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Effects of off-street parking and car sharing on car use and car ownership in low-parking developments

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ABSTRACT

Cities increasingly implement strategies to reduce private car use to meet environmental and safety goals. Car sharing is one solution, offering access to cars without ownership. Another strategy is reducing minimum parking requirements, which many cities allow in combination with mobility services like car sharing. In this paper, we investigate the impacts of car sharing availability (and use) and minimum parking requirements on car ownership and car use. Using survey data from 24 multi-family housing areas in Gothenburg and Malmö, Sweden, this paper analyzes both property and household scale impacts of car sharing and parking on mobility patterns. Across both cities, respondents have lower car ownership than the city average. There is a positive correlation between parking and car ownership at the property level: properties with more parking spaces per apartment had more cars per household. In many cases, parking supply exceeded actual household car ownership, suggesting that minimum parking requirements remain higher than necessary. Properties with more parking had higher overall car use, with residents driving roughly 30% of their total travel time compared to only 10% in low-parking properties. Car sharing use is also correlated with lower rates of car ownership at the property scale. For individual mobility, active car sharing users showed significantly lower car ownership than non-users. Education and distance to work significantly contribute to higher car ownership, while household size, distance to work and distance to the city center contribute to higher rates of car use. Cluster analysis revealed three distinct groups of car users—from low to high use—which showed an inverse relationship between car ownership and car sharing activity. Findings indicate that reducing minimum parking requirements in combination with providing car sharing access is associated with lower car ownership and less driving. The study highlights the importance of integrated parking and mobility policies and points to future research needs, including comparing housing with and without reduced parking and assessing additional mobility services beyond car sharing.

1. Introduction

The transition to sustainable mobility is limited by factors that contribute to high automobile ownership and use, including built environment characteristics and socio-demographic factors (Hrelja and Rye, 2023; Newman and Kenworthy, 2015). It is widely recognized that reducing private automobile use is a necessary step to address environmental issues related to climate change and automobile dependence (Ewing and Hamidi, 2015). Over the last two decades, cities have implemented numerous strategies to provide alternatives to private car use, such as investments in cycling, public bike sharing, investment in public transport, and many others (Buehler and Pucher, 2011; Richardson, 2014; Vega-Gonzalo et al., 2024; Zhu et al., 2022). In this paper, we focus on two strategies – car sharing and minimum parking requirements – and examine their impact on car use and car ownership. Together, these two strategies offer a 'carrot and sticks' approach that disincentivizes car ownership while providing an alternative mobility option.

Car sharing is a viable substitute to private automobile use, allowing residents to have access to a car when they need it, without the need to have their own, thus challenging the dominance of private vehicle use (Kent and Dowling, 2013; Seo and Lee, 2022; Sprei and Ginnebaugh, 2018; Vega-Gonzalo et al., 2024). Many factors influence the adoption of car sharing, but many studies show that the availability of car sharing can reduce private car ownership (Becker et al., 2018; Chicco et al., 2022; Dowling et al., 2018; Efthymiou et al., 2013; Kent and Dowling,

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2018). However, the effect may be moderate by factors such as built environment and access to parking (Clewlow, 2016; Jain et al., 2022). Car sharing – and other types of shared mobility – is predominantly organized by private companies, however, cities can play a number of roles and further enable its adoption with supportive policies, such as agreements to use public parking spaces or requirements to promote equity and accessibility to such services.

Cities also implement numerous strategies to disincentivize and reduce car use and ownership. Among these are reforms to parking policies, with many cities reducing or eliminating their minimum parking requirements for new developments (Parking Reform Network, 2021). Many cities allow lower parking in new developments when certain conditions are met, such as being located close to shopping or public transport (Gabbe et al., 2020), or when certain mobility services are available to residents, including car sharing (E. Johansson and Rosendahl, 2021). In this paper, we define a mobility service as any service, amenity, or information that enables people to travel more easily without a private car. In this way, mobility services address the need to both reduce car ownership and to reduce personal car use. Studies have shown that residents in 'low-parking' developments have more sustainable travel patterns overall (Broaddus, 2010; Sprei et al., 2020).

In Sweden, cities are actively developing policies to meet ambitious goals to reduce transport-related climate emissions, reduce levels of car traffic, and promote safer streets. Many cities now use flexible parking strategies (Holm et al., 2025; F. Johansson et al., 2019, 2025), which allow them to set parking norms at different levels based on the local context of a building project or on the types of mobility solutions offered, and many offer reductions in minimum parking requirements for the implementation of car sharing (Holm and Ivansson, 2022). These strategies are used since research has shown that the availability of parking is associated with higher personal car use and ownership (Guo, 2013b; McCahill et al., 2016; Weinberger, 2012) and that higher minimum parking requirements are associated with higher levels of parking and car ownership (McAslan and Sprei, 2023).

In this paper, we study the mobility patterns of residents in newly built apartments with access to car sharing and a range of p-norms – or the number of parking spaces per apartment. All the newly built apartments have reduced parking compared to previous parking policies but still represent a range of p-norms within the current parking requirements. We focus our analysis on how these factors relate to both car use and car ownership, since reducing private car ownership and reducing the amount of driving are primary transportation goals in many Swedish municipalities, as well as many others globally. Our analysis of parking and car sharing offers a valuable empirical focus, since most existing studies evaluate either parking or car sharing in isolation. Studies that do examine both are limited in scope, examining only a few buildings and do not consider actual car sharing use. In this paper, we study apartment buildings with different degrees of reduced parking and access to car sharing, expanding the scope of our analysis to include car sharing use. By exploring these parallel relationships, this study provides a broader perspective on how these policies correlate with resident mobility choices.

In the next section, we review previous research on the impacts of parking and car sharing on mobility patterns and car ownership. We also examine the policy contexts in the two cities that are the focus of this study – Gothenburg and Malmö, Sweden. In section 3, we present our research methodology, highlighting the resident survey carried out in newly built multi-family housing in Gothenburg and Malmö that have both reduced minimum parking requirements and have access to car sharing. We then discuss how we analyze the survey results to best understand the impacts of reduced parking and the availability of car sharing. In section 4 we present our results, which is followed by a discussion on the implications and limitations of these findings for transport planning and policy in Gothenburg and Malmö, and what they mean for cities more generally.

2. Background: impacts of car sharing and parking on car ownership and use

Previous research has separately examined the impacts of both car sharing and parking in various ways in an effort to understand their impacts on mobility behaviors – particularly on car use and car ownership. These studies have shown that car sharing and parking availability both separately affect rates of car ownership and private vehicle usage patterns, which we discuss below. However, few of these studies examine these effects together, where minimum parking requirements are reduced, and car sharing is available as an alternative to private car use and car ownership. It is increasingly common for cities to integrate reductions in minimum parking requirements with mobility services like car sharing. This is done through regulation and through market forces that deem low-car and low-parking housing areas to be prime locations for shared mobility solutions. Below we highlight research on car sharing, parking and their integration within low-parking housing. We then introduce the Gothenburg and Malmö cases and how they combine reduced parking requirements with mobility services.

2.1. Car sharing, car ownership and mobility

Several studies have found that there is a connection between car sharing and lower car ownership (Becker et al., 2017; Chicco et al., 2022; Jochem et al., 2020; Kolleck, 2021; Le Vine and Polak, 2019; Namazu and Dowlatabadi, 2018). However, the effect may differ depending on factors related to car sharing as well as the built environment and when cofounding factors are included (Mishra et al., 2015) Station based, also called round-trip car sharing shows lower levels of car ownership compared to free-floating (Becker et al., 2017; Kolleck, 2021). And fleet based has lower than peer-to-peer (Jain et al., 2022). The maturity of the car sharing system has shown to have an effect on vehicle ownership (Cervero, 2003). Regarding the built environment, density and access to private parking are factors that influence the effect (Clewlow, 2016; Haustein, 2021; Jain et al., 2022).

The impact on travel behavior varies among users (Jain et al., 2020; Millard-Ball et al., 2005; Ramos et al., 2020). In-depth, qualitative studies of car-sharing users have shown that car sharing often facilitates and enables changes in travel behavior rather than causing them. Car shedding is often also connected to other life events, such as relocation or a change of jobs (Jain et al., 2020). Taking these factors into account, it is thus not always clear what the effect of car sharing is per se and what may be the effect of other factors when studying car sharing, car ownership, and usage.

2.2. Parking and mobility

Parking is an important link between land use and transportation planning efforts (Genter et al., 2013; King, 2022) and is an increasingly important area of policy work in which cities engage. Minimum parking requirements regulate how much off-street parking is required in new urban development. In the U.S., many cities have reduced or eliminated minimum parking requirements in parts or in all of their city or enacted parking maximums. Similarly, California and Oregon in the U.S. have passed laws limiting the amount of parking cities can mandate in areas served by public transport (Parking Reform Network, 2024). High levels of off-street parking contributes to increased levels of urban sprawl and more expensive housing and development costs (King, 2022; Litman, 2021; Shoup, 2011).

Research shows that the availability of parking is an important factor in both car ownership and use (McCahill et al., 2016; Weinberger, 2012). Higher amounts of parking available at home have been associated with higher rates of car ownership and car use (Christiansen et al., 2017; Guo, 2013a; Weinberger, 2012; Weinberger et al., 2008). Studies also point to how poorly managed on-street parking can increase car ownership (Guo, 2013b; Scheiner et al., 2020; Taylor, 2020). Many of these studies only examine the presumed link between parking availability and high minimum parking requirements. However, McAslan and Sprei (2023) demonstrate in their analysis of Swedish municipalities that minimum parking requirements are associated with higher rates of car ownership.

