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Intraurban geographies of car sharing supply and demand in Greater Oslo, Norway

Mari Andrine Hjorteset[a,*], Lars Böcker[b,*], Per Gunnar Røe[a], Terje Wessel[a]

[a] Department of Sociology and Human Geography, University of Oslo, Moltke Moes vei 31, 0851 Oslo, Norway
[b] Institute of Transport Economics (TØI), Gaustadalléen 21, 0349 Oslo, Norway

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ABSTRACT

This paper examines urban patterns of car sharing supply and demand at neighbourhood level. By using literature on spatial inequality and unequal mobility access, we provide new insights into the urban geographies of car sharing. We draw on register data of members and vehicles of station-based car sharing for Oslo, Norway, spatially coupled with population composition, urban form and public transport accessibility ratios. We find both the demand and supply of station-based car sharing to be unevenly distributed. Some of the most profound contributors to car sharing demand include middle income levels, middle and higher levels of education, higher shares of the population working in cultural sectors, higher shares of men, higher shares of multifamily housing, and higher strengths of the public transport regime compared to that of the private car. The paper discusses the implications of these findings for sustainable urban mobility, mobility justice and urban and transport planning.

1. Introduction

In recent years, many cities have seen rapid evolvements of car sharing from a niche concept to an integrated part of transport systems. The adoption of car sharing may also be seen in light of the "return of cities" we have witnessed in recent decades with the deindustrialization of many western cities and a growing service and cultural economy (Rérat, 2019; Glaeser, 2011). The 20th century (Frenken, 2015) was coined "the century of the car" (Dennis and Urry, 2009), with car ownership considered the future of modern transportation and car owners the privileged as opposed to the disadvantaged who travelled by public transport, bicycle or foot. We currently see a shift where urban and transport policies are increasingly reorienting towards compact urban development, and where the use of non-motorised travel, public transport and car sharing to fulfil in incidental car-needs (Frenken, 2015) are gaining in popularity. Car sharing is often conceived as an urban phenomenon (Becker et al., 2017; Stillwater et al., 2009; Celsor and Millard-Ball, 2007; Hjorteset and Böcker, 2020), as higher densities make private automobility more cumbersome, enhance the competitive advantage of alternative transport modes (Newman and Kenworthy, 1999; Næss, 2005; Næss et al., 1995), and strengthen the customer base and service levels for car sharing.

According to Shaheen et al. (2017), car sharing also has the potential to reduce spatial inequalities by providing additional mobility solutions to those otherwise lacking access. To substantiate such claims however, there is an urgent need for empirical evidence on the geographic car sharing adoption differentials, not only between cities and surrounding areas, but especially also *within* cities.

* Corresponding authors.
E-mail addresses: E-mail address: mariahjo@uio.no (M.A. Hjorteset). lars.bocker@toi.no (L. Böcker).

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Moreover, there is a need for theoretical understandings of such patterns with regard to *structural urban and accessibly characteristics and inequalities*. This paper addresses these two overlapping knowledge needs by deploying an urban theory perspective using *spatial capital* – the potentiality of mobility (motility) and relative accessibility by different transport modes – as a lens (see for instance Rérat and Lees, 2011; Rérat, 2018; Revington, 2015) to understand intraurban patterns of car sharing. The overall objective is to examine the geographies of car sharing supply and demand at both city and city region level, and to investigate how the revealed patterns and potential inequalities are explained at the census tract level by urban form, population composition, socio-economic status and the relative strengths of car and public transport regimes. The paper draws on locational register data on the supply and demand of station-based car sharing for Greater Oslo, Norway, spatially coupled with census tract population composition, urban form and public transport-to-car-based job accessibility ratios.

Section 2 discusses relevant car sharing literature and urban theory, particularly with regard to spatial inequality, motility (e.g. Kaufmann et al., 2004), and the re-reading of gentrification literature through the lens of mobility and spatial capital (see for instance Rérat and Lees, 2011; Rérat, 2018; Revington, 2015). Section 3 introduces and discusses the study area, the Geographic Information Systems GIS)-based research design, the calculation of job-accessibility based indicators to measure the relative strengths of public transport and private car regimes, investigations of spatial autocorrelation, and the non-spatial and spatial multivariate statistical modelling techniques. Section 4 presents and discusses our findings. The fifth section provides a short discussion followed by a conclusion (Section 6).

2. Literature review and theoretical framework

Where we live affects the way we travel. Newman and Kenworthy (1989, 1999) were early to point out the clear connection between low-density urban areas and high levels on car dependency on one side (e.g. Los Angeles and Houston), and high-density urban areas and low levels of car dependency on the other (e.g. Hong Kong and Tokyo). Mainstream urban policy and planning has long been attuned to these findings, often resulting in the aim to avoid urban sprawl, promote compact city development (Burton et al., 2003), increase population density, and facilitate for a mix of urban functions. Additionally, many cities promote a more developed public transport system, aiming at lowering the dependency on private vehicles. With the increasing attractiveness and housing prices in former low status districts and housing developments in former industrial and harbour areas (Grubbauer, 2014; Andersen and Røe, 2017), many inner-cities have also experienced demographic and socio-economic shifts resulting from the displacement of working classes and/or the influx of higher socio-economic status groups (e.g. Sassen, 2013; Lees et al., 2013). Despite the clear coevolution of urban and mobility transformations (Sheller and Urry, 2006; Urry, 2007; Urry, 2016), our understanding of how changes in the transport system play into the urban transformation processes and vice versa, remains under-examined and incomplete (Revington, 2015). Nevertheless, important steps in recent theory development have been made towards addressing these gaps.

There is an evolving theorisation of the relationship between urban socio-spatial context and mobility. Although the greening of urban redevelopment might be a central aspect of creating low-emission societies for the future, it is often creating a paradox in relation to increasing social inequalities. It can create financial and social benefits for people, simultaneously as it creates “new and deeper vulnerabilities for some” (Anguelovski et al., 2019). Within transport and mobilities studies there has been increasing attention for issues of justice, most notably in relation to the distributional injustices associated with access to public transport and sustainable mobility (e.g. Banister, 2018; Sheller, 2018). As patterns of more sustainable mobility are emerging in cities, they have been disconnected from issues of transport inequality and mobility justice (Sheller, 2015), which includes the increasing exclusiveness of dense and walkable urban districts with high access to public transport, and where the potential for a sustainable mobility transition is high (Bunce, 2018). This may lead to increasing social and financial inequalities, and concerns about social justice within cities (Fainstein, 2014), as well as between inner city areas and the more peripheral sub- or exurban parts of urban regions (Keil, 2017). With a market-driven housing sector, areas with locational advantages will be reserved for high earning groups, while low paid workers and the urban poor may experience displacement or to be pushed further out to the suburban or exurban periphery, locked into the “old” system of automobility and long commutes (Filion et al., 2019), in many cases on toll roads. Rérat and Lees (2011, p. 126) describes the process of gentrification being sold to us as a sustainable urban form, where both fixity in space and mobility (proximity) are of importance. Inspired by the three forms of capital by Bourdieu (1984), they incorporate the mobile space of opportunity, termed *spatial capital*, thereby adding a fourth and spatially related form of capital (Rérat and Lees, 2011).

