The Journal of Transport and Land Use http://jtlu.org
Vol. 10 No. 1 [2017] pp. 945–964

Which D's are the important ones? The effects of built environment characteristics on driving distance in Oslo and Stavanger

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Abstract: Based on a study in the Greater Oslo and Greater Stavanger urban areas in Norway, this paper employs quantitative and qualitative research methods to investigate the influences of residential location and neighborhood characteristics on car driving distances. Cross-sectional and quasi-longitudinal analyses show that built environment characteristics — especially the distance from the dwelling to the main city center — influence driving distances in both urban areas. In Stavanger, the impact of inward moving seems to be larger than that of outward moving, possibly reflecting self-selection to the inner city. In the relatively monocentric Greater Oslo, the distance to the city center has a stronger impact on weekday driving than on weekend driving. In the more polycentric Greater Stavanger, where the importance of downtown as a destination for commuting is weaker, the distance to the city center has similar effects on weekday and weekend driving. In Greater Stavanger, distance to the secondary center Sandnes also plays a role although the impact is small. Population density and job density have impacts in Greater Oslo but not in Greater Stavanger, where we instead find a weak effect of local-area job surplus. There is no tendency toward compensatory increased weekend driving among inner-city dwellers in either Greater Oslo or Greater Stavanger.

Keywords: Built environment, monocentric, polycentric, self-selection, travel behavior, longitudinal

Article history:
Received: March 29, 2017
Received in revised form: August 14, 2017
Accepted: September 27, 2017
Available online: November 20, 2017

1 Introduction

In many countries, land-use policies have been adopted over the past decades aiming to curb the growth in car traffic in cities and urban regions. Several negative impacts of urban motoring have motivated these policies: noise pollution, congestion and the related heavy costs of adapting road networks to

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The *Journal of Transport and Land Use* is the official journal of the World Society for Transport and Land Use (WSTLUR) and is published and sponsored by the University of Minnesota Center for Transportation Studies.

growing amounts of traffic, vulnerability to fluctuating fuel prices and, not the least, air pollution and greenhouse gas emissions. The purpose of this paper is to shed light on the roles of residential location and neighborhood characteristics in supporting or counteracting the ambition of planning for less car traffic in urban regions.

Norway is one of the countries where such land-use policies have been in place for a long time. So-called *central government policy guidelines for coordinated land use and transport planning* were adopted in 1993 and updated in 2014. These guidelines state that land use and transport systems should "promote the development of compact cities and settlements, reduce the need for transport and facilitate forms of transport that are climate-friendly and environmentally friendly" (Norway's government, 2014: 1). National sector authorities, the county governor, the county council and neighbor municipalities can raise formal objections against land-use plans not complying with these regulations. Moreover, according to an agreement on climate policy in 2012 among six of the by then seven parties represented in the Norwegian parliament, all growth in the amount of traveling in the larger Norwegian urban regions is to take place as public and non-motorized transport. This goal is included in National Transport Plans adopted in the 2013 and 2017 and in the regional land use and transport plan for the municipality of Oslo and the neighboring county of Akershus (2015). With the expected population growth over the next couple of decades, the goal of zero growth in car traffic implies that per capita driving must be reduced by 20-25 % in the urban regions.

But what kinds of land-use development in urban regions can likely contribute to reducing the need for transport and facilitate climate-friendly and environmentally friendly forms of transport? In Norway, the compact city has had a strong status as a planning ideal over the last two or three decades. A long period of urban sprawl in the decades after World War II was replaced in the 1980s and 1990s by a trend of re-urbanization. This trend has been especially strong in major urban regions, with Oslo as the most outstanding example. Within the continuous urban area of Oslo, population density increased by 37% over the period 1985–2016, with densification rates particularly high in the inner zones. However, planners' ideas about more compact built environments do not only refer to inner-city densification in relatively monocentric cities such as Oslo. Internationally, ideas of developing polycentric, more compact urban neighborhoods have long had a quite strong position (Healey & Williams, 1993; Archibugi, 1997), manifested in concepts such as "new urbanism" (CNU, 2013), "smart growth" (EPA, 2017) and "transit-oriented development" (Sustainable Cities Institute, 2017). These trends are also present in the Norwegian context, both as proposed solutions in urban areas that are today predominantly polycentric conurbations (such as Greater Stavanger, see below) and as a way to cope with high expected population growth in present predominantly monocentric urban areas such as Greater Oslo.

By drawing on empirical material (qualitative as well as quantitative) from the two Norwegian urban areas of Greater Oslo and Greater Stavanger, this paper aims to answer the following questions:

- Which built environment characteristics exert the strongest influence on car driving distances in Greater Oslo and Greater Stavanger? Which is more important, distance to the main city center, distance to the second-order center, or distance to the local center?
- Why do built environment characteristics influence car driving distances the way they do?
- Do the influences of built environment characteristics differ, depending on the population size of the urban area and its center structure (predominantly monocentric or predominantly polycentric)?
- Do built environment characteristics influence car driving distances at weekends in ways counteracting the impacts on weekdays?

The two urban areas differ in population size (Oslo is more than four times as large as Stavanger) as well as in their center structure (Oslo is predominantly monocentric whereas Stavanger is predominantly polycentric). The amount of car driving is here defined as the number of kilometers traveled by car as driver, i.e., vehicle kilometers driven by car.

A unique contribution of this study is that it compares the influence of built environment characteristics on car driving in a predominantly monocentric and a more polycentric urban area, with a differentiation between weekday and weekend driving. Moreover, by combining cross-sectional and quasi-longitudinal statistical analyses with rich qualitative interview data, the study provides a more solid ground for its conclusions than in most other studies of the topic.

In the next section, we review the literature on the influences of residential location and neighborhood density on car travel. Section 3 presents the two investigated urban areas, Oslo and Stavanger. Section 4 presents the methodology of the study, including its basic assumptions, the research design and how the methods were actually used. Section 5 presents the results of cross-sectional and longitudinal statistical analyses as well as a discussion of causal mechanisms drawing on the qualitative interviews. Section 6 brings some concluding remarks.

2 Literature review

Numerous studies over the past decades have attempted to identify and estimate the effects of built environment characteristics on individual travel behavior (for overviews, see Saelens & Handy, 2008; Ewing & Cervero, 2010; Næss, 2012; Stevens, 2017). Such studies differ in terms of geographic scale, the built environment characteristics focused on, as well as the aspects of travel behavior investigated.