The availability of parking is not only linked to increasing car use, but also linked to reducing the effectiveness of alternative modes of transportation. Weinberger (2012), for example, demonstrates how even in neighborhoods with good public transport, high levels of parking are still associated with higher car use. De Gruyter et al. (2020) show that while proximity to public transport is associated with reduced demand for parking, public transport frequency and quality are more associated with lower car ownership. In reverse, poor access to public transport has also been shown to increase car use even when there are policies in place aimed at reducing car use (Christiansen et al., 2017). In a review of low-parking housing projects, Sprei et al. (2020) emphasize the need to provide attractive mobility alternatives to compensate for reductions in parking availability.

2.3. Reduced parking requirements combined with mobility services

There are a few studies that have looked at housing with reduced parking requirements in combination with the provision of mobility services such as car-sharing (Kushner, 2005; Melia, 2014; Sprei et al., 2020). These analyses consistently find that such developments are associated with more sustainable mobility practices. However, existing literature primarily relies on isolated, single-development case studies, which limits the geographic generalizability of the observed trends (Sprei et al., 2020). Furthermore, isolating the specific behavioral associations of car sharing and reduced parking remains complex. In Gothenburg, Antonson et al. (2017) find little impact on car use and car ownership attributed to the availability of parking, largely due to availability of parking in surrounding areas that negate the potential effect of lower parking supply in the newly built apartment buildings. Both Smith et al. (2022) and Sprei et al. (2022) study a residential building complex with no residential parking but access to both car sharing and bike sharing. They find that the provision of mobility services has facilitated sustainable travel behaviors and that the lack of residential parking has been important in reducing car use. Johansson et al. (2019) evaluate two developments in Stockholm that both reduce parking while giving residents access to subsidized mobility services. They find a decrease in car ownership, frequency of car use, and some indication of increased use of public transport. These studies all show that while there is a clear link between travel patterns and reduced parking and mobility services, they also point to other factors, such as access to public transportation or changes in life situations (e.g. moving to new city) as influencing the changes in mobility practices.

Because previous research frequently analyzes only one or two properties and focuses on before-and-after effects, it is difficult to determine whether more sustainable travel patterns scale across different buildings and urban contexts or how heavily they rely on actual car sharing usage or the reduction in parking supply. Our current study builds on these foundations. Rather than seeking to establish definitive causal mechanisms (which remains a broader challenge in cross-sectional built environment research) we analyze a large, multi-building sample to evaluate the broader generalizability of these associations. Crucially, we extend the literature by analyzing actual car sharing usage alongside variations in parking supply across 24 apartment buildings to examine these broader correlations with resident mobility choices.

3. Parking policy and car sharing in Gothenburg and Malmö

Parking policies in Sweden are determined by each municipality separately but must adhere to the Planning and Building Act (2010:900), which states that all development must accommodate the need for car parking within the property (Sveriges Riksdag, 2010). This has led municipalities to adopt minimum parking requirements which determine how many parking spaces need to be built for any given use. For housing, this is done by parking spaces per housing unit or parking spaces by gross building area (McAslan and Sprei, 2023).

In Gothenburg, the city has been actively working with parking to meet sustainability goals. The most current parking policy was adopted in 2018 (Göteborgs Stad, 2018), which replaced the previous 2011 policy (Göteborgs Stad, 2011). Both policies outline, among other things, the minimum parking requirements for new housing. The properties surveyed in this study were planned under the 2011 policy, however city planners proactively applied aspects of the new policy to new projects on a case-by-case basis prior to it being officially adopted in 2018. As a result, projects in Gothenburg show a mix of old and new requirements.

The 2011 parking policy divides Gothenburg into three zones, with parking requirements ranging from 0.49 parking spaces per apartment in the city center, 0.54 in the inner area, and 0.65 in the rest of Gothenburg. Apartments with a majority of small apartments had lower requirements, ranging from 0.34 to 0.46 parking spaces per apartment. A 10% reduction in parking was given in areas with good public transport. In the revised 2018 parking policy, updated parking requirements and parking zones were adopted. Table 1 shows the differences in minimum parking requirements between the two policies.

In addition to new minimum parking requirements, the 2018 policy allowed developers to reduce the amount of parking if they also incorporated mobility measures. These include both car sharing and bike sharing, as well as a range of other transport-related services or amenities (Göteborgs Stad, 2011). This policy was not adopted until 2018; however, several projects were allowed to take advantage of these provisions and reduce the amount of parking they were required to build. Under the 2018 policy, parking can be reduced by up to 0.3 parking spaces per apartment in the most central areas, to reach a parking number (or p-norm) of 0.2, or in the outer areas, by 0.5 parking spaces, to reach a p-norm of 0.5 from 1.0 parking spaces per apartment. The p-norm is the final parking number in a building after applying minimum requirements and reductions. A fixed reduction of 0.2 is possible for the inclusion of shared mobility, while additional reductions are allowed based on proximity to public transport and several key destinations (e.g., grocery stores, schools, doctor's office) and the composition of small, medium and large apartment units. The range allowed for each zone is shown in Table 1.

In Malmö, the parking policy in use at the time this study was conducted was adopted in 2010 (Malmö stad, 2010) – subsequent parking policies were adopted in 2020 and 2024. The 2010 policy requires between 0.7 and 1.0 parking spaces per apartment for multi-family housing as a baseline. The policy states that this range provides flexibility to adapt the parking number to the specific conditions of a project, which includes the location in the city, access to services, public transport provision, apartment size and composition, target demographic group, residential density, and expected car ownership (Malmö stad, 2010). The parking policy also allows for a 30% reduction of the minimum parking requirement if car sharing is included within the project, which effectively reduces the minimum parking requirement to 0.5 spaces per apartment. A prerequisite for receiving this reduction is that the

Table 1
Comparison of minimum parking requirements in the City of Gothenburg 2011 versus 2018.

Zone	2011 Policy	2018 Policy
A	0.34 to 0.49	0.2 to 0.5
B	0.42 to 0.54	0.3 to 0.6
C	0.46 to 0.65	0.4 to 0.8
D	-	0.5 to 1.0

apartments have good access to public transport and community services. However, at the time the survey was carried out, the city used a standard reduction of 0.2 parking spaces per apartment if car sharing was accessible by residents in the property, either provided by the property or in the neighborhood.

While car sharing has been present in Sweden since the late 1970s (Bocken et al., 2020), there are not that many studies regarding their use and effects on car-ownership and usage. Sprei and Ginnebaugh (2015, 2018) study how car sharing could reduce the size of vehicles purchased. They do so through interviews of car sharing actors in Sweden and California. However, they do not have any empirical data on actual user behavior or characteristics. Ramos et al. (2020) studied mobility styles, attitudes, and motives of both users and non-users of car sharing in European cities, with almost half of the respondents being from Sweden. Based on their analysis they don't find more sustainable practices among car sharing users than non-users. Bocken et al. (2020) study business models and how car sharing services have evolved in four Swedish cities. Reyes et al. (2020) through a literature review, study behavioral insights related to adoption of car sharing in Sweden and Spain. Svennevik et al. (2021) compare car sharing in Malmö, Rotterdam and Oslo through practice theory perspective.

4. Methods

The central question we aim to answer in this paper is how the availability of car sharing and reductions in minimum parking requirements impact car ownership and car use in newly built and renovated housing developments? In answering this question, we analyze mobility patterns (primarily by car), vehicle ownership, car sharing membership rates, and parking spaces per apartment. Our analysis is based on a survey conducted in Gothenburg and Malmö, Sweden. The survey included questions on socio-demographics, general travel, travel by car, and the use of car sharing as well as on income, age, education, household size, and a number of other socio-demographic factors.

4.1. Research design and data

The survey was sent to residents in Fall (2019) to Winter 2020. In Gothenburg, a mail-based survey was sent to residents and in Malmö, the survey was distributed to residents directly by the city-owned housing company, MKB Fastigheter. A total of 24 properties were included in our sample – seven in Gothenburg and 17 in Malmö. In Gothenburg, the properties were identified based on two parameters. They had to be recently built or rebuilt apartments (2018-2019) and have access to car sharing at the property or nearby. In Malmö, a mix of apartments with higher and lower p-norms was identified in different areas of the city in consultation with MKB Fastigheter, resulting in some older buildings that were newly renovated. The properties also had varying degrees of access to car sharing. In Gothenburg, surveys were sent to 1078 residents in the seven properties, while in Malmö, there were 1317 surveys sent to the 17 properties. A total of 509 surveys responses were collected, of which 454 complete responses were used in the analysis conducted in this paper.

Data on parking in the Gothenburg properties was collected by researchers who identified properties to survey directly, while in Malmö, parking data and selection of properties to survey was done with MKB Fastigheter. In both cities, the amount of parking and p-norms were verified with online resources and visual inspection of properties in Google Earth (for those with surface parking). The parking policies in effect, which set the parking numbers for new multi-family development, were adopted in 2011 in Gothenburg and 2010 in Malmö (Göteborgs Stad, 2011; Malmö stad, 2010).

4.2. Survey analysis

We conduct three different statistical models, two on car ownership and one on car use, to see the impact of the selected variables. Car ownership is investigated on two scales: household and property. We run a cumulative logit model based on a k-means clustering analysis for car use, a binomial logit model for car ownership at the household scale, and a multivariable linear regression model for car ownership at the property scale. The selected variables of interest are the p-norm, distance to work (km), distance to city center (km), distance to nearest public transportation (km), household income (monthly, in 1000 SEK), college education (yes/no), household size (children included), age and active car share use (yes/no).

The respective models are given in Equations (1)–(3). Active car share use was derived from two different questions in the survey, one asking if the respondent is a member of a car share service and the other asking if the respondent uses car share as a driver or passenger for any type of travel. If both questions are answered positively, then the respondent is assigned as an active car share user. The reason behind specifying active car share users is that a preliminary analysis of the data revealed that almost half of car share service members do not actively use the service. Given also that we don't have good data on how easily accessible car sharing is for the different properties (beyond the requirement that it be available within 500m), active car sharing use can be a proxy for better access to car sharing.