Protagonists for dense urban living, often want to reside in close proximity to spaces of importance to satisfy their urban preferences and lifestyles, travel for shorter distances, and do so predominantly by using public transport, walking or cycling. Residing in such urban areas and surrounded by like-minded urban residents further shapes their car-less urban lifestyles (Rérat, 2018, Brown, 2017). As such, socio-spatial contexts are in reflexive and dialectic relationship with travel preferences. The densely populated and centrally located urban areas offers the possibility to travel by foot, bike, and public transport, and hence attract certain people with specific travel preferences. A shift towards sustainable transport preferences affects the demand, market and policies for sustainable modes (including car sharing), and in turn improves the accessibility of these mobility resources.

Based on their study of Swiss urban regions Rérat and Lees (2011) claim that being located on a node in the transport network is a strategic way to access different labour markets and cope with the uncertainty of professional life and with the fact that flexibility has become a job requirement. Such findings underline the comparative advantage of occupying a space in the central city or centralised suburban districts. However, it may be difficult to uncover the precise effect of lifestyle characteristics and socio-cultural factors typical for these urbanites. Danyluk and Ley (2007), who conducted a study of gentrifiers’ mode preference in work journeys in Vancouver and Toronto, argue that gentrifiers buy into the amenity package of inner-city neighbourhoods that greatly promotes walking and cycling and discourage driving. However, it is difficult to separate the independent effects of distance from downtown, population density and the ideology of gentrifiers, which may be associated with culturally and politically motivated lifestyle and mobility choices. Danyluk and Ley (2007) also found that there were variations in choices between different (gentrified) neighbourhoods, based on geographical location and the stage of gentrification. This reveals a complexity in the relationship between gentrification and mobility preferences and choices, signalling that one should be cautious when providing explanations. However, research seems to confirm that people living in gentrified inner-city neighbourhoods are less viable to own or use a private car compared to their counterparts in the suburbs. This is partly caused by their ideological or culturally motivated reaction towards suburban lifestyles and partly because of the accessibility to amenities and public transport, as well as infrastructure for non-motorized mobility (in sum described as spatial capital).

Studies have revealed that most car sharing is taking place in urban and densely populated areas (Shaheen and Cohen, 2007; Shaheen and Cohen, 2013; Shaheen et al., 2017; Becker et al., 2017; Stillwater et al., 2009; Celsor and Millard-Ball, 2007). This is both because the high population numbers in these areas provides a larger customer base for better car sharing services, and because the higher densities lead to stronger public transport regimes, weaker car regimes, and lower car dependency (Newman and Kenworthy, 1999; Næss, 2005; Næss et al., 1995). This opens up for more people to adopt car sharing to cover more sporadic car needs. Even if 'liberation' from motorized transport is described as an asset of urban neighbourhoods (Hjorthol and Bjørnskau, 2005), urban residents may need access to a private car from time to time, and for certain types of trips. Car sharing may then be a viable option, because of its convenience and no need for permanent parking places. Much of the literature on car sharing has been focusing on this urban–rural distinction (Becker et al., 2017; Stillwater et al., 2009; Celsor and Millard-Ball, 2007), with cities as the main variable and study area. In this article our focus is on intra-urban variation in car sharing, and the role that socio-spatial characteristics of neighbourhoods play in its adoption.

Kaufmann et al. (2004) defines 'spatial capital' or 'motility' in conjunction with i) *access*, i.e. the potentiality of mobility a person has or lack thereof, ii) *competence,* i.e. individual skill sets to utilise this potentiality, and iii) *appropriation,* i.e. different mobility strategies, values and practices a person holds. The concept of *access* is especially relevant to this analysis. The *access* of car sharing is both socially and spatially skewed. While much research finds an overweight of young males with higher education and employment among car sharers (Burkhardt and Millard-Ball, 2006; Prieto et al., 2017; Sioui et al., 2012; Morency et al., 2008), Tyndall (2017) finds geographical evidence of this, with car sharing availability being higher in areas with a younger population. In line with others (Firnkorn and Müller, 2011; Sioui et al., 2012), Tyndall (2017) finds no evidence that high income in an area correlates with higher availability of shared cars, but rather middle income levels. Other scholars also find car sharing to attract singles and couples without children more than families with children (Sioui et al., 2012). Celsor and Millard-Ball (2007) also find mobility attributes, such as low vehicle ownership rates and habits of walking to work, to enhance the propensity to use car sharing. Tyndall (2017) have used the availability of vehicles in a free-floating car sharing fleet operating in ten U.S.-cities to analyse inequality of access. His findings suggest first a skewness of access on city level, where affluent cities disproportionally are more prone to have more car sharing. He also finds that shared cars are more frequently available in predominantly white census tracts, with higher education levels and high employment rates. In a study comparing car sharing supply on city-level in five different European countries, Münzel et al. (2020) find car sharing to be more common in cities with higher education levels, and for station-based car sharing, a high level of green votes. Car sharing was found less accessible in areas with high levels of car commutes. Costain et al. (2012) finds that most of the users of a shared vehicle lives within 1000 m of a lot, enhancing mobility only to a segment of the population. When investigating if car sharing can help meet the mobility demand in marginalized neighbourhoods of New York, Kim (2015) finds, in contrast to the above mentioned articles, no differentiation between low-income neighbourhoods and other car sharing areas. Dowling and Kent (2015) explored the way local government supports car sharing in Sydney, in particular the importance of parking restrictions. Car parking space might remain a highly contested necessity in a less car-dependent future.

Additionally, car sharing may be related to what Kaufmann et al. (2004) classifies as *appropriations*. Mobility lifestyle choices are affecting how we conduct our daily travels, and what mobility recourses we decide to own or have access to. For the people living in (gentrified) urban areas, car sharing and/or the choice not to own a car could be considered lifestyle choices (and part of their representation of self), made suitable by the *spatial capital* such areas have to offer in terms of alternatives to the car (Rérat and Lees, 2011). While some are without a car due to financial limitations, others decide that they do not need a car, or that it is not in accordance with their lifestyles. This distinction is defined by Brown (2017) as being *car-less* and *car-free*. There is a spatial differentiation where people living in urban gentrified areas choose not to own a car, while people that cannot afford to own a vehicle often (and more often with the current urban development) need one, due to their living situation, with lower walkability and cyclability. While many of the car-free people are frequently utilizing car sharing, the car-less people are less so (Brown, 2017). The car-free people living in areas with high access, resembles the geographical distinction and the spatial capital of certain gentrified areas. The role of car sharing is interesting also because it combines rational and economic explanations with socio-cultural and life style factors. In their study of gentrifiers of Swiss new-build areas, Rérat and Lees (2011, p. 139) show that their mobility patterns and practices are both "potentially hyper-mobile (they have accrued enough spatial capital to be very mobile) and hyper-fixed (they have strategically chosen particular fixed central city locations where they are locally rooted)". The hyper-mobility may stem from their privileged position both economically and spatially, being able to choose between an array of transport modes and destinations (also long distance because of the connectivity related to international air-travel), guided by cultural and lifestyle choices.