The Newman and Kenworthy (1989) study almost 30 years ago about variations in cities' gasoline consumption and car dependence directed particular attention to urban density as an explanation of variations in fuel consumption. The denser a city, the lower fuel consumption. The more densely an area is developed, the more facilities will normally be available within moderate distances for the residents. Moderate distances, in their turn, provide opportunities to reach relevant facilities on foot or by bike. High density also provides a basis for establishing high-quality public transportation and progressive parking policies. All these factors contribute to the likelihood of reduced car use in dense cities. Newman and Kenworthy's study has been a target of criticism since the investigated cities were very different not only in density, but also in terms of economic, political and cultural conditions and fuel price. However, later studies controlling for the latter kind of variations have supported Newman and Kenworthy's main conclusions (Næss, Sandberg, & Røe, 1996; Kenworthy, 2003; Lefèvre 2010).

However, while Newman and Kenworthy focused on density within the urban area of the city as a whole, most subsequent studies of the relationship between urban density and travel have focused on density at the neighborhood scale. This applies, for example, to all studies of impacts of density included in Ewing and Cervero's (2010) meta-analysis *Travel and the Built Environment*. However, characteristics of the neighborhood itself as well as its location matter. Density is one among the several D-words pointed out in transportation research as being influential on travel distances and modes (Cervero & Kockelman, 1997; UN Habitat, 2013). Other D's included in Ewing and Cervero's (2010) meta-analysis are Destination accessibility, Diversity, Design, Distance to transit, and Demand management. Destination accessibility is a measure for ease of access to trip attractions and may apply to a local scale (e.g. the distance to the closest grocery store or local community center) as well as a city-wide or metropolitan scale ("regional destination accessibility"). In the Nordic countries, there has in particular been a focus on the latter. In monocentric cities and city regions, regional destination accessibility is often conceived of as the distance to the central business district. In some studies, more sophisticated indices have been used, such as the number of jobs or other attractions reachable within a given travel time.

At a city-wide or metropolitan scale, the urban structural conditions pointed out as influential on travel behavior are primarily how housing, offices and other facilities (such as stores and other services) are distributed throughout the agglomeration area. The more housing, jobs and other facilities are concentrated in the central parts of the urban area, the less the use of cars is. On the other hand, the less self-sufficient different neighborhoods within a larger urban region are with grocery stores, schools, kindergartens and non-specialized service functions, the greater is the interaction with other parts of the urban area, and the longer is the average mileage by car per capita. Even in suburbs with a high number of jobs compared to the number of workers, local residents often have to commute long distances in a specialized job market, resulting in considerable "excess commuting" compared to a hypothetical situation where companies recruited their employees from the local neighborhood (Giuliano & Small, 1993).

A large number of studies have, in line with the above, found that suburbanites travel more by car than inner-city dwellers do (Mogridge, 1985; Zhou & Kockelman, 2008; Milakis, Vlastos, & Barbopoplus, 2008; Zegras, 2010; Ewing & Cervero, 2010; Næss, 2005; De Vos, 2015). Apart from suburbanites' need for travel to reach centrally located and other non-local destinations, the impact of residential distance to the city center also reflects the usually poorer quality of the public transport system and better parking conditions in the suburbs. In a similar vein, studies at a regional scale have found higher car usage and transportation energy use in sprawling regions than in regions characterized by urban clustering and containment (De Vos, 2015).

Most of the above-mentioned research has investigated more or less monocentric cities and urban regions. Some of the studies of polycentric urban areas have found effects on commuting distances, energy use and travel mode mainly from neighborhood densities (Hickman & Banister, 2015; Grunfelder & Nielsen, 2012). However, there is still lack of knowledge of how residential location influences travel behavior in polycentric urban areas, compared to more monocentric urban areas. In particular, there is lack of knowledge of differences between monocentric and polycentric urban areas in how relationships between urban form and travel at a neighborhood scale are conditioned by the location of the neighborhood relative to the main city center and other important centers within the urban area. The paper will illuminate this question.

The size of an urban agglomeration has also proven, naturally, to have an impact on the use of car. The larger the agglomeration is, the lower the use and ownership of cars tend to be, internationally as well as in Norway (Banister, 1992; Christensen, 1996; Federal Highway Administration, 2009; Engebretsen & Christiansen, 2011).

While a large number of studies have identified the influences of urban built environment characteristics on travel, some authors still claim that such effects are small or even non-existing (e.g., Bruegmann, 2005; Ehenique, Hargreaves, Mitchell, & Namdeo, 2012; Van Wee, 2013; Woods & Ferguson, 2014). These studies are still relatively few and are sometimes based on model simulations where the results inevitably depend on the assumptions fed into the model (e.g., Ehenique et al., 2012), address other aspects of the built environment than those addressed in the present paper, or rely on old secondary sources that have later been refuted (e.g., Bruegmann's book). Notably, none of the above-mentioned contributions have investigated the causal mechanisms through which different built environment characteristics could be expected to influence travel behavior.

Residential self-selection is often discussed as a problem in land use-travel studies. Several authors claim that the effect of land use on the amount of transport and choice of modes is exaggerated since there may be a tendency of people to choose places of residence based on their travel abilities, needs and preferences (Kitamura, Mokhtarian, & Laidet, 1997; Boarnet & Crane, 2001; van Wee, 2009 & 2013; Cao, Mokhtarian, & Handy, 2009; Cao, Xu, & Fan, 2010). Most studies still conclude that there are significant associations between the built environment and travel behavior, independent of self-selection influences (e.g., Schwanen & Mokhtarian, 2005; Cao et al., 2009; Ewing & Cervero, 2010; De Vos, Derudder, Van Acker, & Witlox, 2012). We pay attention to residential self-selection by controlling for residential preferences as well as demographic and socioeconomic characteristics of respondents when assessing the effects of built environment characteristics on car driving.

Moreover, some researchers have hypothesized that people who save money and time from living in an urban context that does not require much daily-life travel will carry out greater amount of leisure travel during weekends and holidays (Vilhelmson, 1990; Schafer & Victor, 1997; Holden, 2007). In this paper, we address the extent to which any such compensatory mechanism can be seen for weekend car driving compared to car driving on weekdays.

Among the above-mentioned D's, this paper focuses on destination accessibility (at a local, district and a urban area scale), neighborhood density, neighborhood diversity (in terms of jobs/workers ratio), and distance to transit.

3 Case cities

This study was conducted in two urban areas in Norway: Oslo and Stavanger. The continuous urban area of Oslo has about one million inhabitants, while the continuous urban area of Stavanger has about 215,000 inhabitants. The difference in population implies that Oslo has substantially larger spatial extent than Stavanger. Population density is higher in Oslo than in Stavanger: 36.7 and 29.0 inhabitants per hectare, respectively, within the continuous urban area of each city.