Cumulative logit model on car use **Eq. (1)**

$$\text{logit}\ [\ P\ (Y \geq k)\ ] = \alpha_k + \beta_1\ (\text{ActiveCarShare})_i + \beta_2\ (\text{PNorm})_i + \beta_3\ (\text{HHPop})_i + \beta_4\ (\text{CollegeEdu})_i + \beta_5\ (\text{HHIncome})_i + \beta_6\ (\text{DistWork})_i + \beta_7\ (\text{DistCity})_i + \beta_8\ (\text{DistPT})_i + \beta_9\ (\text{Age})_i$$

where:

- $Y = 1, 2, 3$. Y is the ordinal car use variable: 1 (low), 2 (medium) and 3 (high).
- $k = 2, 3$. k is the cut-point between adjacent ordinal categories. In three ordered categories, there are only two cut-points.
- α_k = category-specific thresholds/intercepts (cut-points) for each cumulative logit.
- $\beta_1, \ldots, \beta_9$ are slope coefficients
- ActiveCarShare = active car share use (yes/no), PNorm = P_norm of property (0 to 1), HHPop = household population (children included), CollegeEdu = college educated (yes/no), HHIncome = household income (monthly, in 1000 SEK), DistWork = distance to work (km), DistCity = distance to city center (km), DistPT = distance to nearest public transportation (km)

Binomial logit model on car ownership at the household scale **Eq. (2)**

$$\text{logit}\ [\ P\ (Y_i = 1)\ ] = \beta_0 + \beta_1\ (\text{ActiveCarShare})_i + \beta_2\ (\text{PNorm})_i + \beta_3\ (\text{HHPop})_i + \beta_4\ (\text{CollegeEdu})_i + \beta_5\ (\text{HHIncome})_i + \beta_6\ (\text{DistWork})_i + \beta_7\ (\text{DistCity})_i + \beta_8\ (\text{DistPT})_i + \beta_9\ (\text{Age})_i$$

where:

- i refers to households
- $Y_i = 1$ if the household owns a car, and 0 otherwise.
- β_0 is intercept term and $\beta_1, \ldots, \beta_9$ are slope coefficients
- •ActiveCarShare = active car share use (yes/no), PNorm = P_norm of property (0 to 1), HHPop = household population (children included), CollegeEdu = college educated (yes/no), HHIncome = household income (monthly, in 1000 SEK), DistWork = distance to work (km), DistCity = distance to city center (km), DistPT = distance to nearest public transportation (km)

Multivariable linear regression model on car ownership at the property scale **Eq. (3)**

$Y_j = \beta_0 + \beta_1$ (ActiveCarShare)$_j$ + β_2 (PNorm)$_j$ + β_3 (AvgHHPop)$_j$ + β_4 (CollegeEdu)$_j$ + β_5 (AvgHHIncome)$_j$ + β_6 (DistCity)$_j$ + β_7 (DistPT)$_j$ + β_8 (AvgAge)$_j$ + ε_j

where:

- j refers to properties
- Y = number of cars per person at the property or number of cars per household at the property
- β_0 is intercept term and β_1, …, β_8 are slope coefficients
- ε_j is the error term
- ActiveCarShare = % of households with active car share use, PNorm = P_norm of property (0 to 1), AvgHHPop = Average household population (children included), CollegeEdu = % of households with college educated respondent, AvgHHIncome = average household income (monthly in 1000 SEK), DistCity = Distance to city center (km), DistPT = distance to nearest public transportation (km), AvgAge = average age of respondents

In our analysis, we draw on multiple questions from the survey instrument. Variables on socio-demographic characteristics are used, including age of respondent, household income, total household size, and education levels. We combine this with questions on car ownership, membership in car sharing, and car use. Car ownership included both a yes/no question and a question on how many cars the respondent's household owned. Based on this, we also calculate cars per 1000 residents, based on cars owned and household size. For car sharing, we look at membership and well as frequency of car sharing usage. For car use, we develop a composite variable that combines two survey questions.

The analysis on car use is based on two questions from the survey: (1) time spent in a car (minutes/week) and (2) driving frequency. The driving frequency, on the other hand, asks the respondent how often in the last 12 months they have driven a car. The replies consist of seven levels: never, any time in the last 12 months, 6 months, 3 months, one month, one week, or several times a week. A preliminary analysis showed that the two variables did not match one to one on car use due to the different characteristics of the questions asked. Therefore, we use a k-means clustering algorithm to create a single car use estimate based on the two questions. K-means clustering analysis is based on two variables: *time spent in a car* and *driving frequency*. To find the optimal number of clusters, we use the traditional elbow, silhouette, and gap statistic methods. Users without a driving license were filtered out. Driving frequency, which is an ordinal and categorical variable, was converted to a discrete numerical variable with weights. Clustering was done on the mixed group (entire dataset) and separately for users in Gothenburg and Malmö. Clustering analysis results in assigning a cluster to each observation that ranges from low car use to high car use, creating a ranked single variable for car use for each observation. This car use variable was then used as the dependent variable in a cumulative logit model where we tested the impact of other variables of interest on car use.

In our analysis, we also include variables related to accessibility. Specifically, we include the distance to the city centers of Gothenburg and Malmö from each property and the distance to the closest public transport stop. From the survey, we also use the reported distance to work variable. Each of these three factors has been shown to contribute to higher or lower levels of car ownership and use, making them important to include in the analysis.

The household scale car ownership is based on a yes/no survey question on car ownership; hence the dependent variable is dichotomous, leading to a binomial logistic regression model. Additional filtering of users with driving licenses was performed for the analysis on car ownership at the household scale. The model was then run on the mixed group (entire dataset) and also separately for Gothenburg and Malmö.

Property-scale car ownership is based on property averages regarding cars per person and cars per household. A multivariable linear regression model was used for analysis. Unlike the analysis on the household-scale, the data was not filtered for users with driving licenses. The variable *distance to work* was removed from the independent variables due to high collinearity with *distance to city center* and *distance to transit*. The model was run only on the mixed group (entire dataset) and not separately for Gothenburg and Malmö due to the limited number of observations (properties).

5. Results

In this section, we present the results of multiple analyses. First, we present an overview of how mobility patterns and car ownership vary between the 24 properties and between car sharing members and non-members. We then show results for regression models on car ownership for both the household and property scale, followed by the regression results for car use. A summary of demographic and built environment characteristics by residential property is shown in Table 2.

5.1. Car ownership

In the survey responses for both Gothenburg and Malmö, the rates of car ownership are, on average, lower than in each city as a whole (Table 3). In Gothenburg, survey respondents have 0.27 cars per person compared to 0.33 for the entire city. In Malmö, survey respondents have 0.22 cars per person compared to 0.35 cars per person in the city. With this, we see that the impact of measures to reduce car use is likely effective, with a larger impact on the surveyed properties in Malmö compared to Gothenburg. The use of rental properties in Malmö versus owner-occupied apartments in Gothenburg is one possible factor for this difference. Household incomes are lower among Malmö respondents compared to Gothenburg respondents, with a 10,000 SEK difference between the two groups (43,300 SEK versus 53,900 SEK, respectively), which may also explain different levels of car ownership between the two cities in the surveyed properties.

When analyzing car ownership among survey respondents who are car sharing members versus non-members, we see rather large differences, shown in Table 4. For all respondents, the car ownership of those without car sharing memberships is about double that of members. This difference is much larger in Gothenburg, where car ownership among car sharing members is 70% less than that of non-members, compared to Malmö, where it is only 30% less.

Further analysis of car ownership shows a positive association between p-norms and the average number of cars per person, where we see an r^2 of 0.238. The same relationship exists between the average number of cars per household and the p-norm for each property, with an r^2 of 0.253, shown in Fig. 1. Cars per person and per household increases with the minimum parking requirement, as shown in Table 3. Additionally, we see that for lower p-norm ranges (0-0.6), car ownership per household closely matches the average parking number for those properties. However, in properties in zones with higher minimum parking requirement, there is a greater mismatch between the p-norm and household car ownership. In the properties with the highest average p-norm of 0.93, the household car ownership is only 0.67. This indicates that in these properties, the p-norms are too high and are resulting in a surplus of parking being built. This difference is particularly strong in Malmö where the average p-norm across all properties is 0.62 and the average household car ownership is 0.42. This is compared to Gothenburg, where the average p-norm for the surveyed properties is 0.52 and car ownership is 0.56. In Gothenburg we also see in Fig. 1 that nearly all the properties have higher car ownership than the p-norm.

5.2. Car use and mobility patterns

Turning to how car use and mobility patterns vary between the properties, a summary of time spent traveling between driving, walking, biking and public transport use is shown in Table 5. Average modal

Table 2
Demographic and built environment summary statistics by residential project, by city, and by p-norm range.