In relation to the last aspect mentioned by Kaufmann et al. (2004), we know that there are *competence* barriers in relation to car sharing practices. To use car sharing, you need to have the competence to drive a car, and you need to have a valid driver's licence. Additionally, you need knowledge and insight into the user interfaces of related apps and platforms. Many potential customers might find it difficult to manoeuvre this landscape of online booking, paying and handling of vehicles, and for others, the actual usage of unknown vehicles might function as a barrier.

This section has pointed to central literature on the connection between travel habits and mobility opportunities on one side, and how this can be explained by spatial attributes of various population compositions and urban form. In this study, we examine transport accessibility by using the case of car sharing, as this is proved in the literature to be unequally spatially distributed between urban and suburban/exurban areas. By implementing this theoretical backdrop, we hope to go beyond the explanations as car sharing being linked only to density and degree of urbanism, describe intraurban variations in car sharing based on traits of the population living there, and their spatial capital. By dividing the analysis into two different geographical levels – both the Oslo region and the municipality, our aim is to make the distinction between explanations of urban form and cultural aspects clearer.

3. Study area, data and methods

3.1. Study area

This study examines the geographic distribution of supply and demand of Norway's most used car sharing scheme "Bilkollektivet" in the Greater Oslo metropolitan area, the capital and largest city region in Norway, ranging from inner-city districts to more suburban, exurban and rural areas in the outskirts of cities and fringes of our study area. This area includes eight municipalities in the core and intermediate parts of the Oslo metropolitan region. We exclude outer parts of the region due to a complete lack of car sharing opportunities in these areas.

The rationale for selecting the Greater Oslo metropolitan region as our area of study is fourfold. First, car sharing has gained a foothold in the Norwegian market, particularly in Oslo. Simultaneously, initial preliminary empirical observations reveal great differences in its geographic diffusion, which raises questions of how car sharing is spatially distributed both in the Greater Oslo region, and within the municipality borders, and which urban factors underlie these distributions. Second, the Oslo region has ambitious goals in reducing CO_2-emmisions, with a special focus on the transport sector. Both Oslo and the surrounding county of Viken are facing rapid population and travel demand growth, and are actively targeting a shift away from private car ownership and use, through road tolls, taxations, parking fees, the reallocation of car road space to bicycle and pedestrian purposes, and compact city developments, particularly around public transport hubs. Whilst parking for private vehicles has been increasingly restricted, designated parking spaces for car sharing have been expanded, increasing the overall supply and proximity of the car sharing network, enhancing its user

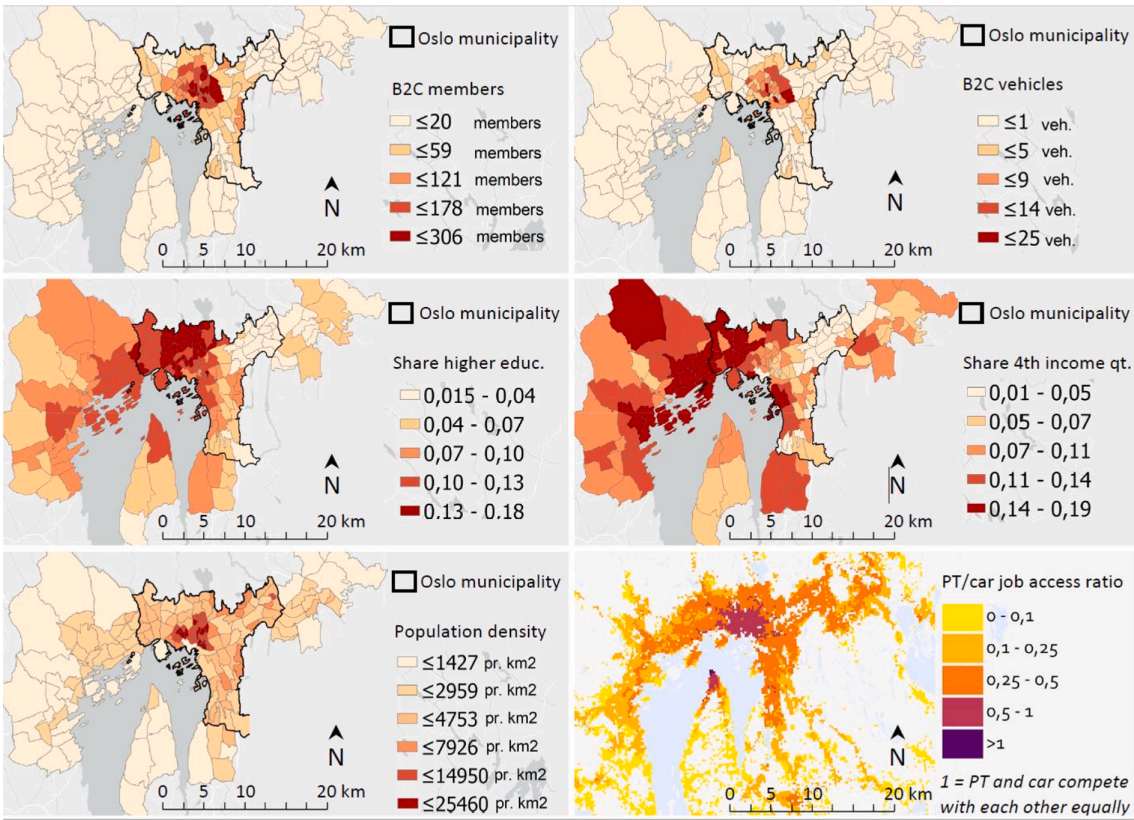

Fig. 1. Map of study area with density of members and vehicles, share higher education and income, population density indicator and public transport job accessibility ratio.

friendliness and new user adoption potential. Third, the region is characterised by strong internal differences in the relative strengths of car and alternative mobility regimes, coinciding with strong historical urban-suburban-rural divides. The private vehicle came late into the public domain in Norway (a rationed good until 1960), but has since then had an enormous impact on spatial planning and development. The private vehicle was considered the desired system, in line with the individualized and modern society of that time. Even though the majority of our study area is of relatively high population density, the divides are still large when it comes to car ownership, car dependency, car usage and qualities of alternative transport systems. While the central municipality, Oslo, has a low car dependency, the opposite situation prevails in the surrounding hinterland (Hjorthol et al., 2014). Fourth, there are large differences in living conditions within the study area. These differences go far back in time, and sum up to a divide between west, the affluent part of the city, and east, the more deprived part of the city (Wessel, 2000). In recent years, we have also been witnessing gentrification in the inner east. At least *one* study emphasizes that this shift from lower to higher status has a marked cultural nature (Hjorthol and Bjørnskau, 2005).

