDI [c]	270.5	366.2	1.590	2356	FDI per capita	Dollar
Car [c]	0.141	1.165	0.135	1.000	Vehicle ownership per capita	Unit
NOx [a]	5.700	4.041	1.151	30.78	Nitrogen oxide emissions per capita	Kilogram

Sources: [a] MEE of the People's Republic of China (2011, 2012, 2013, 2014b, 2015); [b] Calculated based on LandScan grid data (Bright et al., 2016); [c] National Bureau of Statistics of China (2011, 2012, 2013, 2014, 2015).

during the study period (about 1%), so the variable *Car* can be approximated to represent the number of FFVs per capita.

Because some variables are likely to be correlated (e.g., FDI and GDP), we checked for multicollinearity. According to the variance inflation factors (VIF) test, the VIF values of all variables are less than five, with the mean VIF value being 2.07, indicating that there was no significant multicollinearity in our dataset.

3.5. Empirical Model

To investigate the impact of UP on PMV and take the spatial spillover effects into account, we use a time and individual fixed spatial error model based on panel datasets (see Appendix B in Supplementary File for more details on the selection of spatial models), in which PMV is examined as a function of a series of socio-economic factors and with the spatial spillover effects captured in the stochastic disturbances:

$$PMV_{i,t} = C + \beta_1 UP_{i,t} + \beta_2 Ln\left(GDP_{i,t}\right) + \beta_3\left[Ln\left(GDP_{i,t}\right)\right]^2 + \beta_4 Ln\left(Density_{i,t}\right) + \beta_5 Industry_{i,t} + \beta_6 Ln\left(FDI_{i,t}\right) + \beta_7 Ln\left(Car_{i,t}\right) + \gamma_i + \varphi_t + u_{i,t}\,,$$
$$\text{with: } u = \lambda W u_{i,t} + \varepsilon_{i,t} \qquad (3)$$

Where C is a constant term, β represents the coefficients of the independent variables, γ_i and φ_t are the individual fixed effect (FE) and the time FE, respectively, $u_{i,t}$ and $\varepsilon_{i,t}$ are the stochastic disturbances term, W is the row-normalized k-nearest (k = 4) spatial-weighting matrix, and λ is the spatial coefficient. $\left[Ln\left(GDP_{i,t}\right)\right]^2$ is used to study the possible nonlinear relationship between GDP and PMV (Y. Li & Liu, 2018). We use the logarithms of the variables in order to reduce the influence of extreme values and heteroskedasticity. Exceptions are *Industry* as this is percentual data and *PMV* and *UP* as they contain a large number of zeros.

As in many UP analyses, the above model may suffer from endogeneity issues (Chen et al., 2021; Y. Li & Liu, 2018). There are two main possible causes of endogeneity: omitted variables and bidirectional causality. In our case, omitted variables are largely controlled by time and individual FEs in the panel model, and they are therefore unlikely to cause biased estimates. In addition, the UP data is calculated from 5-year-period population data. Large-scale population changes due to PMV are unlikely to occur during this short period, suggesting that the effect of PMV on UP should be either non-existent or very weak, and thus bidirectional causality is unlikely to be a major factor. Accordingly, endogeneity issues will not significantly weaken the validity of our model. Given the low chances of endogeneity being an issue in our model, we treat UP as an exogenous variable. Nonetheless, we also empirically analyzed the endogeneity problem using instrumental variable estimation. The instrumental variable is the interaction terms of the number of rivers and the exchange rate. These estimation results (see Appendix C in Supplementary File) validated the robustness of our model.

Drawing on previous studies (e.g., Y. Li et al., 2019; Zhang et al., 2017), we also construct extended models by adding quadratic and interaction terms to the spatial error model, including *UP*UP*, *UP × Density*, *UP × GDP*, and *UP × Industry*. These terms can help to a more comprehensive analysis of the effect of UP and other factors on PMV. For example, adding *UP × Density* to the model helps to further explore how *UP* and *Density* jointly influence PMV: Positive (or negative) coefficients of *UP × Density* indicate that UP and PMV offset (or enhance) each other's PMV-reducing impacts.

4. Empirical Results

Table 2 shows the regression results for the spatial error model models. Model 1 is the benchmark model as described in equation (3), Models 2–5 are the extended models, and Model 6 is the NO_x analysis introduced for robustness checks.

In benchmark Model 1, the core variable *UP* is negative at the 1% significance level, suggesting that after controlling for other variables, a city is indeed less PMV-polluted if it has a higher level of UP. This result is consistent with earlier studies (e.g., Sun et al., 2020; Zhang et al., 2017). However, our finding contrasts with Y. Li et al. (2020), which may be due to their focus on $PM_{2.5}$, which has multiple sources/components.

As for the control variables, the coefficients for *GDP* and GDP^2 are positive and negative, respectively, suggesting that the functional relationship between *PMV* and *GDP* is best described as an inverted U-shaped curve. When a city's economic size achieves a certain threshold, an increase in GDP will be associated with a reduction in PMV. *Density* influences PMV (significant at the 10% level), suggesting that the negative effects (related to a shorter commute time and less vehicle demand) of population density on PMV likely exceed their positive effects (related to traffic congestion and a longer commute). The coefficient for *Industry* is negative at the 10% level, which might be because the concentrated industrial areas can increase transport accessibility, and thus reduce the commuting/transportation distance for people/industrial products, and consequently lower PMV. *Car* is significantly positive because it is directly related to *PMV*. In addition, FDI is not significant: it is either unrelated to PMV, or the two opposite effects of FDI on PMV (see Figure 1) offset each other.