City	Property	Responses (n)		Demographic characteristics				Built Environment		
				Age	Household size	Household income (SEK)	College degree (%)	Distance to city center (km)	Distance to work (km)	Distance to public transportation (m)
Gothenburg	BRF Byabacken	28		53	2.4	57,273	57%	5.5	11.4	500
Gothenburg	Kroksättsfabriker	9		36	3.0	75,714	100%	5.5	10.4	450
Gothenburg	Kronhusgatan	34		28	1.4	30,038	94%	0.3	3.9	300
Gothenburg	Kvarteret Venus	62		41	2.1	63,867	71%	1.9	9.5	500
Gothenburg	Kvillebäcken	28		44	2.1	55,522	64%	3.0	14.0	425
Gothenburg	Studio 256	59		31	1.6	55,109	76%	4.1	29.0	170
Gothenburg	Trekantsgatan	27		55	2.0	42,838	52%	5.1	34.8	200
Malmö	Borrsnäckan	11		46	2.1	39,500	64%	6.5	21.0	300
Malmö	Föraren	7		36	2.3	53,571	86%	1.9	16.0	280
Malmö	Greenhouse	15		41	3.2	51,146	87%	3.5	8.1	300
Malmö	Halvslaget	14		28	2.0	47,511	71%	6.4	14.2	300
Malmö	Holmen	1		57	3.0	48,000	100%	1.3	5.0	120
Malmö	Koggen	13		39	2.5	54,455	85%	2.0	7.4	140
Malmö	Kronborg	22		49	1.8	31,507	73%	2.1	7.3	350
Malmö	Kv Gjuteriet	20		39	2.9	49,832	55%	4.8	12.7	350
Malmö	Kv Sofia	30		42	2.2	56,685	73%	1.2	19.3	170
Malmö	Munin	5		30	2.2	50,833	100%	5.8	17.6	300
Malmö	Pedalvagnen	10		40	1.8	34,700	70%	1.8	5.5	350
Malmö	Rapsbaggen	5		46	3.6	37,940	60%	8.4	16.0	200
Malmö	Rönnen	7		46	1.0	28,167	71%	2.4	5.2	70
Malmö	Sjöporten	13		27	1.8	33,960	100%	2.0	7.6	350
Malmö	Städet	3		59	1.7	44,833	67%	8.4	46.0	450
Malmö	Stämpen	15		24	1.0	15,893	60%	1.8	4.8	170
Malmö	Stora Högesten	16		38	2.9	49,646	56%	6.3	16.5	150
Gothenburg		247	Pooled avg.	40	1.9	53,939	70%	3.6	16.2	364
Malmö		207		39	2.2	43,317	73%	3.9	13.5	256
P-norm groups	0.00 to 0.40	129	Pooled avg.	40	2.3	46,427	81%	3.7	16.5	240
	0.41 to 0.60	173		40	1.9	46,765	73%	2.6	10.1	305
	0.61 to 0.80	128		39	2.2	46,275	74%	3.6	11.9	315
	0.81 to 1.00	24		48	2.7	44,140	61%	7.7	26.2	267
Total		454	Pooled avg.	41	2.2	46,189	74%	3.8	14.3	287

share is quite varied across all properties, and we do see slight differences between the two cities. For example, time spent driving is slightly higher in Gothenburg compared to Malmö, which makes sense given that Gothenburg is a larger city (by population and area). Cycling differs significantly, with respondents in Malmö cycling almost 2.5x more. This is compensated for when looking at public transport, where residents in Gothenburg use public transport significantly more than those in Malmö. Minutes spent walking and total travel are quite similar between the two cities. The main difference in cycling and public transport rates is likely explained by the specific locations of the properties, but also the general cyclability of Malmö, being a smaller area and having a flatter topography.

Examining differences in car use and mobility across different p-norms, a clear pattern emerges. Fig. 2 shows that average car use among respondents is higher in properties with higher p-norms (and minimum parking requirements). Car use increases from approximately 10% of time spent traveling in the lower p-norm ranges to over 30% in the highest. Public transport use is similar across all groups, with the exception of 0.6-0.8 p-norm, where it drops, with cycling being a much larger share. Within this p-norm group, a majority of the properties are in Malmö, where across all properties, rates of cycling are much higher than in Gothenburg. With walking, we see it accounting for 50% of all trips across all properties but ranging from 55% in the lower p-norm groups to 35% in the highest p-norm group.

Fig. 3 shows a strong correlation between the number of cars per person and the time spent driving. The higher the number of cars per person across each of the properties, the higher the average time spent driving. As shown in the previous section, since p-norms are associated with more cars per person, we can infer that higher p-norms contribute to higher average rates of car use.

5.3. *Regression on car ownership*

5.3.1. *Property scale*

The regression model results for the property level analysis are given in Table 6. We find that a higher p-norm is associated with a higher number of cars per person and cars per household, with a confidence level of 95%. This shows that, at the property level, a higher p-norm is associated with higher car ownership. Similarly, we find that a higher percentage of households with active car share use is associated with a lower number of cars per person and cars per household, with a confidence level of 99% and 95% respectively. This shows that, at the property level, a higher active car share use correlates with lower car ownership.

Shown in Table 6, we also find that average household income and average age of respondents are positively correlated with cars per person and cars per household at the property level, with a confidence level of 95% to 99%. This shows that higher income and age are associated with higher levels of car ownership, as expected from existing literature on car ownership (Pyddoke and Creutzer, 2014).

To assess the robustness of the property-level regression results, we also estimated more parsimonious models with fewer covariates. Although these simpler models exhibited lower explanatory power (lower R^2), the key predictors—active car sharing use, p_norm, and household income—retained the same sign, similar magnitude, and remained statistically significant. This consistency across reduced specifications indicates that the main associations reported in the full model are stable.

5.3.2. *Household scale*

The results of the binomial logistic model on car ownership are given

Table 3
P-norm, car ownership, and car sharing membership statistics by residential project, by city, and by p-norm range.

City	Property	Responses (n)		Parking	Car Ownership		Car sharing	
				P-norm	Cars per person	Cars per household	Car share members (%)	Active car share (%)
Gothenburg	BRF Byabacken	28		0.80	0.46	1.07	4%	4%
Gothenburg	Kroksättsfabriker	9		0.50	0.45	1.11	22%	22%
Gothenburg	Kronhusgatan	34		0.75	0.08	0.09	15%	15%
Gothenburg	Kvarteret Venus	62		0.50	0.26	0.53	10%	10%
Gothenburg	Kvillebäcken	28		0.45	0.38	0.71	14%	14%
Gothenburg	Studio 256	59		0.32	0.24	0.37	59%	29%
Gothenburg	Trekantsgatan	27		0.34	0.28	0.62	7%	7%
Malmö	Borrsnäckan	11		0.70	0.45	0.73	9%	0%
Malmö	Föraren	7		0.80	0.12	0.29	57%	29%
Malmö	Greenhouse	15		0.30	0.04	0.13	53%	33%
Malmö	Halvslaget	14		0.40	0.13	0.29	57%	7%
Malmö	Holmen	1		0.00	0.00	0.00	0%	0%
Malmö	Koggen	13		0.80	0.32	0.54	38%	23%
Malmö	Kronborg	22		0.42	0.14	0.32	9%	0%
Malmö	Kv Gjuteriet	20		0.80	0.24	0.60	50%	20%
Malmö	Kv Sofia	30		0.60	0.20	0.37	53%	37%
Malmö	Munin	5		0.65	0.30	0.60	40%	20%
Malmö	Pedalvagnen	10		0.80	0.38	0.50	40%	20%
Malmö	Rapsbaggen	5		0.90	0.07	0.20	0%	0%
Malmö	Rönnen	7		0.50	0.14	0.14	43%	14%
Malmö	Sjöporten	13		0.50	0.12	0.15	62%	15%
Malmö	Städet	3		0.90	0.83	1.33	67%	0%
Malmö	Stämpen	15		0.50	0.07	0.07	20%	13%
Malmö	Stora Högesten	16		1.00	0.42	1.06	38%	19%
Gothenburg		247	Pooled avg.	0.52	0.27	0.54	19%	14%
Malmö		207		0.62	0.22	0.42	37%	15%
P-norm groups	0.00 to 0.40	129	Pooled avg.	0.29	0.13	0.28	40%	15%
	0.41 to 0.60	173		0.50	0.23	0.49	24%	16%
	0.61 to 0.80	128		0.76	0.29	0.46	32%	16%
	0.81 to 1.00	24		0.93	0.44	0.67	35%	6%
Total		454	Pooled avg.	0.58	0.25	0.49	32%	15%

Table 4
Cars per 1000 people for car sharing members and non-members in Gothenburg and Malmö.

	Total survey	Gothenburg	Malmö
Member	142	94	174
Non-member	294	325	246

in Table 7. We find that active car share use is negatively associated with car ownership in the mixed group (Gothenburg & Malmö) and in Gothenburg, with a confidence level of 99.9%. The odds of car ownership are 5 times lower (1 to exp(-1.589)) for active car share users in Gothenburg and Malmö combined. For Gothenburg alone, the odds of car ownership are 75 times lower (1 to exp(-4.329)) for active car share users.

In the Gothenburg sample, only 6% of active car share users owned a

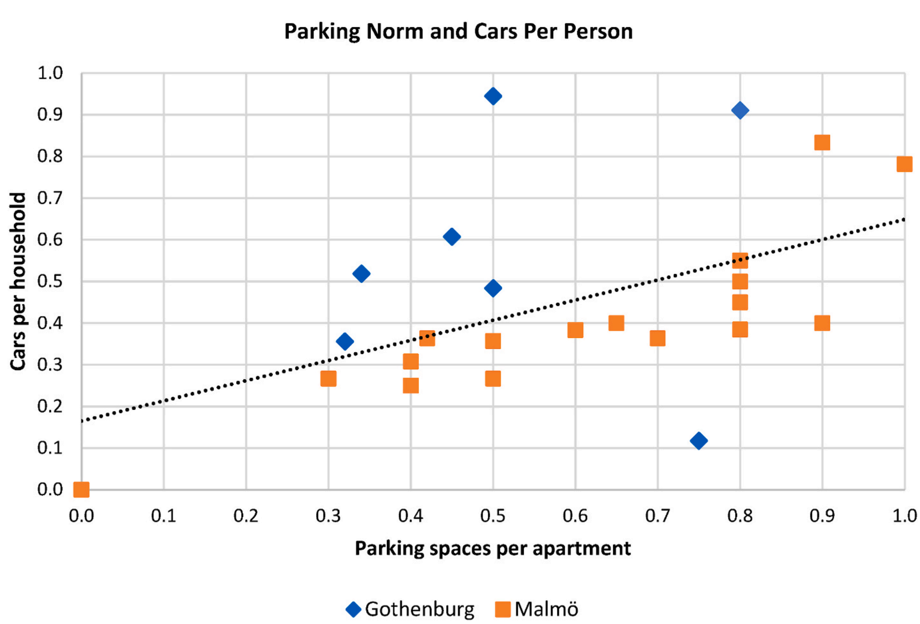

Fig. 1. Parking spaces per apartment versus cars per household across property averages with a combined linear trendline.