3.2. Data

We employ data from several sources, all aggregated at the census tract level, and all relating to the year 2018. The first source covers activities within a station-based, business-to-consumer (B2C) car sharing scheme. For more information on various ways to organise car sharing, see Shaheen et al. (2019). This organisation, *Bilkollektivet*, includes 296 vehicles and 6881 members, who are served from 136 stations in the study area. The second source is a collection of demographic and socio-economic indicators that derive from public registers under the control of Statistics Norway, the Norwegian Directorate of Taxes and other Norwegian authorities. Norwegian census tracts are constructed on the basis of physical, demographic and socio-economic features. The current study includes 1318 census tracts with an average area of 0,579 km^2 (SD: 1.87), an average population size of 735 (SD = 621.0) and an average density of 59.1 inh./ha (SD = 73.3) per census tract. Census tracts are constructed on the basis of physical, demographic and socio-economic features.

3.3. Variables

As basis for the analysis, we run two separate models, each with two dependent variables, where the first is number of shared cars stationed in each census tract, and the second, number of registered members in each tract. We consider these two variables to capture car sharing supply and demand. The two dependent variables are naturally affecting each other, as the two reinforce some feedback mechanism onto each other. The supply of car sharing makes access easier, which could lead to a higher demand, and higher demand provides the initiative for platforms to increase supply. We have run a sensitivity analysis to test their interdependence directly, by including car sharing supply as a predictor in a car sharing demand model. The effect of supply had a positive effect on demand, but including or excluding it did not change anything to the directions and significance levels of others predictors in the model. We have ultimately decided against including supply from the demand model to limit the list of predictors to exogenous variables only, and instead opted for model the endogenous supply and demand variables as dependent variables in separate models.

The independent variables describe ecological features with a plausible impact on car sharing supply and demand. *High education* is the share of individuals with a master's degree or a PhD degree. *Medium education* is the corresponding share for those with completed education at the bachelor's level, whereas *low education* covers the remaining population. We estimate these shares for people in the "prime" 35–59 year age span to secure optimal representativeness for the working population. By disregarding younger and older age groups when calculating these shares, we avoid potential distortion due to high student shares, or due to high shares of (early) retirements and/or health impairments respectively. *Household income* separates between three fractions: 1) The first quartile, 2) the second and third quartiles, 3) the fourth quartile. The underlying distribution is equivalized according to composition and size (The EU-scale). *Cultural capital*, as we coin it, is a measure of labour-market activity. We have identified individuals aged 30–59 who work in industries that represent cultural, artistic or scientific activities, added by some activities that combine high education with low pay. Part of our rationale derives from previous observations of culture-based gentrification in Oslo (Hjorthol and Bjørnskau 2005), i.e., we use an indicator of *gentrifier presence* rather gentrification per se. The exact collection of industries is inspired by the so-called ORDC scheme (Hansen et al., 2009) (see Appendix 1 for a full list of industries). Other population characteristics are less complicated: we measure the share of immigrants and descendants from Asia and Africa (coined "non-western immigrants"), the share of students, the share of females and mean household size. Our final independent variables measure population density, i.e., population per 250 square meter, and the relative competitiveness of public transport systems. The latter index assesses how fast one can reach all potential nearby job locations by public transport, relative to doing so by car. The index is based on 250 m^2 grid cell time-based job accessibility indices by car and by public transport, using a 0.07 exponential distance decay function matching the Oslo region's travel time distribution in national travel survey data, and subsequently aggregated to the census tract level. Although specifically based on access to jobs by these two transport modes, the variable arguably represents also strength of the public transport compared to the private car regime more generally, as job locations are often co-located with other destination locations, including that of shops, services and amenities. VIF test and correlation matrix revealed no issues of multicollinearity, with all VIF scores below 5, and low scores in the correlation matrix (highest correlation revealed between income dummies, with a value of below 0.6).

3.4. Non-spatial and spatial regression

The basis of the regression models conducted in this study are count data, as the dependent variables are number of car sharing members and vehicles on each census tracts. A negative binomial regression was preferred over the default Poisson regression model for count data, as it better deals with over dispersion in the dependent variable, i.e. where the variance exceeds the mean. We run both models for the entire larger Oslo study region, as well as for an Oslo municipality subsample. This enables us to see if there are geographical differences, not only on an urban/suburban scale, but also investigate more thoroughly the potential intraurban differentials. The non-spatial model is a generalized linear model (GLM), estimating linear relationships between the variables. For this modelling, we use R software and the MASS package (Ripley et al., 2013). In addition to our non-spatial negative binomial models we run Negative Binomial General Additive Models (GAM) with a spatial smoother for count data, using the mgcv package (Wood, 2011). All other variables are treated linearly within the model, as with the non-spatial GLM. We do so in order to account for potential spatial autocorrelation in our multivariate analyses. The non-spatial and spatial models will be cross-compared to investigate if spatial uniqueness significantly affects the outcomes of our models and improves model fit.

The reason for running both spatial and non-spatial models is that we assume spatial autocorrelation on car sharing users and vehicles, in alignment with Tobler's Law, the first law of geography, stating that all things are related to all others, but that near things are more closely related than distant things (Tobler, 1970). Spatial autocorrelation is a statistical measurement of geographic

Table 1
Model output for all non-spatial and spatial models.