Although both urban areas include a hierarchy of major and minor centers, Greater Oslo is a relatively monocentric urban area, with one dominant downtown area where many jobs are concentrated. In contrast, Greater Stavanger has a clearly more polycentric employment structure, with job concentrations in the central part of Stavanger and the neighboring town center Sandnes and not the least in the second-order center Forus. The latter area is located between the centers of Stavanger and Sandnes and was developed mainly in the 1980s and 1990s. A significant number of jobs are currently located in this employment center. The number of workplaces in the central area of Stavanger is about 25,000, compared to about 40,000 at Forus and about 10,000 in the central area of Sandnes (Tjeldflaat, n.d; Rogalandsavisen, 2017). For other facilities than workplaces, the historical center of Stavanger is still the dominant center of the region.

Urban areas have historically evolved differently and emerge at a particular time with different spatial distributions of housing, jobs, trade and services over the urban settlement. One way to characterize this variation or inequality within urban areas is to establish a GINI coefficient-like expression of activity distribution over the urban area. Christiansen, Gundersen, and Gregersen (2016) have established a so-called monocentric bias indicator to capture the monocentric or polycentric character of an urban area. A coefficient of 1 indicates strong concentration of activity to a sub-district within the urban area, while a coefficient of 0 represents activity evenly spread across the urban area. Such a calculation for our two study areas Oslo and Stavanger for the year 2014 shows that Stavanger has an extremely uniform distribution of jobs, while Oslo has quite a strong concentration to the main center. Regarding residents, Stavanger features a slightly stronger concentration towards the center than that found in Oslo (Figure 1).

Distinct from the more centralized location of jobs than dwellings in Greater Oslo, the dwellings and jobs of Greater Stavanger respondents are located at relatively similar distances from the city center of Stavanger (10.1 km and 9.2 km, respectively). Among the Greater Oslo respondents, the average distance from the dwelling to the city center of Oslo is 14.4 km, compared to 9.7 km between their jobs and the city center. Figure 2 shows how job densities vary between different parts of each of the two urban areas.

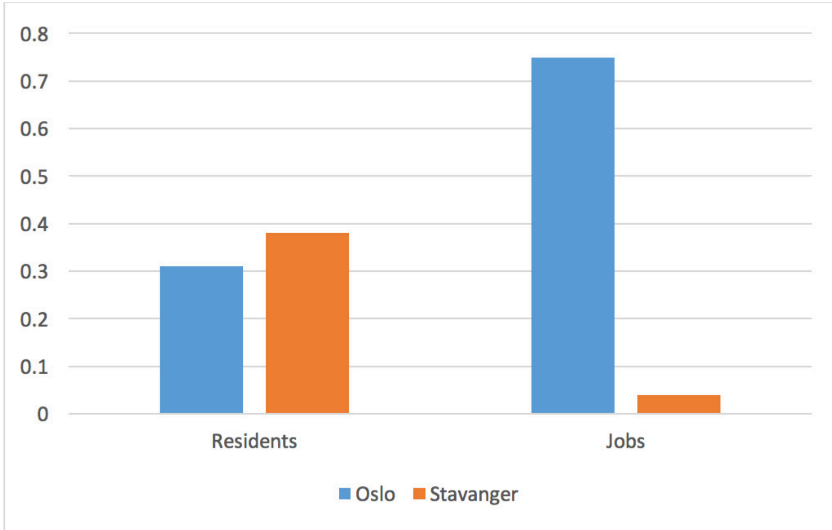

Figure 1: Monocentric bias indicator for the distribution of residents and jobs relative to the city centers of Oslo and Stavanger in 2014.

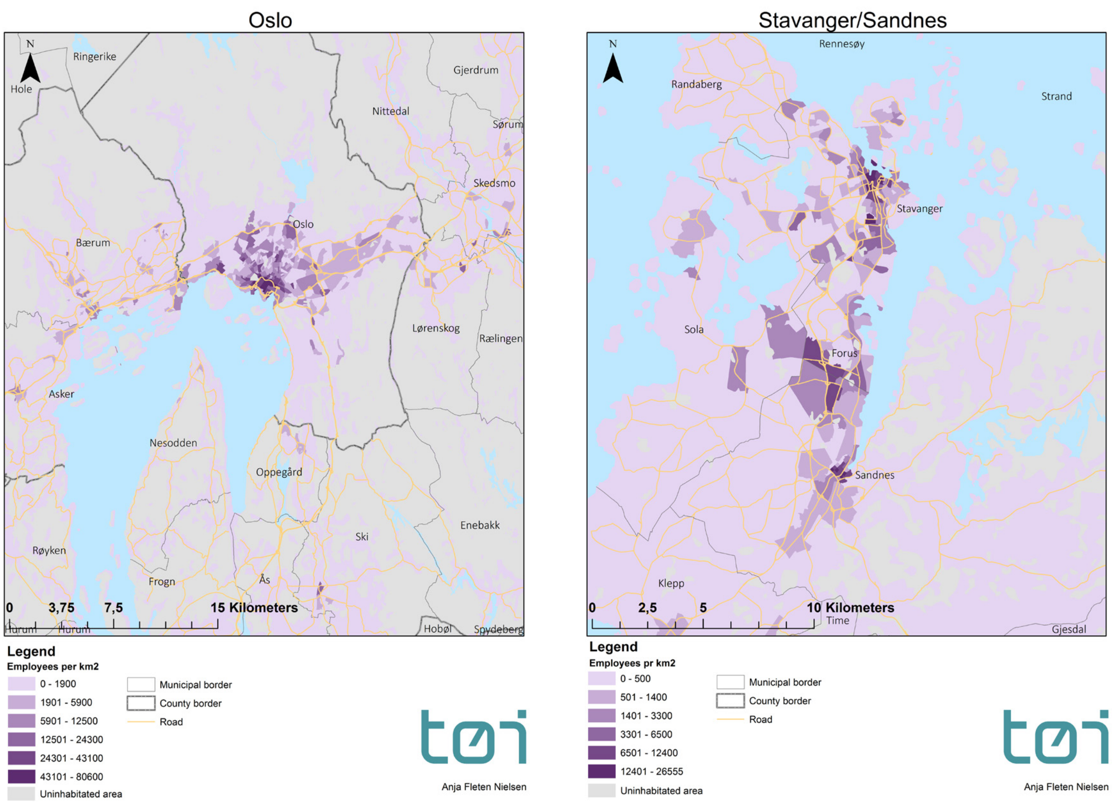

Figure 2: Job densities within different parts of the urban areas of Greater Oslo (to the left) and Greater Stavanger (to the right). To highlight intra-urban variation, the color scales differ between the two geographical cases, reflecting the generally higher densities in Oslo. Maps by Anja Fleten Nielsen, Institute of Transport Economics.