Table 5
Travel mode in minutes per week per mode by residential project, by city, and by p-norm range.

City	Property	Responses (n)		Minutes per week by each mode				Total travel time
				Drive	Walk	Bike	Transit	
Gothenburg	BRF Byabacken	28		116	216	67	140	538
Gothenburg	Krokslättsfabriker	9		113	297	47	197	654
Gothenburg	Kronhusgatan	34		21	242	62	110	435
Gothenburg	Kvarteret Venus	62		82	284	28	149	543
Gothenburg	Kvillebäcken	28		83	331	41	214	669
Gothenburg	Studio 256	59		120	213	38	219	590
Gothenburg	Trekantsgatan	27		114	294	69	218	695
Malmö	Borrsnäckan	11		210	344	222	80	856
Malmö	Föraren	7		18	219	145	40	421
Malmö	Greenhouse	15		42	222	181	41	487
Malmö	Halvslaget	14		59	227	17	43	346
Malmö	Holmen	1		0	600	0	80	680
Malmö	Koggen	13		71	316	105	111	603
Malmö	Kronborg	22		31	479	138	128	777
Malmö	Kv Gjuteriet	20		83	169	153	53	458
Malmö	Kv Sofia	30		90	312	86	67	554
Malmö	Munin	5		93	206	100	10	410
Malmö	Pedalvagnen	10		105	158	156	45	464
Malmö	Rapsbaggen	5		36	264	54	250	604
Malmö	Rönnen	7		25	411	177	42	655
Malmö	Sjöporten	13		51	258	191	124	624
Malmö	Stàdet	3		316	153	0	2	471
Malmö	Stämpen	15		32	308	47	113	500
Malmö	Stora Högesten	16		158	104	124	86	472
Gothenburg		247	Pooled avg.	91	261	46	176	574
Malmö		207		79	274	122	80	555
P-norm groups	0.00 to 0.40	129	Pooled avg.	64	303	83	121	570
	0.41 to 0.60	173		65	346	81	130	622
	0.61 to 0.80	128		90	234	126	74	523
	0.81 to 1.00	24		170	174	59	112	516
Total		454	Pooled avg.	86	276	94	107	563

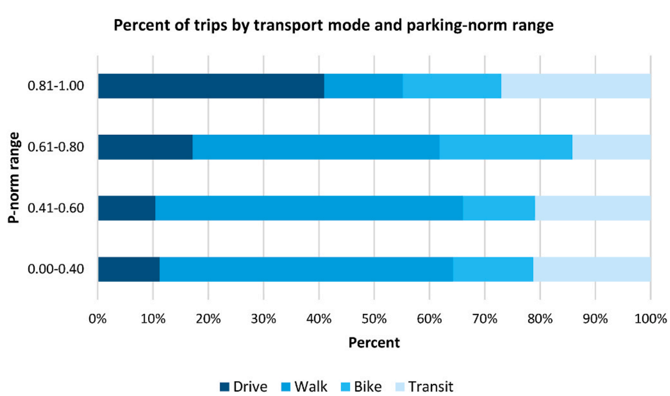

Fig. 2. Percent of trips by driving, walking, biking, and public transport for different p-norm ranges.

car, resulting in sparse data in one contingency cell. A Firth-penalized logistic regression produced a somewhat smaller coefficient for active car share use ($\beta = -3.75$ vs. -4.33), demonstrating that the original estimate was partly inflated by quasi-complete separation. However, the effect remained large and highly significant after adjustment (see Appendix 2).

In Table 7, we also find that household income is positively correlated with car ownership in the mixed group and in Gothenburg, with a confidence level of 99%. A 10,000 SEK increase in household income increases the odds of car ownership by 19% (1 to exp(10*0.017)) in Gothenburg and Malmo combined, and 48% (1 to exp(10*0.039)) in Gothenburg.

5.4. *Regression on car use*

In this analysis we combine two car use variables included in the survey: *car driving frequency* and *time spent in a car*. Taken together, these variables expand on the way in which people use cars by considering both total time spent driving and how often they drive. This helps us better understand differences between households that drive many short trips versus few long trips, for example.

To identify patterns between these two variables, we use a k-means clustering analysis to identify groups. The k-means clustering analysis is based on the variables *time spent in a car* and *car driving frequency* suggests the optimal number of clusters to be three, both for users in Gothenburg and Malmö combined, and also for users separately in Gothenburg and Malmö. In few instances, the elbow, silhouette and gap statistic methods also suggest alternative number of clusters (four and above), however tested in the cumulative logit model, cluster differences are found to be statistically insignificant for increasing the number of clusters. For more on the optimal number of clusters, see Section 5.5 and Appendix 1.

Clustering of survey respondents in Gothenburg and Malmö (combined) are shown in Fig. 4. Based on the geometric central point of each cluster, we observe that both the *car driving frequency* and *the time spent in a car* increase, going from cluster A to C. Car use is interpreted as being low in cluster A, medium in cluster B, and high in cluster C. The elliptical outlines around each cluster are provided solely for visualization purposes, representing the approximate spatial extent of the cluster. These ellipses are constructed using the cluster's centroid and its most distant point. It is important to note that each survey respondent belongs to exactly one cluster (indicated by color in Fig. 4). Any overlap between ellipses simply reflects the visualization method and the proximity of clusters.

In Fig. 4 and Table 8, we observe that car ownership increases with

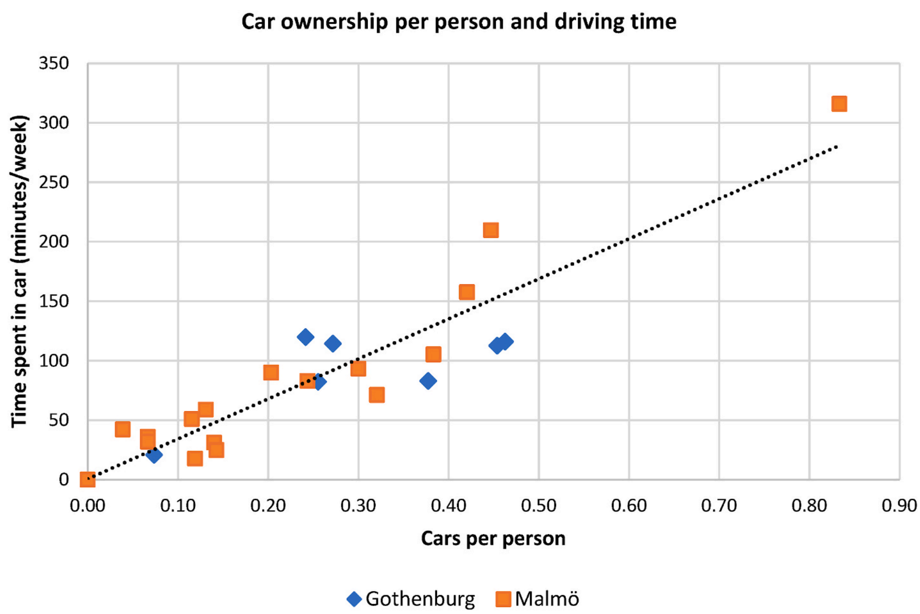

Fig. 3. Cars per person versus car use in time spent in a car with combined linear trendlines.

Table 6
Property level multivariable linear regression on cars per person and cars per household. Gothenburg and Malmö combined. Shown are coefficient estimates with standard errors in parentheses.

Dependent variable	Cars per person			Cars per household		
Intercept	−0.638	(0.251)	*	−1.075	(0.469)	*
% of HHS with active car share use	−0.196	(0.047)	***	−0.255	(0.088)	*
P_norm of property (0 to 1)	0.307	(0.117)	*	0.569	(0.219)	*
Average HH population (children included)	0.203	(0.188)		0.083	(0.351)	
% of HHs with college educated respondent	0.005	(0.003)	.	0.014	(0.005)	*
Average HH income (monthly, in 1000 SEK)	0.011	(0.003)	**	0.014	(0.006)	*
Distance to city center (km)	0.356	(0.225)		0.629	(0.421)	
Distance to nearest public transportation (km)	0.320	(0.327)		0.248	(0.612)	
Average age of respondents	0.046	(0.013)	**	0.076	(0.024)	**
Multiple R-squared	0.794			0.809		
Adjusted R-squared	0.685			0.708		
F-statistic	7.24 (p-value<0.001)			7.96 (p-value<0.001)		
N	24			24		
Variance inflation factors (VIF) for all variables	<2.9			<2.9		
Confidence levels: *** %99.9, **% 99, *%95, .%90						

higher car use, going from 41% car ownership on average for the low car use cluster (Group A), to 67% for the medium car use cluster (Group B), to 73% for the high car use cluster (Group C). Similarly, but inversely, car sharing use for any purpose goes down with increasing car use, going from 25% for the low car use cluster, to 14% for the medium car use cluster, to 7% for the high car use cluster. We thus find three distinct groups with varying combinations of car use, vehicle ownership, and car sharing. Group A, being more "car sharers," has the lowest and most infrequent car use. Group B is a more mixed user (even if car ownership is relatively high here as well), and Group C, where private car ownership is dominant, as well as the most car use. This allows us to better understand how various factors influence car use.

The results of the cumulative logit model on car use are given in Table 9. We observe that active car share use is negatively associated with the level of car use, with a confidence level of 95% in Gothenburg and Malmö combined, and with a confidence level of 90% in Gothenburg. The odds of higher car use (interpreted as going one level up in car use, e.g., from low car use to medium car use) are 3 times lower (1 to exp (-1.065)) for active car share users in Gothenburg and Malmö combined. Similarly, the odds of higher car use are 4 times lower (1 to exp(-1.322)) for active car share users in Gothenburg.