	Non-spatial models				Spatial models	
	Supply, Greater Oslo	Supply, Oslo municipality	Demand, Greater Oslo	Demand, Oslo municipality	Demand, Greater Oslo	Demand, Oslo municipality
(Intercept)	−3.73*	−2.13	−0.62	0.51	−1.26**	−0.26
	(1.87)	(2.05)	(0.49)	(0.47)	(0.46)	(0.51)
share medium educated (ref = lowest educated)	4.18	6.78*	2.56***	4.23***	1.83**	1.62*
	(2.57)	(2.98)	(0.62)	(0.69)	(0.60)	(0.66)
share highly educated (ref = lowest educated)	0.47	0.55	2.94***	2.82***	3.42***	3.03***
	(2.16)	(2.38)	(0.52)	(0.53)	(0.52)	(0.57)
share cultural capital	7.25**	4.36	9.70***	6.35***	4.83***	3.13***
	(2.60)	(2.77)	(0.69)	(0.64)	(0.61)	(0.62)
share non-western background	0.67	0.45	1.40**	0.64	0.63	0.04
	(1.78)	(1.94)	(0.47)	(0.46)	(0.44)	(0.47)
share 1st income quartile (ref = second and third quartile)	0.11	0.25	−1.98***	−2.26***	−1.76***	−1.59**
	(2.07)	(2.21)	(0.54)	(0.51)	(0.51)	(0.54)
share 4th income quartile (ref = second and third quartile)	−1.02	−0.97	−2.46***	−3.25***	−2.55***	−2.23***
	(1.68)	(1.97)	(0.43)	(0.46)	(0.42)	(0.47)
share detached housing (ref = multifamily housing)	−3.62***	−4.48**	−0.73***	−0.91**	−0.32	−0.77**
	(1.10)	(1.72)	(0.21)	(0.28)	(0.21)	(0.28)
share semidetached housing (ref = multifamily housing)	−2.02*	−2.29*	−0.72***	−0.48*	−0.51**	−0.42*
	(0.82)	(1.00)	(0.18)	(0.19)	(0.17)	(0.19)
student share	−0.35	−0.95	−2.16*	−2.26**	−1.49	−1.17
	(3.16)	(3.26)	(0.89)	(0.83)	(0.77)	(0.77)
female share	−4.37	−4.98	−3.06***	−2.46**	−0.57	0.35
	(2.63)	(3.03)	(0.72)	(0.76)	(0.69)	(0.78)
mean household size	−0.17	−0.17	−0.20*	−0.10	−0.03	0.04
	(0.36)	(0.41)	(0.10)	(0.10)	(0.09)	(0.09)
employment density	0.00	0.00	−0.00	−0.00	−0.00	−0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
population density	−0.01***	−0.01**	−0.00*	−0.00	−0.00*	−0.00*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Relative competitiveness of public transport (PT-car job access ratio)	5.88***	3.39*	3.74***	2.62***	2.03***	1.80***
	(1.23)	(1.44)	(0.31)	(0.34)	(0.35)	(0.40)
Population size	0.00***	0.00**	0.00***	0.00***	0.00***	0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
EDF: s(X,Y) (spatial smoother)					19.16***	21.92***
					(23.50)	(26.14)
AIC	909.61	840.77	4534.38	3278.06	4195.33	3127.96
BIC	997.74	914.35	4622.50	3351.63	4386.27	3299.85
Log Likelihood	−437.81	−403.39	−2250.19	−1622.03	−2060.8	−1524.26
Deviance	282.10	251.52	1233.56	635.67	1153.74	594.04
Num. obs.	1318	560	1318	560	1318	560
Deviance explained					0.85	0.78
Dispersion					1.00	1.00
R^2					0.79	0.74
GCV score					2123.36	1592.29
Num. smooth terms					1	1

*** $p < 0.001$.
** $p < 0.01$.
* $p < 0.05$.

relatedness – that there is a positive or negative correlation between close entities (Miller, 2004). In the case of this paper, we test if the patterns of car sharing supply and demand are geographically clustered or dispersed, and if these overlap with clusters or dispersions of sociodemographic and socio-economic variables. To test whether spatial correlations influence our car sharing outcomes, we first run a non-spatial regression on members and vehicles, and then test the regression residuals for spatial autocorrelation. We do this using the index of Moran's *I*: a measure of discerning the degree of clustering or dispersion of a specific phenomenon (Anselin, 1995). We run a global Moran's *I*, giving a value addressing the spatial structure of all data points in the dataset. Values range from −1 to 1, with −1 indicating dispersion and 1 indicating clustering. Values close to 0 are indications of no dispersion or clustering, but a random spatial pattern. To investigate if the patterns are spatially distributed (clustered or dispersed), we test the regression residuals for spatial autocorrelation by running a Moran's *I*-test on the distribution of car sharing members and vehicles. For members, we find a clear spatial relationship, with a Moran's *I*-value of 0.614 ($p = 0.001$; $z = 39{,}6$), particularly explained by so-called "high-high" clusters: regions consisting of neighbourhoods where car sharing is high and that of adjacent neighbourhoods is also high. For vehicles, we observe a similar pattern, albeit with weaker clustering (Moran's $I = 0.153$; $p = 0.001$; $z = 9{,}8$). After confirming spatial autocorrelation, we run a negative binomial GAM (general additive model) with a spatial smoother for count data, to see if the spatial component gives additional explanation to the model, and improves model fit. If this spatial smoother is significant and improves overall model fit, this indicates that spatial clustering provides additional explained variance in car sharing outcomes not already explained by independent variables in the model. If it does not, the non-spatial model sufficiently explains all (potential) spatial clustering already.

For the first part of the analysis, we will run the non-spatial GLM on car sharing demand (members) and supply (vehicles). There are large variations on both members and vehicles, with ranges from 0 to 93 members and 0 to 14 vehicles in each census tract. Following this, we investigate spatial autocorrelation in the data, and introduce a spatial component to the model, and run a spatial GAM with a smoother, which might give further nuance to our analysis, and improve model fit. As for the non-spatial model, we assume all predictors to have a linear distribution. The only predictor we assume a non-linear relation for in the spatial model, is the spatial component, which is given a smoother. The linear model is a Generalized Linear Model, while the spatial is a General Additive Model. Lastly, we analyse Oslo municipality separately, to investigate variations of car sharing on a lower geographical scale.

4. Analysis

4.1. Non-spatial GLM analysis

Table 1, presented at the end of our analyses section, summarises all multivariate model results. The first column presents the multivariate regression results of how car sharing supply in the Greater Oslo region, measured by the number of shared Bilkollektivet cars stationed at the census tract, gets affected by population composition, socio-economic status, housing composition and urban form, controlled for all other variables and a control variable for population size to account for the obvious larger likelihood that a census tract has a higher number of car sharers when its population is larger. There are a few significant variables affecting car sharing supply in this model, and we can see strongest correlation on factors of the built environment, with both population density and the relative competitiveness of public transport having a strong effect, as well as share of housing types.

After accounting for population size, we find no significant effects of either education or income on car sharing supply, but we find a significant positive effect on areas with higher shares of cultural capital, indicating more car sharing to be accessible in areas where a higher share of the population work in this sector. Ethnicity (western versus non-western) was not found to have any significant effect. As for housing types, we find car sharing mostly in supply in areas with a larger share of multifamily housing, which often are areas with a higher share of people (higher demand) and larger difficulty in owning a private vehicle, making a shared car more appealing. This is evident as car sharing is less frequent in both areas with higher shares of semi-detached and detached housing. Neither share of students, share of females, mean household size, nor employment density, affects car sharing supply significantly. It is rather the strong positive effects of detached housing, population density and public transport competitiveness that seem to be dominating the variance in car sharing supply. This is in line with our hypothesis, as well as extant literature, focussing on car sharing mostly being an urban phenomenon, and mostly in areas where many people live, and where these people can use public transport for daily travels. It is apparent that the car sharing suppliers are mainly focussed in these areas, and that they assume the largest customer base to be here. It might be riskier and less profitable for suppliers to have many (or any) vehicles in less dense and/or more car dependent areas, due to the potentially lower turn-over rates. This is one potential drawback of business-to-consumer (B2C) car sharing systems when compared to peer-to-peer (P2P) schemes that are often spread more widely as they require no fleet investments and high vehicle turn-over rates, being based on pre-existing idle capacities (Meelen et al., 2019).