4 Methods

4.1 Built environment and causality

A basic assumption of this study is that built environment characteristics have the capacity to exert causal influences on human actions such as travel (Næss, 2015, 2016). These influences are not of a deterministic nature. The causal influences of built environment conditions are always only contributory, since a large number of other circumstances also influence individuals' decisions about whether, where, and how to travel. The ensuing transportation pattern is a result of people's resources, needs and wishes, modified by the constraints and opportunities given by the built environment as well as several other structural conditions of society. Individuals' transport rationales, i.e. the backgrounds, motivations, and justifications they draw on when they make transport-relevant decisions, make up important links in the mechanisms by which urban structures influence travel behavior (Næss, 2013). Philosophically, our study is inspired by the position known as critical realism (Bhaskar, 1993, 1998, & 2008; Danermark, Ekström, Jacobsen, & Karlsson, 2001; Sayer, 1992).

4.2 Research design

Empirically, the paper draws on a mixed-methods research design. The method combines questionnaire surveys with in-depth qualitative research interviews and careful studies of the geographical contexts of the investigated cities and urban areas. So far, this approach has been applied and gradually developed further in studies of residential location and travel in the cities/urban regions of Frederikshavn, Copenhagen, Hangzhou, Oporto and most lately Oslo and Stavanger. Distinct from the purely quantitative approach dominating mainstream research into the relationship between the built environment and transportation, an important strength of this research design is its better ability to identify causal mechanisms. The qualitative interviews provide insight into the rationales underlying people's decisions about participation in activities, location of these activities, and modes of transportation.

The gross samples of the web-based questionnaire survey were drawn randomly among residents living within broadly defined distance belts around the centers of each urban area, supplemented with inhabitants of 112 new residential developments identified by developers and realtors. In total, we sent invitation letters to 30,000 addressees. Around 3400 respondents returned acceptably completed questionnaires, yielding a response rate of 11.3%. Although not very high, the response rate is within the mainstream for studies on this topic[1]. Some respondents turned out to have moved away from the case regions and were therefore excluded, reducing the final samples to 3232 persons (1904 in the Oslo case and 1328 in the Stavanger case). The questionnaire included questions about demographic and socio-economic characteristics of the respondents, residential mobility (used to define movers), residential preferences, travel characteristics, physical activity and health. Besides cross-sectional multivariate analyses of the questionnaire data, we also carried out quasi-longitudinal analyses based on respondents' information about previous residential addresses, activity locations and travel behavior.

The households of the respondents and interviewees are on average bigger than for the population in their counties, and households with more than one workforce participant are somewhat overrepresented (Table 1). The respondents and interviewees also have higher education than typical for their counties. Household income levels are therefore considerably higher among the respondents and interviewees than among the county populations at large. However, there is also a higher proportion of pensioners among the respondents and interviewees, reflected in higher age and lower proportions of workforce participants in our samples. Car ownership rates are similar among the respondents to those of the county populations, and the same applies to the gender distribution. Since the statistical analyses

[1] For example, the response rate is similar to a much-cited American study (Kitamura et al., 1997), where a net response rate of 11 percent was achieved.

of this study do not aim to describe univariate distributions of car driving but to investigate its relationship with built environment characteristics when controlling for sociodemographic and residential preference characteristics, we do not expect the overrepresentation of certain groups of people in the sample to substantially affect the results (Babbie, 2007; Crano, Brewer, & Lac, 2015). Two of the most over-represented population groups (pensioners and high-income respondents) are relatively evenly distributed within each urban area. Respondents with education at master level or above tend to live closer to the city center than respondents with a lower education level do, but on the other hand, they tend to live in less dense neighborhoods.

Participants of the qualitative interviews were recruited among questionnaire respondents who had stated their willingness to be interviewed. In each urban area, we selected interviewees living at different types of residential locations (inner-city, close to second-order center and non-central) and who differed in terms of age, household composition, employment and education. Altogether, we conducted 33 interviews, 17 in Oslo and 16 in Stavanger. Each interview lasted 1–1.5 hours, was audio-recorded and transcribed. Some textbooks on interview interpretation focus on discovering unexpected phenomena and a "bottom-up" way of generating research questions. However, in the present study, specific research questions had already been formulated, based on earlier research. The main purpose of the qualitative interviews was explanatory, although we also tried to be open for new, previously neglected aspects. In our earlier studies, we had developed an *interpretation scheme*, designed for explanatory qualitative research as a tool for interview analysis. The scheme was refined and developed further in the present study. Two project team members interpreted each interview, and subsequent synthesizing of each group of research questions across the 33 interviews was also conducted by at least two project team members. More details about the methods of the study are available in Næss, Strand, Wolday, and Stefansdottir (2018).

Table 1: Comparison of demographic and socioeconomic characteristics of the survey respondents in the two urban regions, the participants in qualitative interviews, as well as averages for the groups of counties to which each urban region belongs

	Respondents of Oslo survey (N = 1,992)	**Respondents of Stavanger survey (N = 1,373)**	**Interviewees (N = 33)**	**Inhabitants of the counties Oslo and Akershus (including Greater Oslo)**	**Inhabitants of the county Rogaland (including Greater Stavanger)**
Average number of persons per household	2.29	2.49	2.79	1.94	2.29
Average number of children aged 0 - 6 years per household	0.23	0.24	0.55	0.15	0.18
Average number of children aged 7 - 17 years per household	0.35	0.43	0.36	0.13	0.15
Average age of respondents/interviewees (all aged 16 or more)	49.3	46.4	49.4	45.5	45.5
Gender (proportion female)	50.6%	51.6%	54.5%	50.3%	49.2%
Proportion of workforce participants among respondents/interviewees	68%	72%	73%	81%	83%
Average annual household income (1000 NOK)	1018	1053	1110	812	884
Proportion with education at master level or higher	40%	34%	47%	16%	9%
Average number of cars per household	1.23	1.45	1.39	1.18	1.49

4.3 Data and variables

Respondents were asked to report the approximate distances (in kilometer) they travel as a car driver in a typical week during the spring over the weekdays (Monday-Friday) and during the weekends (Saturday-Sunday), respectively. Weekly driving distance is computed as the summation of the two distance variables. On average, the Oslo respondents drive 104.5 km over the week, of which 58 km on weekdays and 46.5 km in the weekend. Mean driving distance among the Stavanger respondents is 102 km, with 61 km on weekdays and 41 km in the weekend.[2]

In the survey, the respondents who moved within the last two years (called movers) were asked to indicate whether moving from their previous to present dwelling has caused any changes (reduced, kept the same or increased) in the distance they travel by car in a typical week during the spring. Respondents were also asked to indicate the importance of 19 characteristics of housing and neighborhood when they were looking for a place to live (or if they were to move to a new dwelling) on a four-point scale from "not at all important" (1) to "highly important" (4). Because some of the characteristics are highly correlated, an explanatory factor analysis was used to obtain six underlying factors of residential preferences: exercise, amenity, children, shopping, transit, and investment (Table 2).