In Table 9, we also find that distance to work is positively associated with the level of car use, with a confidence level of 99.9% in Gothenburg and Malmö combined, and with a confidence level of 99% in Gothenburg. A kilometer increase in distance to work increases the odds of higher car use by 3% (1 to exp(0.026)) for both users in Gothenburg and Malmö combined, and also for users in Gothenburg. Similarly, distance to the city center is also positively associated with the level of car use, with a confidence level of 99% in Gothenburg and Malmö combined, and with a confidence level of 95% in Gothenburg. A kilometer increase to the city center increases the odds of higher car use by 25% (1 to exp (0.221)) in Gothenburg and Malmö combined, and by 36% (1 to exp (0.307)) only in Gothenburg. We observe that distance to city center has a larger impact on car use than distance to work.

These results indicate that while built-environment variables such as distance to work and distance to city center remain strong predictors of car use intensity, active car sharing use is associated with lower car use. These findings show that reduced parking requirements and car sharing availability are associated with changes in mobility patterns: by lowering car use through access to shared mobility, and indirectly by being associated with decreased car ownership in response to reduced p-norms.

5.5. Sensitivity analysis

The independent variables used in the regression models were chosen from a pool of available variables based on the survey data. The variables are first narrowed down based on research interests (probable impact on the dependent variable based on previous literature) and then follow a rule of better model fit that increases the explanatory power of the model. For the multivariable linear regression models, that corresponds to a higher adjusted R-squared value; for the binomial logit models, a lower AIC value; and for the cumulative logit model, a lower

Table 7
Binomial logistic regression on car ownership. Shown are coefficient estimates with standard errors in parenthesis.

Dependent variable	Car ownership (yes/no)							
	Gothenburg & Malmo			Gothenburg			Malmo	
Intercept	−1.432	(0.768)	.	−6.007	(1.664)	***	−0.323	(1.190)
Active car share use (yes/no)	−1.589	(0.377)	***	−4.329	(1.003)	***	−0.487	(0.477)
P_norm (0 to 1)	0.539	(0.728)		2.737	(2.002)		1.610	(1.157)
Household population (children included)	−0.014	(0.128)		0.889	(0.348)	*	−0.326	(0.191)
College educated (yes/no)	−0.506	(0.361)		−0.764	(0.676)		−0.176	(0.520)
Household income (monthly, in 1000 SEK)	0.017	(0.006)	**	0.039	(0.013)	**	−0.001	(0.010)
Distance to work (km)	0.013	(0.007)	.	0.036	(0.019)	.	0.003	(0.011)
Distance to city center (km)	0.041	(0.074)		0.288	(0.172)	.	−0.079	(0.108)
Distance to nearest public transportation (km)	0.974	(1.053)		−0.557	(2.264)		3.005	(2.230)
Age	0.009	(0.012)		0.022	(0.025)		−0.007	(0.016)
AIC	342.7			126.7			176.9	
N	270			150			120	
Variance inflation factors (VIF) for all variables	<1.3			<1.9			<1.6	
Confidence levels: *** %99.9, **%99, *%95, .%90								

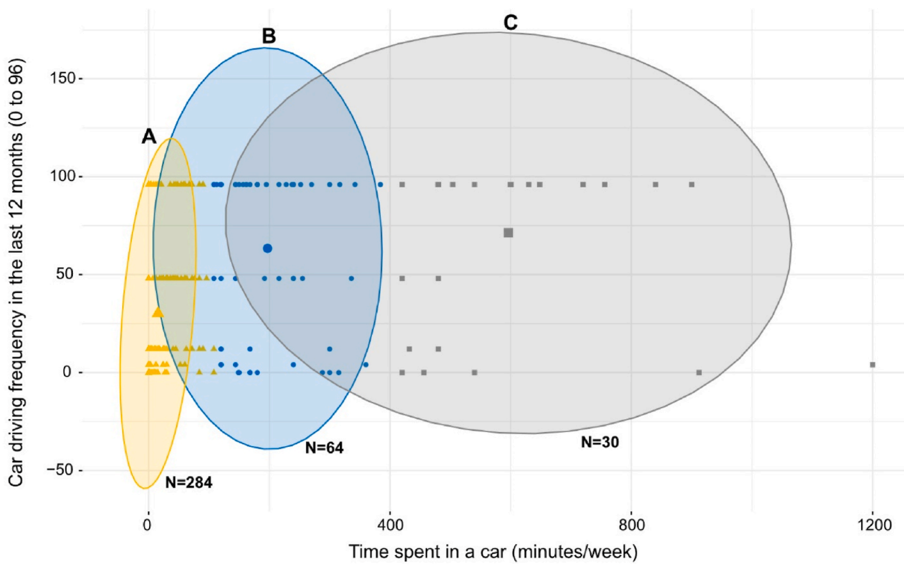

Fig. 4. Clustering of car use in Gothenburg and Malmö, filtered by survey respondents with a driving license.

Table 8
Car ownership and car sharing use among car driving frequency clusters.

	Clusters (from Fig. 4)		
	A	B	C
Car ownership	41%	67%	73%
Car sharing use (any)	25%	14%	7%
P_norm (mean)	0.54	0.63	0.51

Brier score. Each model has also been checked for multicollinearity. For the multivariable linear regression models on the property level car ownership, the variable *distance to work* was taken out due to high collinearity with *distance to city center* and *distance to nearest public transportation*.

The k-means clustering analysis uses *driving frequency in the last* 12 months as one of the base variables. This variable is an ordinal and categorical variable, the respondents could choose one of 7 levels: never, anytime in the last 12 months, 6 months, 3 months, one month, one week, or several times a week. We tested this variable using different assumptions for the clustering analysis and ran a sensitivity analysis on its impact on the cumulative logit model. The first assumption is that the driving frequency can be converted to a direct discrete numerical variable, as in 1 (lowest) to 7 (highest). The second assumption is that the driving frequency can be converted to a discrete numerical variable with weights based on the interpretation that original response choices follow a straightforward difference between each ordinal level, e.g. there is a factor of 2 between *anytime in the last* 12 months and *anytime in the last* 6 months. Additionally, a factor of 2 was assigned for the difference between *anytime in the last week* and *several times in a week*. Thus, the driving frequency was converted to the number of occurrences in a year, that is from 0 (never) to 96 (several times in a week). The clustering analysis using both assumptions resulted in consistently finding the same optimal number of clusters for a majority of the used traditional methods (elbow, silhouette and gap statistic), for both the mixed group and subsets of users only in Gothenburg and only in Malmo. This highlights the robustness of the clustering analysis in finding the number of clusters. An alternative number of clusters suggested by a minority of the traditional methods – e.g. six clusters in Gothenburg based on the gap statistic method under assumption 2 – was tested in a cumulative logit model. This resulted in the finding that while the coefficient estimates and the significance of the variables did not change to a large extent, the cluster differences became statistically insignificant in the logit model. A further comparative analysis of the cumulative logit model with 3+ clusters – for the mixed group, and Gothenburg and Malmö separately – showed that increasing the number of clusters beyond three results in statistically indifferent clusters. Hence, in the

Table 9
Cumulative (ordinal) logit model on car use, showing coefficient estimates with standard errors in parenthesis.

Dependent variable	Car use cluster (low, medium, high)								
	Gothenburg & Malmo			Gothenburg			Malmo		
$y \geq 2$	−3.624	(0.865)	***	−3.066	(1.120)	**	−3.741	(1.534)	*
$y \geq 3$	−5.193	(0.910)	***	−4.482	(1.172)	***	−5.348	(1.584)	***
Active car share use (yes/no)	−1.065	(0.475)	*	−1.322	(0.804)	.	−0.614	(0.591)	
P_norm (0 to 1)	0.926	(0.801)		0.167	(1.680)		1.294	(1.325)	
Household population (children included)	0.191	(0.129)		0.144	(0.257)		0.090	(0.151)	
College educated (yes/no)	−0.526	(0.371)		−0.747	(0.526)		−0.560	(0.575)	
Household income (monthly, in 1000 SEK)	0.003	(0.007)		−0.014	(0.011)		0.020	(0.011)	.
Distance to work (km)	0.026	(0.007)	***	0.030	(0.011)	**	0.016	(0.011)	
Distance to city center (km)	0.221	(0.083	**	0.307	(0.145)	*	0.187	(0.124)	
Distance to nearest public transportation (km)	0.126	(1.195)		0.647	(2.285)		−0.712	(2.852)	
Age	0.024	(0.013)	.	0.038	(0.020)	.	0.014	(0.018)	
Pr (>chi2)	<0.0001			<0.0001			0.009		
Brier score	0.147			0.138			0.146		
N	267			150			117		
Confidence levels: *** %99.9, **%99, *%95, .%90									

Note: $y \geq 2$ corresponds to the cumulative probability of belonging to the medium or high car-use clusters; $y \geq 3$ corresponds to the cumulative probability of belonging to the high car-use cluster.

final cumulative logit models presented in Table 9, the dependent variable *car use* is based on three clusters, and we use the second assumption (driving frequency converted to a discrete numerical variable with weights) for cluster assignment due to better observational interpretability. Please note that the Brier scores under both assumptions are almost identical, meaning that when the optimal number of clusters is chosen as 3, the models behave similarly in assigning the individual observations to clusters.

The clustering analysis presented here uses a subset of data where users without driving licenses are filtered out. However, the analysis was also repeated for the entire raw data as an additional robustness check. We find that the optimal number of clusters given by the traditional methods of elbow, silhouette and the gap statistic does not change. Yet, we observe a buildup of observations where the driving frequency is low and the time spent in a car is scattered along that line, indicating observations that belong to passengers in cars. Since the analysis mainly focuses on car use by drivers, and the clustering analysis is robust, users without driving licenses were filtered out. This results in fewer observations that could potentially belong to passengers in cars.