When zooming in to Oslo (second column), for the analysis of car sharing supply on a lower geographical scale, we find similar patterns to that of the whole region. Population density has the highest explanatory power, while we see the effect of housing remains an important factor for explaining car sharing supply. It is evident that although Oslo municipality (compared to the larger Oslo region) has a lower share of both semidetached and detached housing, the areas with a predominant share of detached and semidetached housing have a much lower access to shared cars than areas with a higher share of multifamily housing. On the other hand, the effect of the relative competitiveness of public transport is drastically reduced when zooming in to Oslo, which is a highly interesting distinction. One explanation might be that most areas of Oslo have good to reasonable public transport accessibilities, but that for some areas, the private car is more dominant, and still easily accessible (in addition to the public transport access). The semidetached and detached areas might serve as some kind of proxies for exactly these types of car-friendlier neighbourhoods.

Table 1, column 3 presents the multivariate regression results of how car sharing *demand*, measured by the number of members of the car collective Bilkollektivet at the census tract for the whole study area gets affected by the same set of independent variables (i.e. population composition, socio-economic status, housing and urban form) as estimated earlier in the models for car sharing supply. Again, we control for population size to normalise for the higher probability that more cars are present in neighbourhoods that are more populous. In this model, we get more significant effects than in the supply models, although some patterns are similar. This does not come as a surprise, as both are part of reinforcing feedback mechanism. Car sharing operators are expected to station and expand their vehicle fleets at locations where they expect, or have previously observed, demand to be highest. Similarly, in areas with lower access, people choose (or are forced to choose) other mobility solutions than car sharing. The larger supply of shared cars stationed in neighbourhoods at the other end of the spectrum, may enhance the utility of the service to existing or potential new users, which may fuel further demand for car sharing.

We find a strong correlation between car sharing demand and cultural capital, which indicates more car sharing demand in neighbourhoods where a higher share of the working population is employed in jobs and industries related to cultural industries. It is important to note that this effect also holds strongly even when controlled for other factors such as education level. Separately from cultural capital, we find car sharing also to positively correlate with education level. The share of higher educated on the census tract has the strongest positive effect on car sharing demand, in reference to lower education levels. A higher share of medium educated residents in the neighbourhood compared to lower educated also has a significant positive, slightly weaker effect, indicating a linear pattern from lower to medium to higher education levels. Another important factor is high income, yet, unlike the typical high income, early adopter profiles for the adoption of sustainability innovations, shares of the highest income quartile correlates strongly *negative* with car sharing demand. We observe a weaker, yet significant negative effect of car sharing demand on the first income quartile as well. Rather, it appears that the reference category of the second- and third-income quartiles combined is associated with car sharing demand most positively. This is in line with extant literature (Tyndall, 2017; Sioui et al., 2012; Firnkorn and Müller, 2011) that also finds the strongest correlation between middle income levels and car sharing. The findings also give evidence to the findings of Tyndall (2017) on a lower geographical scale, with less car sharing being present in poorer cities.

We also find car sharing supply to be higher in locations with a higher share of people with non-western backgrounds. It is important to note that this does not necessarily mean that non-western immigrants themselves are more likely to use car sharing. It may indicate car sharing to be more prominent in socially mixed and urban neighbourhoods, and might indicate car sharing to be more prominent in areas undergoing a process of change, with a population with high levels of spatial capital. Car sharing demand also appears to be lower in areas with a higher share of students. This could be explained by students using public transport more, not being able to afford to drive, or that these are mainly younger people, with many not having their drivers' license (Hjorthol et al., 2014). It appears that car sharing demand is significantly weaker in more female dominated areas, as compared to more male dominated neighbourhoods, in correspondence with extant literature, with car sharing being utilized more by male participants (De Lorimier and El-Geneidy, 2013; Mishra et al., 2015; Hjorteset and Böcker, 2020).

Concerning housing patterns, we find both semidetached and detached housing to have a significantly negative effect on car sharing demand, indicating fewer members in areas with higher shared of these residential housing types, compared to multi-family housing. An explanation for this could be that the ease and convenience of owning, using, parking and/or possibly the charging of a private car is higher in these areas compared to multi-family housing, where parking restrictions often are in place, street parking could be limited, and where parking prices might be relatively high. Neighbourhoods with smaller household sizes (and thereby larger shares of singles and/or couples without children) boast higher numbers of car sharers than neighbourhoods where households are typically larger, although the effect found here is only significant at a 0.05 level. The finding is in line with what Sioui et al. (2012) finds, car sharing is most often used by people living without children in their household. Although you might want to live a car-free lifestyle, having children might be a life-event that complicates this. Travelling in a shared car with children often demands the installation of car seats, making this less desirable for many.

Lastly included in the model, is an index describing the public transport to car job accessibility ratio (a measure of public transport competitiveness), and two predictors of population density and employment density of each census tract. In the current model, the index of public transport competitiveness has a strong significantly positive effect, while the two others are non-significant. These two urban form effects are, nevertheless, positively significant when the public transport-predictor is left out of the model. An explanation for this is that most jobs are in the city centre, so high employment densities are characteristics of the most centrally located areas. Population density can both occur in these areas, as well as in some suburbs and satellite towns/areas, like the Norwegian "Drabantbyer", that also have a high population density, without being an inner-city area. However, both population and employment density show large geographic overlap with public transport competitiveness, which is likely why their significances disappear when adding this dominant variable. The strong effect of public transport competitiveness is in line with our initial expectations. Higher values of this public transport to car job accessibility ratio indicate a stronger public transport regime, which opens up the alternatives for living car-less lifestyles, and using car sharing for more incidental car needs. On the other end of the spectrum, lower values for this variable indicate a strong private car regime, high car dependency and few suitable alternatives, making it almost a necessity to own a private car and a redundancy to use car sharing, in addition to that car sharing service are likely inadequate.

To better understand the intraurban effects of car sharing demand, we run a separate model for the municipality of Oslo. For the Oslo-demand model, we see a similar pattern to that of the whole study area, with a few exceptions. The effect of non-western immigrants is no longer significant, indicating no correlation between ethnic background and number of car sharers. We also find a weakened effect of housing types, compared to the other model, especially concerning areas with a higher share of semidetached housing types. Although still significantly negative, the effect is not as strong on building types for Oslo as they are for the region as a whole.

The findings in both the supply- and demand models indicate interesting relationships between the neighbourhood profiles and car sharing. We find a relationship between shares of the population and car sharing, and we find car sharing to be more prominent in areas with a specific built environment. What we cannot see from these models is whether or not there is also spatial uniqueness underlying these patterns of car sharing in addition to our explanatory factors. Are areas of a higher demand or supply being geographically located close to other similar areas (in line with Tobler's law). In the methods section, we presented spatial autocorrelation (Moran's I) tests that reveal that both car sharing supply and demand are spatially clustered, although demand to a much higher degree than supply. In the next section, we will address these questions of spatiality, and see if including a spatial smoother will improve model fit further.