Table 2: Pattern matrix of factor analysis for residential preferences based on the data of both Oslo and Stavanger

	Exercise	Amenity	Children	Transit	Investment	Shopping
Opportunities for physical exercise	0.622					
Proximity to green areas	0.530	0.485				
Nice view		0.595				
Undisturbed location		0.515				
Architecture		0.359				
Private garden		0.343	0.609			
Good school/kindergarten			0.674			
Proximity to train/metro				0.705		
Proximity to bus/streetcar				0.765		
No social problems					0.403	
Favorable investment object					0.661	
Good property management					0.571	
Proximity to shops						0.714
Easy access to shopping mall						0.625
Extraction Method: Principal Axis Factoring						
Rotation: Varimax with Kaiser Normalization						
Variance explained: 68.7%						
Loadings smaller than 0.333 were suppressed						

Because of low loadings or conceptual interpretability, the following five items were dropped from the factor analysis: low housing costs, proximity to workplace, proximity to relatives and friends, distance to major road/rail line, and familiar neighborhood. The Eigenvalues of four factors are larger than one and the remaining two are 0.98 and 0.88 respectively. We kept the latter two factors because of conceptual interpretability.

Based on the addresses of residences, jobs and places of education and a set of center coordinates (the main city center, second-order centers and local centers) in each urban region, a number of GIS-based variables were added to the data file. These variables include, among others, distances from the dwelling to the three hierarchical center categories (the main center, the closest second-order center[3] and the closest local center), neighborhood population density, job density, and job-housing ratio. We also created a dichotomous variable indicating whether the residence was located in an area with high transit

[2] In these figures and in the following statistical analyses, respondents with extreme driving distances over the whole week were excluded, i.e., those driving more than 581 km in the Oslo case and more than 451 km in the Stavanger case. We also limited the sample to those who hold a driver's license.

[3] In Stavanger, separate distances to the two main second-order centers Sandnes and Forus were also measured.

accessibility[4]. For movers, some of the variables are measured at their former residence.

5 Results

5.1 Cross-sectional analysis

In this subsection, we present model results for driving distance in Oslo and Stavanger. For each of the two regions, we present three models: a model for the whole week, a model for weekdays, and a model for weekends. Because the histogram of driving distance has a long right hand tail, we employ Poisson regression with robust error, which relaxes the Poisson assumption that mean equals variance (Gould, 2011). The explanatory variables include the aforementioned residential preferences, demographic characteristics, and built environment elements. In the models for weekends, job density is not included because most people do not go to work on the weekends. To obtain a parsimonious model, we manually dropped the explanatory variables insignificant at the 0.1 level. Deviance R-squares for the six models range from 0.107 (Oslo weekend) to 0.206 (Oslo weekday). While not very high, they are typical for a disaggregate study with a large sample size.

Table 3 presents the Oslo model. After controlling for demographics and residential preferences, the distance to the city center is positively associated with driving distance. The elasticity for weekly distance is 0.287: associated with a 1% increase in the distance to the city center, the weekly driving distance will increase by 0.287%. The size of the influence is consistent with the literature (Ewing & Cervero, 2010; Stevens, 2017). On the other hand, the elasticity of the distance to the city center is much larger on weekdays (0.442) than on weekends (0.130). This is not surprising since the city center is oriented towards employment rather than daily life. However, suburbanites travel on average longer distances and have higher car shares of car travel for visits to non-work facilities such as cultural events, fitness centers and especially restaurants/coffee places (Næss et al., 2018). Furthermore, population density as well as job density within the residential neighborhood contributes to shorter driving distance. This is especially the case for visits to grocery shops, kindergarten, primary schools and short-duration outdoor recreation. Population density appears to have a slightly larger impact than job density. The size of the two influences is also similar to the findings by Stevens (2017).

In terms of demographics, being female is negatively associated with driving distance. The association seems to be stronger on weekends than on weekdays. It makes sense because women tend to shoulder more in-home household responsibility than men. As we expected, income has a positive association with driving distance. It is worth noting that it has the largest elasticity among all the variables tested in this study, indicating its dominant influence on driving distance. Age is negatively associated with weekday driving but positively associated with weekend driving. This is reasonable because the younger people tend to drive more on weekdays because of commute than the older people. However, the net impact of age on the weekly driving is insignificant. The models for weekly driving and weekend driving show that those who have a graduate degree tend to drive less than those without a graduate degree. The associations are marginally significant. It is worth noting that having a graduate degree is also negatively associated with weekday driving but the association is insignificant at the 0.1 level.

The investment factor is positively associated with driving distance. That is, those who consider dwellings an investment option and prefer nice neighborhood are more likely to drive. Preferences for transit and proximity to workplace have, as expected, negative associations with driving distance. The

[4] Mass transit provision is generally high in the largest Norwegian cities, especially compared to a North American context. Due to the different urban contexts of Greater Oslo and Greater Stavanger, the transit accessibility variable was constructed differently in the two urban areas. In Greater Oslo, the transit high-accessibility zone was defined as all addresses within 7 km road network distance from the city center, plus addresses within 1 km road distance from the closest second-order center, 0.5 km road distance from the closest local center and/or within 1 km walking distance (including formal and informal paths for non-motorized travel) from the closest heavy rail station. In Greater Stavanger, the transit high-accessibility zone was defined as addresses within 1 km walking distance from the closest heavy rail station and/or 0.4 km walking distance from the closest stop along the two major bus corridors of the urban area.

models also show that these impacts are from weekdays because the two variables are insignificant in the model for weekend driving. These relationships are reasonable.