To evaluate the robustness of the cumulative logit model, we examined the proportional odds (PO) assumption using the Brant Test, which is the standard diagnostic tool for ordinal regression. The global test indicated a violation of the PO assumption ($\chi^2 = 21.11$, $df = 9$, $p = 0.01$), and four predictors (P_norm, household population, college education, and distance to the city center) showed individual violations. Notably, the key predictor in our analysis – active car share use – did not violate the PO assumption. Because the dependent variable is derived from k means clustering and the clusters are highly imbalanced, some degree of PO violation is expected. As a robustness check, we estimated a partial proportional odds (PPO) model, which relaxes the PO constraint only for the violating predictors. Although PPO models are not well suited for our context due to small cluster sizes and interpretability issues, the results confirm the stability of our main findings: all predictors that were significant in the original cumulative logit model remain significant with consistent direction and magnitude. Given the interpretability advantages of the cumulative logit model and common practice in related literature (Harrell, 2020) we retain the original specification. Additionally, all models achieve Brier scores below 0.15, indicating good predictive performance.

6. Discussion

Our results show, through several measures, that the effect of having both reduced parking and access to car sharing is associated with lower car ownership and lower car use. The studied properties have lower car ownership compared to the average car ownership in both cities, with the highest effect in properties with more frequent car sharing users. Higher minimum parking requirements are associated with more cars per person and per household, which has also been shown in an analysis of minimum parking requirements across Swedish municipalities (McAslan and Sprei, 2023). Similar to previous research, we also find that age and income are correlated with higher vehicle ownership (Dargay, 2001; Johansson-Stenman, 2002; Klein and Smart, 2017). Age and income have important implications for car ownership, but our results show that reducing parking requirements can partly contribute to reducing car ownership at any age or income level.

We also find that a majority of properties in our study have lower car ownership than the parking-norm, indicating that the minimum parking requirements could be set too high, even after the reductions allowed for access to car sharing. We do, however, see a difference between the two cities, where the properties in Gothenburg tend to be at or higher than the parking-norm, whereas those in Malmö tend to be much lower. Although no explanation for this emerges from the data, it is likely that in Gothenburg there are more (and likely cheaper) parking options available in nearby areas (e.g., street permit parking or other paid parking lots) that allow more households to park their private vehicles. As previous research shows, it is the overall access to parking that is important for levels of car ownership (Guo, 2013a; Weinberger et al., 2008).

When it comes to car use, we find that the most significant variables are distance to work and distance to city center, with the distance to work having the highest impact. This is in line with findings that travel to work is one of the most common uses for a private vehicle in Sweden, after leisure trips (Smidfelt Rosqvist and Winslott Hiselius, 2019; Strömblad, 2025). Regarding car sharing we find a larger effect for active members compared to only membership. This could partly be explained by the fact that some of the households had car sharing membership included in their rent or housing association fees, and thus, there was not necessarily an active choice on their side.

Our results show little evidence that lower parking-norms lead to lower car use for individuals, however it is associated with lower vehicle ownership. This is despite a clear linear trend between car ownership and car use, also seen in other studies (McAslan and Sprei, 2023). This could be an indication similar to the findings of Stenman (2002) that once an individual owns a car, there is not much difference in driving distance and the largest impact is related to the initial choice of ownership. Another aspect is that p-norms typically increase with distance from city center. There is thus a certain relationship between these, and the effect of p-norms might be captured by the distance to city center variable instead.

We also do not find any effect of distance to public transport stops. However, this variable may not adequately capture the quality of public transport since this will also be dependent on factors such as frequency of service, travel time to destinations, perceived safety, etc. (Abenoza et al., 2017; Vande Walle and Steenberghen, 2006). Factors such as frequency, reliability and travel time have been shown to be more important than the availability or proximity of transit nearby (McAslan, 2019).

6.1. Limitations

The study has a few limitations that may affect the representativeness of our results and their interpretation. First, the survey has limitations in terms of the selection of properties and possible response bias. The survey respondents do not represent a random sample within the population of either city since the properties surveyed were specifically chosen to meet the criteria of having reduced parking requirements and having access to car sharing (either in the building or nearby in the neighborhood). Within each property surveyed, those more likely to be concerned about parking and mobility issues would be more likely to respond to the survey. This possibly skews the results towards those who have cars and have issues with parking or alternatively skews results towards those who do not own cars and use car sharing and other alternatives. These are, however, competing concerns making it likely that the survey results balance out in most properties between those more concerned about car parking and those more concerned about alternative modes.

The other main limitation in the survey concerns residential self-selection among respondents. Since properties with reduced parking and the availability of mobility services often advertise these to potential residents, it is likely that households that already do not own cars are more likely to choose to live in these properties than those with cars. At the same time, in both cities, it is common for properties with reduced parking to charge higher parking fees, and although we do not have data on this, it may also contribute to those with cars opting out of living in such places, since those with cars are more likely to consider the price and availability of parking when making housing decisions. However, in the case of Malmö, this may be less of an issue since all the surveyed properties are rental properties owned by MKB. In Sweden, there is a long housing queue to wait for firsthand rental contracts and many residents will take an apartment when it becomes available and are likely less concerned with parking and alternative mobility options and simply want a firsthand rental contract in a certain location of the city.

These limitations imply that our analysis primarily captures correlations and not causation. The small number of properties restricts degrees of freedom and increases the risk of overfitting in the property-level regressions. A larger property sample might have enabled more rigorous causal inference or the construction of a meaningful control group; however, given that car sharing is widely available across apartment buildings in both cities, such a design would have been difficult to implement. Moreover, several properties have relatively few respondents, which reduces the stability of property-level averages. For this reason, we complemented the property-level regressions with household-level analyses using the full respondent sample. Household-level models provide higher statistical power and show patterns consistent with the property-level results, lending additional robustness to our findings.

6.2. Policy implications

The findings in this paper have important policy implications. With many cities aiming to reduce car use, our results add to a growing evidence base that demonstrates reductions in minimum parking requirements contribute to reductions in car ownership and car use. Further, lowering parking requirements in combination with policies that require or enable the provision of alternative mobility options – in this case car sharing – can be a useful way to reduce both car ownership and car use. The approach used in both Gothenburg and Malmö to allow reduced parking when car sharing is provided is a useful policy approach that combines 'carrot and sticks' into a single policy tool that has been attractive to many property owners in both cities and can easily be implemented alongside other policies used to reduce minimum parking requirements.

A second policy recommendation is for cities to better align reductions in parking requirements across all areas of the city. Our results show that in the majority of the housing areas studied, calculated car ownership is lower than the minimum parking requirement, indicating that even lower parking-norms could be implemented. This is especially true for properties with higher parking-norms which are located farther from the city center. Current policies in many cities emphasize reducing parking in the most accessible areas with good public transport and high accessibility to jobs, shopping and services. Our results indicate that current policies to reduce parking-norms in central areas work well to align parking-norm and car ownership but fail to do so in lower accessibility areas with higher parking-norms. This indicates a greater possibility of reducing parking-norms than previously thought and is even more viable if parking policies are combined with mobility policies to provide options other than private cars.

7. Conclusion

The aim of this paper has been to investigate the effects of both reduced parking requirements in newly built and renovated multi-family housing and the availability and use of car sharing services on car ownership and car use. The focus of the analysis in this paper has been on how the availability of and active use of car sharing and property level parking numbers (e.g., how many parking spaces per apartment) impact car ownership and car use. Our results show that the effects of reductions in minimum parking requirements and access to car sharing are associated with lower rates of car ownership. The properties studied have lower car ownership compared to the average in both cities. We also see the highest effect in properties with a higher proportion of frequent car sharing users. Lastly, we see a clear pattern in car use, where residents in properties with higher levels of parking drive 30% of the time, compared to only 10% in properties with lower p-norms.

This study supports previous research in its findings that reduced parking requirements – which constrain the availability of parking – and the availability of car sharing reduce car ownership and private car use. The paper analyzes both households and aggregated property level data to see how parking and car sharing have an effect at these different scales. Both parking and car sharing have an effect when analyzing the different properties, but only car sharing use has a statistically significant effect when analyzing households, and instead factors such as income and accessibility have a greater impact at the household scale. These findings show that parking has a strong influence on mobility patterns when aggregated to the property, even if it has a lower impact on individual and household mobility patterns.

Future research can further explore these issues to gain even more understanding of the effects of parking on mobility behaviors, which is important as more cities turn to parking as a strategy to meet transportation and climate goals and reduce car dependency. Future research could more systematically investigate parking impacts by comparing properties with reduced parking with properties without reduced parking. There are also opportunities to further explore how parking in combination with alternative mobility options beyond only car sharing can contribute to more sustainable travel behaviors and reduce car use and car ownership.

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CRediT authorship contribution statement

Devon McAslan: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Ahmet Mandev:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Frances Sprei:** Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Appendix 1. Selection of optimal number of clusters

To determine the appropriate number of clusters used in the cumulative logit models, we conducted a two-step assessment. First, we applied the elbow, silhouette, and gap statistic methods to three datasets: (i) the mixed sample (Gothenburg & Malmo combined), (ii) Gothenburg users only, and (iii) Malmo users only. Users without driving licenses were filtered out. The results in Figure A1 indicate that three clusters are the most frequently suggested option (appearing in four of nine cases) while alternative suggestions included four (twice), five (once), eight (once), and nine (once). Notably, the elbow method consistently identified three clusters across all datasets. Second, we evaluated the cumulative probabilities of cluster thresholds (e.g., $y \geq 2$, $y \geq 3$) within cumulative logit models for solutions ranging from three to seven clusters. As shown in Table A1, when more than four clusters were used, several cluster thresholds—particularly $y \geq 2$ for the Gothenburg and Malmo subsets—became statistically insignificant, indicating weak separation between the first cluster and the remaining clusters. Combining these two evaluations, we concluded that a three-cluster solution provides the most robust and interpretable structure for the cumulative logit model.