4.2. GAM with spatial smoother

For the supply model, we see a do not see a large increase in model fit on AIC when adding the spatial smoother, and the spatial component is not significant within the model. The model gives less complexity than the non-spatial model, with no new predictors being significant, and the significant predictors from the non-spatial model are kept the same, or lose some explanatory power where the spatial smoother is included. This is the case for both the Oslo region and the Oslo municipality, indicating no variation between the two geographical scales. We do not, because of this, see car sharing supply to be affected spatially, and keep the non-spatial model.

For the spatial model of car sharing demand in the Greater Oslo region, we find relatively similar patterns to that of the non-spatial model, but with some key differences, and an improved model fit. The improved model fit tells us that adding the smoother on the spatial component better explain our data, due to spatial clusters of car sharing demand. Both areas with more members and those with fewer members tend to be clustered together in separate parts of the study area. The improved fit for the spatial demand model could be that car sharing demand may be more diffuse and harder to predict by non-spatial factors alone. Since people can use car sharing at different places, not just their place of residence (e.g. from nearby work or other destinations), demand may be more sensitive to spatially-unique characteristics, for instance in relation to specific local/regional commute patterns. One example might be higher-than-expected car sharing demand at the headland of the Nesodden peninsula just south of Oslo – a short ferry crossing but a long drive from the Oslo city centre. Fig. 2 presents exactly how car sharing is spatially clustered after controlling for all other variables in our spatial multivariate analyses. Fig. 2a shows car sharing demand for the whole study area to be clustered slightly east of the Oslo city centre, an area that combines some of the regions high urban densities, but without the highest levels of socio-economic status found more west of the centre. Areas with lower demand tend to be clustered further outwards away from the centre, and perhaps most notably westward in Bærum and Asker, some of the region's wealthiest sub-/exurban areas with some of the highest car ownership levels. Weaker car sharing demand clusters can also be found outward towards east but not as weak as to the west. Car sharing demand in the south, even outwards from the centre remains rather strong.

When looked at the other explanatory factors in the model the spatial model reveals a somewhat similar pattern to the non-spatial model, but some of the effects previously significant in the non-spatial model are no longer significant here. Non-western background does not correlate positively with car sharing when adding the spatial component, indicating that the relation might rather have been spatially. Similarly, the negative effects on the share of students and females shown in the non-spatial model, is now covered by the spatial smoother. It is therefore not car sharing demand is necessarily lower in areas with more students and women, but rather that there is something else uniquely spatial that supresses car sharing demand in some of the areas that happen to have lower female and student shares.

However, the positive middle and higher education effects on car sharing demand still hold when accounting for spatial uniqueness. The effect has even stronger impact for areas with the highest education levels compared to the non-spatial model. Cultural

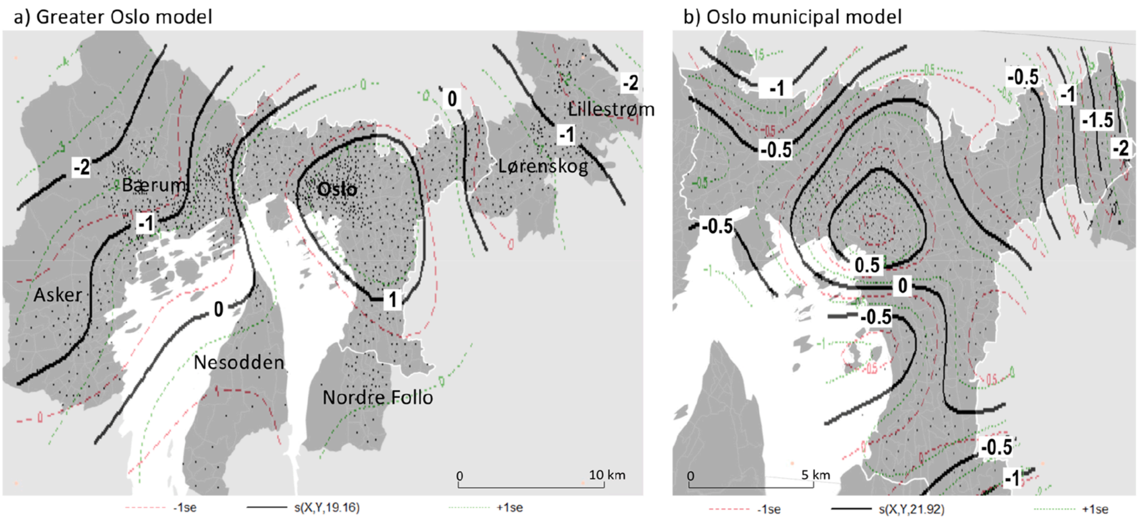

Fig. 2. GAM spatial smoother plots for car sharing demand in a) Greater Oslo and b) Oslo municipality.

capital is also in the spatial model highly positively significant, although with a weakened effect here compared with the non-spatial model. Income is also an important signifier on car sharing demand, where we still find, after controlling for spatiality, car sharing to be less frequent in the lowest and highest income quartiles. On housing types, we find this to geographically overlap with the spatial clusters to a high degree, and for detached housing, the effect is no longer significant, while the effect on semidetached housing types is less significant than in the non-spatial model. The relative competitiveness of public transport is still positively related to car sharing access, indicating a strong relationship between car sharing usage and access to public transport.

When zooming into the municipality of Oslo, we see a weaker effect of both share of population with medium education levels and on the 1st income quartile compared with the regional model. Detached housings are a negative signifier on car sharing demand for Oslo, while the effect if semidetached housing decreases in comparison. The clusters shown in Fig. 2b are more nuanced for the municipality of Oslo. Positive car sharing demand is clustered inside and slightly east of the city centre. Car sharing appears to be lower outward towards the city border and suburban municipalities to the west, to the south, and especially towards the east.

5. Discussion

Many of today's urban areas are undergoing transformations in relation to population composition and an increased focus on creating more sustainable cities, but there are questions as to what the implications of such policies and transformations are for social inequality and social divides (Anguelovski et al., 2019; Sheller, 2015). The adoption of car sharing is situated in the transforming lower-carbon urban landscapes, in which, spatial capital and motility play an increasingly important role as enablers to live aspired advantageous lives. Our results reveal that car sharing varies greatly within both the region and city of Oslo. Besides expected core-periphery differentials highlighting a higher car sharing demand and supply in inner-city areas, we find strong intraurban patterns explained by structural factors of urban form, accessibility and socio-economic status at the census tract level. We find cultural capital to be an important signifier in car sharing supply and demand, both for the larger region of Oslo, and within the municipality borders. Car sharing is more present and in higher demand in census tracts with a high score on jobs in the cultural economy, suggesting a link with higher levels of car sharing activity among people with high levels of cultural and spatial capital. This coincides with the findings by Tyndall (2017), who finds car sharing on city levels to be more common in cities with higher shares of young, highly educated, employed white people, often in accordance with high levels of cultural capital. The concentration of car sharing in areas with these population types can be explained within the theoretical framework of Kaufmann et al. (2004), as these groups often score higher on motility or spatial capital. We find car sharing accessibility to be higher in areas scoring higher on cultural capital and higher education levels, giving these groups better access to car sharing, and hence increasing their motility further. We also find car sharing in higher demand in areas with a highly educated population. We know that car sharers often are highly educated (Hjorteset and Böcker, 2020), and these findings also coincide with findings on city levels by both Tyndall (2017) and Münzel et al. (2020). Furthermore, car sharing demand in the Oslo region correlates strongly with income and the relative strengths of public transport compared to the private car. More specifically, we find car sharing demand to be significantly stronger in middle income areas (2nd and 3rd quantiles) and significantly weaker in areas with the lowest incomes, and in areas where accessibility to jobs by public transport is relatively poor compared to that by car. This supports the claim that being a car sharer often prerequisites a high utilization of public transport in daily live. It might seem that living in these areas makes the private car superfluous for many, as car sharing seem to be a good fit and an enabler of car-free lifestyles (Brown, 2017). These findings can be explained in light of *appropriation* – mobility strategies held by people with higher motility. People prone to utilizing public transport, and with lower car dependency seems to reside in areas more dominated by car sharing services, which increases their motility further, and enables these car-free lifestyles.