Table 3: Poisson models for driving distance in Oslo

	Week			Weekdays			Weekends		
	Beta	P-value	Elasticity	Beta	P-value	Elasticity	Beta	P-value	Elasticity
Constant	4.129	0.000		3.806	0.000		2.822	0.000	
Demographics									
Female	-0.228	0.000	-0.111	-0.124	0.099	-0.060	-0.356	0.000	-0.174
Income	0.109	0.000	0.654	0.110	0.000	0.654	0.101	0.000	0.602
Age				-0.007	0.008	-0.369	0.011	0.000	0.537
Graduate degree	-0.122	0.051	-0.059				-0.162	0.063	-0.078
Residential preferences									
Investment factor	0.128	0.001	0.007	0.143	0.003	0.008	0.106	0.046	0.006
Transit factor	-0.105	0.006	-0.021	-0.178	0.000	-0.034			
Proximity to workplace	-0.054	0.060	-0.186	-0.103	0.008	-0.358			
Built environment									
Distance to city center	0.020	0.000	0.287	0.030	0.000	0.442	0.009	0.054	0.130
Population density	-0.003	0.049	-0.096	-0.003	0.086	-0.119	-0.003	0.031	-0.116
Job density	-0.005	0.014	-0.076	-0.006	0.053	-0.077	NA	NA	NA
Number of observations	1379			1370			1370		
Deviance R-square	0.181			0.206			0.107		

Notes: we tested the following built environment variables in the models: distance to city center, distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit. However, most of them are insignificant at the 0.1 level and hence dropped out of the models.

Table 4: Poisson models for driving distance in Stavanger

	Week			Weekdays			Weekends		
	Beta	P-value	Elasticity	Beta	P-value	Elasticity	Beta	P-value	Elasticity
Constant	4.252	0.000		4.429	0.000		2.690	0.000	
Demographics									
Female	-0.359	0.000	-0.180	-0.292	0.000	-0.147	-0.452	0.000	-0.227
Income	0.069	0.000	0.410	0.072	0.000	0.428	0.085	0.000	0.502
Age				-0.009	0.000	-0.438	0.008	0.003	0.366
Graduate degree				-0.147	0.049	-0.060	0.166	0.066	0.067
Residential preferences									
Investment factor	0.067	0.083	-0.003	0.092	0.042	-0.004			
Transit factor	-0.143	0.000	0.053	-0.177	0.000	0.065			
Proximity to workplace	-0.068	0.022	-0.247	-0.140	0.000	-0.509			
Built environment									
Distance to city center	0.025	0.000	0.259	0.027	0.000	0.279	0.021	0.001	0.215
Distance to Sandnes	0.003	0.001	0.029	0.003	0.047	0.027	0.003	0.000	0.030
Job-housing ratio				-0.018	0.008	-0.032			
Number of observations	944			944			944		
Deviance R-square	0.162			0.162			0.133		

Notes: we tested the following built environment variables in the models: distance to city center, distance to second-order center, distance to local center, population density, job density, job-housing ratio, and distance to transit. However, most of them are insignificant at the 0.1 level and hence dropped out of the models.

Table 4 presents model results for Stavanger. After controlling for demographics and residential preferences, the distance to the city center has a positive association with driving distance. The elasticity for weekly distance is 0.259, which is also consistent with the literature. Different from the Oslo model, the impacts of this variable on weekday driving distance and weekend driving distance are similar in size (0.279 vs. 0.215). Therefore, the distance to the city center in the large urban area seems to have a stronger impact on weekday driving than that in the medium urban area. The results are as expected given the high concentration of jobs in the central urban region of Oslo compared to the city center in Stavanger. Furthermore, because Stavanger has a polycentric urban form, the distance to the city center of Sandnes is also significant. However, its impact is much smaller than the impact of the main city center. Moreover, the larger the job-housing ratio is at the neighborhood level, the fewer kilometers a resident drives. Therefore, job-housing balance appears to reduce weekday driving. However, the variable has a positive sign in the model of weekend driving although it is insignificant. This suggests that there is a weak tendency that job-housing ratio increases non-work travel. Presumably, residents in the neighborhoods with high job-housing ratio need to travel slightly farther to meet their needs for weekend activities. Accordingly, the net effect of job-housing ratio is insignificant for weekly driving distance.

For demographics, being female is negatively associated with driving distance whereas income has a positive association in all three models, consistent with the Oslo models. The impacts of age on weekday and weekend driving distance are also similar to those in the Oslo model: negative for weekday driving and positive for weekend driving. Those with a graduate degree also tend to drive less on weekdays but drive more on weekends. The influences of residential preference for investment, transit, and proximity to workplace are similar to those in the Oslo model. The only difference is that the investment factor is insignificant in the model for weekend driving.

5.2 Quasi-longitudinal analysis

This subsection explores the impacts of inward or outward relocation on change in driving distance. Since change in driving distance was measured on an ordinal scale, ordered logit models were adopted. Using the addresses of current and previous dwellings, we computed change in the distance from residence to the city center. Based on this variable, we created a dummy variable to indicate whether respondents moved away from the city center. Then we multiplied the dummy variable with change in the distance to the city center and included the interactive variable in the model to show whether inward moving and outward moving have different impacts on driving distance. In the survey, we also asked about auto ownership and household size at current and previous residences so that we can control for the influence of change in household structure and change in auto ownership on change in driving distance. Because change in household size is insignificant in either models, the variable is dropped from the models (Table 5).

Table 5: Ordered logit models for change in driving after residential relocation

Oslo	**Beta**	**P-value**
Change in the distance to city center (current-previous)	0.093	0.001
Outward moving X change in the distance from city center	0.043	0.337
Change in the number of cars	0.802	0.003
Threshold 1	-0.738	
Threshold 2	1.597	
R-square	0.116	
N	306	
Stavanger	**Beta**	**P-value**
Change in the distance to city center (current-previous)	0.194	0.001
Outward moving X change in the distance from city center	-0.138	0.058
Change in the number of cars	0.347	0.157
Threshold 1	-1.073	
Threshold 2	1.524	
R-square	0.081	
N	178	

The Oslo model showed that the distance to the city center has a positive association with change in driving distance. As expected, moving away from the city center tends to increase driving distance and moving toward the city center tends to reduce driving distance. Because the interactive term between outward moving and the distance to the city center is insignificant, outward moving and inward moving have similar impacts on change in driving distance. An increase in auto ownership is associated with an increase in driving distance, also as expected. When it comes to the Stavanger model, the interactive term is negative and marginally significant, with a p-value smaller than 0.06. This indicates that although inward moving reduces driving distance and outward moving increases driving distance, the impact of inward moving seems to be larger than that of outward moving. A possible explanation is that residential self-selection is at work: mismatched suburbanites (who prefer transit but live in suburban areas) move towards the city center for alternative modes of transport and then reduce driving substantially, whereas mismatched urban dwellers (who are indifferent to transit) drive when they live in the city and then increase driving slightly after the relocation. On the other hand, the Oslo model does not show such a finding although we expect self-selection to be more salient in Oslo. Change in auto ownership has a positive sign but its effect is insignificant even at the 0.1 level. It is worth noting that we also tested the models without change in auto ownership because it is affected by change in residential location (Cao et al., forthcoming). The coefficients of other explanatory variables change slightly but their significance remained the same.