In Model 2, the higher log-likelihood value indicates a more considerable explanatory power. *UP* is positive and *UP × UP* is negative, indicating an inverted U-shaped relationship—a polycentric structure reduces a city's PMV only when UP exceeds a threshold value of 0.222 (= 1.623/(−3.650 × 2)). A possible explanation could be that a lower level of UP implies that

Table 2. Regression results.

Dependent variable	PMV					NO_x
Models	1	2	3	4	5	6
UP	−0.792***	1.623***	−4.796***	−1.351	−3.166**	−0.522***
GDP	4.680***	5.473***	5.397***	4.585***	4.565***	6.510***
GDP²	−0.206***	−0.241***	−0.237***	−0.200***	−0.199***	−0.280***
Density	−0.680*	−0.871**	−1.121***	−0.667*	−0.667*	−0.677**
Industry	−0.014*	−0.017**	−0.017**	−0.014*	−0.026**	−0.022***
Car	0.204***	0.152**	0.194***	0.204***	0.202***	0.149**
FDI	0.042	0.029	0.038	0.042	0.040	−0.054**
UP × *UP*		−3.650***				
UP × *Density*			0.700***			
UP × *GDP*				−0.076***		
UP × *Industry*					0.045*	
Constant	0.220***	0.216***	0.221***	0.222***	0.221***	0.196***
λ	−0.141*	−0.071*	−0.125*	−0.143*	−0.135*	0.259***
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes
Log-likelihood	34.504	46.994	36.809	34.407	35.920	83.806
Observations	510	510	510	510	510	510

Notes: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

the sub-centers have less population, housing, and job opportunities, and therefore less likely to achieve the jobs-housing balance. As a result, residents will have a greater need for cross-center commuting and therefore generate more PMV. Another reason might be that the sub-centers with relatively smaller populations may not have a well-established public transportation system so residents' commuting needs are more likely to be met by private vehicles.

In Model 3, *UP* × *Density* and *Density* are significantly positive and negative, respectively, suggesting that Model 3 provides a more comprehensive explanation for the impact of population density on PMV. This result shows that UP and population density interact in reducing PMV pollution—the PMV reduction effect of UP is reduced as the population density increases. This is consistent with the studies of X. Li et al. (2018) and Y. Li et al. (2019). Accordingly, we could argue that for areas with high population density, it is better to maintain a high level of polycentricity to reduce PMV.

In Model 4, *UP* × *GDP* is negatively significant but *UP* is not significant, implying that UP's effect on PMV might be indirect, and dependent upon the level of urban economic development. Specifically, the higher the GDP, the greater the effect of UP on PMV reduction. The finding can be corroborated by the study of Y. Li et al. (2020): A polycentric structure may play a larger role in reducing PMV in cities with higher levels of economic development.

In Model 5, *UP* × *industry* is positively significant at the 10% level, implying that UP will increase PMV when the share of manufacturing output in GDP exceeds 70.35% (*Industry* = 3.166/0.045). In our case, only Panzhihua and Yan'an reach this threshold. This implies that a monocentric instead of a polycentric urban structure might be more suitable for predominantly industrial cities in the case of PMV reduction. Because the polycentric structure might decentralize factories and industrial areas, increasing the transportation distance of industrial products between different industrial areas, and therefore generating more demand for vehicles and more PMV.

In the above models, the spatial coefficient *λ* is consistently negative and significant at the 10% level, which can be interpreted as the PMV of a city being negatively influenced by some omitted factors of the surrounding cities, such as inter-urban trade, labor migration, and regional (environmental) policies. In other words, if we ignore these unobservable spillovers, our regression models will likely lead to biased estimates. We can therefore argue that the spatial error models are indeed appropriate and necessary for our study.

In Model 6, we replaced PMV with NO_x. The result shows that the significance and direction (positive or negative) of the coefficients for most variables did not change. This finding reaffirms the reduction effect of UP on pollutants emitted from FFVs. It also implies that our analytical framework (e.g., in the choice of spatial model and control variables) is reasonable and the results presented by our empirical models are robust.

5. Conclusions and Policy Implications

The purpose of this article has been to contribute to the longstanding debate on what kind of urban-spatial structure is conducive to PMV reduction. To this end, we engaged in a spatial panel econometric analysis of 109 prefectural-level cities in China. Our regression results reveal that a polycentric structure can help reduce PMV. In addition, the relationship between UP and PMV follows an inverted U-shaped pattern, meaning that for lower levels of UP, more UP increases the level of PMV, but UP starts leading to decreases in PMV when it exceeds a threshold value. We also analyzed the different roles a polycentric structure played in different types of cities. We find that polycentric urban structures can help reduce PMV for cities with high population density and high levels of economic development, and the monocentric structure which may lead to less PMV for the ones with the low level of economic development and industry-dominated cities.

Based on our findings, we propose the following policy recommendations:

1. A polycentric structure does not always contribute to PMV pollution reduction, and it may even bring about more pollution in certain cities. Therefore, policymakers should not blindly implement polycentric-related policies. Rather, such policies should above all be applied to less-industrialized cities with higher levels of economic development and population density.
2. Promoting a polycentric structure should not only focus on the number of sub-centers but on also the development of these sub-centers. If the sub-centers do not have sufficient population, employment, and public infrastructure potential, more sub-centers will create more cross-center commuting thus resulting in more PMV pollution.

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Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

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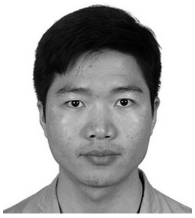

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