Yet from an egalitarian perspective, it also reveals that (so far) car sharing does little to benefit spatial and mobility inequalities and enhance motility in marginalised areas. Residents in lower income areas could have benefitted from accessing car sharing as a less expensive alternative to private car ownership, if car sharing supply were to be well established and public transport were more sufficient enough to fulfil for the majority of trips. However, being uncorrelated to income levels, car sharing supply is not specifically targeting lower or even middle-income areas as it could have done. Moreover, with strong positive correlations to the privileges of strong public transport competitiveness, car sharing supply remains out of reach in public transport deprived parts of the study area, including some of the most marginalised outer-urban areas and many high as well as low-income car dependent suburban areas. Even if one were to aspire car-less lifestyles in such areas, car sharing does not seem to function as a viable option. At the other end of the spectrum, car sharing supply is not correlated to the highest income levels either, but it becomes clear from our demand analysis that car sharing demand is also clearly lowest in the highest income (fourth quantile) neighbourhoods. Spatial model smoother plots of car sharing demand, reiterate that car sharing is least in demand in the wealthiest parts of the study area, as well as in more suburban, less expensive areas. In these areas, even though public transport is not necessarily insufficient, private car ownership seems to be the preferred mobility solution, and the car might for many still be an important hallmark. Restrictions on car ownership are by and large financial (e.g. tolls, fixed and annual taxes, parking costs), but such restrictions may not have the same demand-reducing effects for wealthier groups in society.

In this paper we have investigated the adoption differentials of car sharing, mainly from the perspective of (uneven) access to car sharing and the public transport alternatives that enable car free lifestyles. Although this study looks at both car sharing supply and demand, the analysis themselves are quite separate. Further research may look more at the interdependencies of the two, to better understand how supply follows demand, perhaps through interviews with operators to better understand the supply decision making process. Another limitation to this study concerns data access. While we did not have access to individual level background data, we used population data at census tracts. This way, we cannot say anything specific about who in each neighbourhood is using car sharing. This also comes with limitations on ecological fallacy and multi-area unit problem (MAUP). The average values in each neighbourhood do not represent the whole variance of people living there. Further research may investigate individual and neighbourhood effects simultaneously (multilevel analyses), to unravel the complexity within a neighbourhood in relation to who are using car sharing more. Furthermore, this study focuses on station based B2C car sharing only. Further studies may investigate differences between B2C and P2P car sharing, as these are known to have different geographies (Meelen et al., 2019). A challenge in doing research on the field of car sharing concerns the rapid changes happening in this landscape. Since the collection of our data, more car sharing operators have emerged, in addition to other modes of micromobilities. The outbreak of the COVID-19 pandemic have affected both travel patterns generally, and car sharing specifically. More research is needed to address the potential newly shaped levels of car sharing demand (e. g. potential changes in commutes and home office frequencies, infection fears, the seeking of alternatives to public transport, etc.) and supply (e.g. potential changes in operators' income streams). Further research needs also to delve into other types of adoption barriers for the inclusive societal adoption of car sharing, such as those related to levels of *competence* (Kaufmann et al. (2004). There are demographic variations in having a driver's license, e.g. women, younger people and lower income groups being less likely to have so (Hjorthol et al., 2014, p.117), which is a necessary skill to access shared cars. Additionally, there might be barriers to accessing shared cars in relation to technology and an experience of feeling safe. In line with both literature on spatial capital and car-free lifestyles, using car sharing might for many be a question of identity, and our findings correspond to the findings of Rérat and Lees (2011) pointing to a certain group of hyper-mobile gentrifiers. Less privileged parts of the population might not have the same access to car sharing, as they are frequently moving further out of the city core, and they might not feel at home with the identity of a car sharer (Rérat, 2018). As such, car sharing may be more utilized in areas fitting with a shifting population demographic with higher spatial capital, and as such relate directly to specific aspects of ongoing urban transformations, such as gentrification and displacement.

6. Conclusion

This paper investigates the intraurban geographies of car sharing supply and demand in Greater Oslo, Norway, drawing on locational register data on car fleets and members of Norway's largest station-based car sharing scheme and population, urban form and accessibility statistics calculated at the census tract. We find uneven spatial distributions of car sharing within the city and city region when looked at the demand side, and even more so when looked at the supply side. Patterns clearly intersect with pre-existing spatial inequalities in income, education, cultural capital and the relative job accessibility by public transport compared to that by private car: an overarching conclusion that challenges the extent to which car sharing, at least in its present form, is able to enhance the mobility options for marginalised groups.

The significance of our findings for policy and planning is fourfold. First, policy makers are advised to provide incentives to car sharing operators (for example through parking concessions) to pilot the expansion of car sharing supply in lower income and more public transport deprived areas. This could help bridge the market imperfection of constraint demand due to constraint supply waiting for induced demand. Second, policy makers and planners are advised to simultaneously improve the competitiveness of alternatives to automobility, including public transport, walking, cycling and micro-mobility, as well as the more seamless integration of such alternatives with car sharing, including Mobility as a Service types of subscriptions and integrated pricing schemes. Third, policies should be designed to help overcome barriers of competence and appropriation, such as those associated with peoples' (perceived) lack of skills or perceived hassles of integrating car sharing into the practices of everyday life. This may include information-based policies or the incentivisation of locally embedded trial schemes, particularly targeting marginalised groups. Fourth, policy makers may consider reinforcing restrictive policies on private car ownership, and consider measures that affect lower and higher socio-economic status groups more equally (e.g. reduced traffic speeds, parking restrictions, higher taxes on second cars). In light of this, careful considerations need to be paid to whether the expansive policies to incentivise EVs, especially in high-adoption countries like Norway, still contribute solely to their original goals to shift out fossil-based propulsion, or whether they have come to strengthen private automobility at large, at the cost of other transport modes and increasing mobility divides.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2021.103089.

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