5.3 Why do residential location and neighborhood density influence car driving distances the way they do?

The qualitative interview material can shed light on some of the underlying reasons why the respondents' driving behavior shows the geographical differences presented in the previous sections. The interviewees' *rationales* for location of their out-of-home activities and for choosing modes of transportation make up important links in the causal mechanisms through which built environment characteristics influence travel.

Activity location rationales contribute to the relationship between residential location and travel distances. Among our 33 interviewees, we encountered the following five main rationales for location of activities: choosing the best facility, minimizing the friction of distance, limiting other travel-related expenses, maintaining social contacts, and variety seeking, with the first two as the most influential. For many activities, people do not necessarily choose the closest facility, but rather they travel a bit farther if they can then find a better facility. This is especially true in regards to workplaces. Commuting distances therefore depend more on the location of the dwelling relative to large concentrations of facilities than on the distance to the closest facilities. That is, the distance from the dwelling to the city center of Oslo (in the Oslo case) and to the Forus area and the city center of Stavanger (in the Stavanger case) has a dominating influence on commuting distance. For activities that are less specialized, such as grocery shopping, acceptable opportunities can usually be found closer to home, and the distance minimizing rationales therefore plays a greater role. The threshold distances within which an individual looks for relevant grocery stores is therefore much shorter than the threshold distance for seeking employment. For non-specialized activities, the density of the local neighborhood plays a greater role, since high local density gives a population base for more facilities near the dwelling. Still, most respondents from the two city regions travel out of their local areas to reach the destinations of nearly all regular trip purposes. This is especially the case for commuting trips, where respondents' commuting distances are on average 12.5 and 7.8 km in Oslo and Stavanger, respectively. The vast majority of commuting trips thus have destinations outside the local area of the dwelling, and as we have shown elsewhere, the density of the local area therefore is of little importance to commuting distances (Næss et al., 2018). For intra-urban non-work purposes, respondents' trip destinations are usually closer to home, and except visits to coffee places and restaurants, the majority of trip destinations for the seven non-work activities investigated in the survey[5] are located within 2 km from home. For such trips, local densities are important to travel distances (Næss et al., ibid.).

Travel mode rationales contribute to the relationship between residential location and modal split. Trip distances are important when choosing modes of travel. We identified three main rationales for choosing modes of travel among the interviewees: convenience and comfort, frustration aversion and time saving. In addition, seven other rationales also play some role: physical exercise, long-term habits, costs, safety, social contacts, esthetics and environmental concerns. While the convenience rationale does not affect the geographical differences in travel mode choice much, the time-saving rationale is, together with time-geographical constraints, an important part of the explanation why suburbanites tend to travel much more frequently by car than inner-city residents do. The frustration aversion rationale also contributes to this tendency. The remaining travel mode choice rationales are of little importance to the relationships between built environment characteristics and travel mode choice.

For both commuting and non-work trips, respondents' car trips are on average substantially longer than non-motorized trips, reflecting a rationale of time-saving (and to some extent a sub-rationale of avoiding too much physical efforts). For journeys to work, one-way commuting distance by car is on average 15.9 and 10.0 km among Oslo and Stavanger respondents, respectively, compared to 4.0 and 3.9 km for commuting trips by non-motorized modes[6]. Commuting distances by public transport are nearly the same as by car in both regions. The stores visited by Oslo and Stavanger respondents who regularly travel by car to do grocery shopping are on average located 2.5 and 2.6 km from home, respectively, compared to 1.0 and 1.1 km for those who regularly go by non-motorized modes.

As mentioned in the literature review, street design (often operationalized as intersection/street density or percentage of 4-way intersection) is one of the D's often held to be influential on travel behavior. However, none of the participants of our qualitative interviews indicated that the local street pattern was important to their travel– this feature of the built environment was barely mentioned at all. In Norwegian suburban residential districts, there are often a number of formal or informal shortcuts available for pedestrians and bicyclists, and the connectivity for non-motorized travel is therefore often considerably

[5] Civic or religious building, service provider, grocery store, restaurant or coffee place, place for entertainment/culture, place to exercise, and place where you pick up or drop off a passenger.

[6] The distances for non-motorized modes refer to workforce participants commuting by foot or on bike four or more days a week and by other modes less than once a week. Mean commuting distances on foot in Oslo and Stavanger are 1.4 km and 1.2 km, respectively, and by bike 6.2 km and 5.3 km.

higher than what might appear when looking at the routes for car traffic.

The interplay among residential location, the above rationales and time-geographical constraints (Hägerstrand, 1970) influences travel distances and modes directly, but also by influencing people's need for owning a car. If you live far away from daily trip destinations and have to travel by foot, bike or public transport, the time tied up in everyday travel may supersede other, desired doings. By acquiring a car (or possibly a second car), higher travel speeds are obtained, releasing more time for other everyday activities. Among Oslo and Stavanger respondents, cross-sectional as well as longitudinal analyses demonstrate clear influences of characteristics of the built environment – especially the distance from the dwelling to the main city center – on auto ownership rates (Cao, Næss, & Wolday, 2017).

There are still some important differences between the large, monocentric Oslo urban area and the smaller, polycentric Stavanger urban area. Although car driving distances in the Stavanger case depend mainly on how far the dwelling is located from the main centers of the region (the city center of Stavanger and the Forus and Sandnes second-order centers), driving distances by car in the Oslo case depend on residential distances to the city center as well as local-area densities. In Oslo, local-area density affects travel modes for non-work trips because distances to the relevant facilities visited tend to decrease with higher densities. In Stavanger, no neighborhoods are as dense as those in inner-city Oslo and there is less variation in neighborhood densities. Differences in local-area densities are not very influential on trip distances to intra-urban non-work activities, and the effect of local density on travel modes for such trips via trip distances is therefore much weaker than in Oslo (Næss et al., 2018). This is also consistent with the results of weekend driving in Tables 3 and 4: population density is significant in the Oslo model but insignificant in the Stavanger model. In Stavanger, non-work trip distances instead depend more one-sidedly on the location of the dwelling relative to the major concentrations of non-work facilities, i.e. downtown Stavanger and (to a lesser extent) the town center of Sandnes. In both regions, trip distances for commuting depend mainly on the location of the dwelling relative to the main employment centers, i.e. the city center in the Oslo case and the Forus second-order center and downtown Stavanger in the Stavanger case. In Oslo, the centrally located jobs have low car accessibility compared to the rest of the metropolitan area, so living close to the city center not only reduces commuting distances but also discourages car commuting. In the Stavanger case, the main concentration of workplaces (Forus) is easy to access for car drivers, with ample parking space and wide and relatively uncongested local roads (and not very good accessibility by public transport). Therefore, although living close to Forus reduces commuting distances, the high share of car commuting to this area implies that a short distance from the dwelling to Forus does not contribute to reduce car driving distances for commuting trips (Næss et al., 2018).