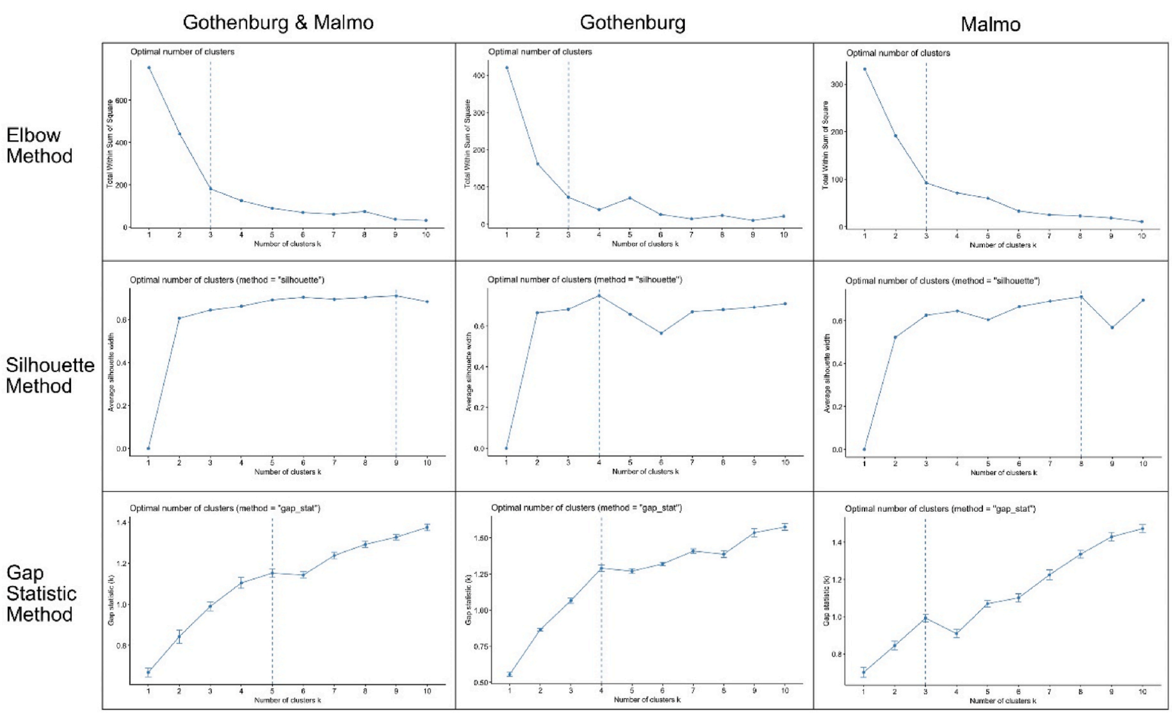

Fig. A1. Elbow, silhouette and gap statistic methods results for estimating the number of clusters

Table A1
Cumulative probabilities of clusters when tested in the cumulative logit model. Bold text reveals insignificance.

Number of clusters	Gothenburg & Malmo						Gothenburg						Malmo					
		Coef	S.E.	Wald Z	Pr(>|Z|)			Coef	S.E.	Wald Z	Pr(>|Z|)			Coef	S.E.	Wald Z	Pr(>|Z|)	
3	y ≥ 2	−3.62	0.87	−4.19	<0.0001	***	y ≥ 2	−3.07	1.12	−2.74	0.0062	**	y ≥ 2	−5.06	1.99	−2.54	0.011	*
	y ≥ 3	−5.19	0.91	−5.71	<0.0001	***	y ≥ 3	−4.48	1.17	−3.82	0.0001	***	y ≥ 3	−8.46	2.29	−3.70	0.0002	***
4	y ≥ 2	−3.86	0.86	−4.46	<0.0001	***	y ≥ 2	−2.76	1.05	−2.63	0.0085	**	y ≥ 2	−4.85	1.54	−3.15	0.0016	**
	y ≥ 3	−5.04	0.90	−5.61	<0.0001	***	y ≥ 3	−4.56	1.11	−4.12	<0.0001	***	y ≥ 3	−6.08	1.59	−3.83	0.0001	***
	y ≥ 4	−6.59	0.96	−6.86	<0.0001	***	y ≥ 4	−5.75	1.16	−4.97	<0.0001	***	y ≥ 4	−9.03	1.90	−4.76	<0.0001	***
5	y ≥ 2	−1.57	0.66	−2.37	0.0176	*	**y>=2**	**−1.27**	**0.93**	**−1.37**	**0.1719**		y ≥ 2	−2.64	1.14	−2.31	0.0209	*
	y ≥ 3	−3.30	0.70	−4.76	<0.0001	***	y ≥ 3	−3.02	0.96	−3.14	0.0017	**	y ≥ 3	−3.84	1.17	−3.28	0.001	***
	y ≥ 4	−4.42	0.73	−6.09	<0.0001	***	y ≥ 4	−4.14	0.99	−4.16	<0.0001	***	y ≥ 4	−5.16	1.21	−4.25	<0.0001	***
	y ≥ 5	−7.00	0.97	−7.20	<0.0001	***	y ≥ 5	−6.87	1.32	−5.22	<0.0001	***	y ≥ 5	−7.73	1.56	−4.97	<0.0001	***
6	y ≥ 2	−2.03	0.66	−3.06	0.0022	**	y ≥ 2	−1.86	0.91	−2.04	0.0411	*	**y>=2**	**−1.32**	**1.04**	**−1.27**	**0.2034**	
	y ≥ 3	−3.34	0.69	−4.85	<0.0001	***	y ≥ 3	−3.35	0.96	−3.50	0.0005	***	y ≥ 3	−2.97	1.07	−2.77	0.0057	**
	y ≥ 4	−4.44	0.72	−6.18	<0.0001	***	y ≥ 4	−4.08	0.98	−4.17	<0.0001	***	y ≥ 4	−3.82	1.10	−3.46	0.0005	***
	y ≥ 5	−5.85	0.78	−7.49	<0.0001	***	y ≥ 5	−4.75	1.00	−4.73	<0.0001	***	y ≥ 5	−4.69	1.14	−4.11	<0.0001	***
	y ≥ 6	−7.51	1.00	−7.47	<0.0001	***	y ≥ 6	−7.47	1.32	−5.65	<0.0001	***	y ≥ 6	−7.02	1.48	−4.73	<0.0001	***
7	y ≥ 2	−1.70	0.65	−2.63	0.0085	**	y ≥ 2	−1.93	0.92	−2.11	0.0351	*	**y>=2**	**−1.33**	**1.03**	**−1.29**	**0.1978**	
	y ≥ 3	−3.09	0.67	−4.60	<0.0001	***	y ≥ 3	−3.41	0.96	−3.55	0.0004	***	y ≥ 3	−2.98	1.07	−2.79	0.0053	**
	y ≥ 4	−3.86	0.69	−5.58	<0.0001	***	y ≥ 4	−4.14	0.98	−4.22	<0.0001	***	y ≥ 4	−3.47	1.09	−3.20	0.0014	**
	y ≥ 5	−4.82	0.72	−6.68	<0.0001	***	y ≥ 5	−4.80	1.00	−4.78	<0.0001	***	y ≥ 5	−3.81	1.10	−3.47	0.0005	***
	y ≥ 6	−5.98	0.78	−7.67	<0.0001	***	y ≥ 6	−5.72	1.05	−5.43	<0.0001	***	y ≥ 6	−4.68	1.14	−4.12	<0.0001	***
	y ≥ 7	−7.53	1.00	−7.55	<0.0001	***	y ≥ 7	−7.77	1.40	−5.55	<0.0001	***	y ≥ 7	−7.00	1.48	−4.73	<0.0001	***
Confidence levels: *** %99.9, **%99, *%95, .%90																		

Appendix 2. Diagnostics for binomial logistic regression on car ownership

To assess whether the large negative coefficient for active car share use in the Gothenburg subsample was influenced by sparse data or quasi-complete separation, we conducted two diagnostic checks: (i) inspection of the contingency table of car ownership versus active car share use, and (ii) estimation of a Firth bias-reduced logistic regression model using the same specification as the main analysis. The contingency table revealed that only ~6% (2 out of 31) of active car share users in the analysis sample owned a car, indicating a highly unbalanced distribution that can lead to instability and inflated coefficient estimates in standard maximum-likelihood logistic regression. The Firth regression results, reported below, confirm that the coefficient for active car share use is reduced in magnitude (from −4.329 to −3.749) when penalized likelihood is applied, consistent with partial quasi-complete separation. Nonetheless, the effect remains large and statistically significant at $p < 0.001$, demonstrating that the relationship between active car share use and car ownership in Gothenburg is robust even after accounting for data sparsity. See Table A2.1 for the contingency table of car ownership vs active car share users, and Table A2.2 for the Firth regressions results.

Table A2.1
Contingency table for car ownership vs active car share use for the binomial logistic model on car ownership for Gothenburg.

Car Ownership	Active car share use	
	Yes	No
Yes	2	67
No	29	52

Table A2.2
Firth bias-reduced logistic regression on car ownership in Gothenburg to test for quasi-complete separation

Dependent variable	Car ownership (yes/no)					
	Coefficient	Std. err.	Lower 0.95	Upper 0.95	p	
Intercept	−5.366	1.475	−8.582	−2.517	<0.001	***
Active car share use (yes/no)	−3.749	0.845	−5.747	−2.204	<0.001	***
P_norm (0 to 1)	2.418	1.798	−1.160	6.221	0.187	
Household population (children included)	0.785	0.310	0.202	1.489	0.007	**
College educated (yes/no)	−0.711	0.609	−2.005	0.508	0.256	
Household income (monthly, in 1000 SEK)	0.036	0.012	0.014	0.062	0.001	**
Distance to work (km)	0.026	0.011	0.004	0.068	0.017	*
Distance to city center (km)	0.255	0.153	−0.051	0.582	0.103	
Distance to nearest public transportation (km)	−0.468	2.073	−4.790	3.651	0.826	
Age	0.020	0.022	−0.024	0.069	0.384	
N	150					
Confidence levels: *** %99.9, **%99, *%95, .%90						

Data availability

The data that has been used is confidential.

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