The driving distances reported by the respondents include all travel as a car driver in a typical week during the spring. Some of this is travel to places outside the urban area, such as large forested or heathland areas and cabins in the mountains or by the sea. However, the survey also asked specifically about commuting and trips to seven types of non-work activities. Below, we refer to trips for these seven non-work purposes and commuting to jobs less than 100 km from home (Oslo) and 50 km from home (Stavanger) as intra-metropolitan travel and the remaining driving distance reported by the respondents as extra-urban travel. Calculated this way, extra-urban driving accounts for about 45% of the respondents' total weekly car driving distance in both regions.

In both regions, the center-periphery gradients for overall driving distances are less steep than the corresponding gradients for intra-urban car travel. For overall car driving distances, the quartile of Oslo respondents living farthest away from the city center drive on average 2.2 times as long weekly distance as the most centrally residing quartile, with a corresponding ratio among Stavanger respondents of 1.45. Looking only at intra-urban car travel, the ratios are higher in both regions. In Oslo, the most peripherally residing quartile of workforce participants travel on average 5.3 times as long weekly distance by car for commuting and the seven non-work purposes investigated in the survey as the most centrally residing quartile of respondents do. In Stavanger, the corresponding ratio is 2.2. The steeper center-periphery gradients for intra-urban car travel than for overall driving distances does not imply that inner-city residents travel longer distances by car to destinations outside the urban area. The extra-urban travel distances of suburbanites and inner-city dwellers are similar in both regions. However, when a more or less constant extra-urban driving distance is added to the intra-urban car driving, the center-periphery gradient becomes less steep.

6 Concluding remarks

In both the Oslo and the Stavanger urban areas, the feature of the built environment showing the strongest effect on car driving distances is the location of the dwelling relative to the main city center. Although the distance to other centers has some impacts, they mostly become insignificant once the distance to the city center is controlled. That is, the distance to the city center has a dominant influence. Those respondents who live far away from the city center tend to drive considerably longer weekly distances than their inner-city counterparts do. This is evident from our cross-sectional as well as from our quasi-longitudinal analyses. In Oslo, high local population and (on weekdays) job densities also affect driving distances, but the effects of high density in terms of less driving are weaker than the effect of residential proximity to the city center. It should also be noted that local densities depend heavily, for economic as well as cultural reasons, on how centrally or peripherally a neighborhood is located[7]. In Stavanger, residential proximity to the Sandnes second-order center also contributes to less driving on weekdays, as does local surplus of jobs compared to the number of residing workforce participants (the latter only for weekday travel).

Residential location and neighborhood densities influence travel through their interplay with time-geographical restrictions and the inhabitants' rationales for location of activities and travel mode choice. For commuting and trips to specialized non-work activities, people do not necessarily choose the closest facility, but rather they travel a bit farther if they can then find a better facility. For less specialized activities, people are more prone to use local facilities, but such trips usually make up a small part of the total distance traveled in daily life. Traveling distances therefore tend to depend mostly on how far the dwelling is located from the largest concentrations of jobs and other specialized facilities. Travel mode choice rationales of time saving and frustration aversion contribute, in combination with time-geographical constraints and suburbanites' usually longer trip distances, to make driving an attractive option for many of those who live far from the city center. Poorer public transportation opportunities and easier parking in the suburbs also contribute to this.

Both in predominantly monocentric Oslo and more polycentric Stavanger, driving distances are influenced more strongly by residential distance to the city center than by any other built environment characteristic. Although living close to the major suburban employment center Forus contributes, as we have shown elsewhere, to shorter commuting distances (Næss et al., 2018), Forus has ample parking opportunities, wide roads and rather low accessibility by mass transit. Higher shares of car commuting therefore counterweigh the shorter commuting distances among those who live close to Forus. Instead, Stavanger respondents tend to drive slightly shorter distances if they live close to the second-order center Sandnes, which is a more traditional downtown area. Distinct from the Stavanger case, where we see no effect of local density, Oslo respondents tend to drive somewhat less if local job or population densities are high. In Oslo, several areas in the inner city make up a large population base for various services, and residents of these areas often do not need to travel out of their neighborhood to find relevant facilities. In Stavanger, the neighborhoods are generally less dense, also in the inner districts, and the need for non-work driving thus depends more on where you live relative to the concentration of facilities in the

[7] Alonso, 1964; Fishman, 1996; see also Næss et al., 2018 for evidence from the Oslo and Stavanger metropolitan areas.

city center.

We also notice that mean car driving distances are only slightly longer among the Oslo than the Stavanger respondents. Despite the wider spatial extent of the population-wise considerably larger Oslo urban area, poorer public transport opportunities and generally easier access by car in Stavanger appears to counterweigh the lower need for traveling long distances in the smaller city region.

In both city regions, the main built environment characteristics contributing to increase car driving distances on weekdays also do so for weekend driving. We thus find no tendency of "compensatory" weekend driving, as has been postulated by some authors. In Oslo, the effects of built environment characteristics on weekday driving distances are still stronger than those for weekend driving, with a particularly strong contribution to shorter weekday driving distances when living close to the city center. In Stavanger, the influences of built environment characteristics are nearly as strong on weekend as on weekday driving distances. This reflects that the city center of Stavanger is just as much an attractor of non-work trips as commuting, with the former trips often taking place during the weekend.

Among the D's mentioned in the literature review, our study thus finds that regional *destination accessibility*, understood as distance from the dwelling to downtown, exerts the strongest influence on car driving distances in both regions. We also find some influence of district-level destination accessibility and neighborhood *density*, but these effects are considerably weaker. We find some impact in Stavanger of *diversity* in the terms of neighborhood job surplus, but although this contributes to a slight reduction in driving distances among local residents, this does not imply that local jobs-housing surplus or balance contributes to reduced driving distances among non-local employees (who are the majority for most kinds of jobs). *Distance to transit* showed only insignificant effects in this study. The level of service of public transportation in both regions depends heavily on the distance to the main city center and (to a lesser extent) to lower-order centers and local-area densities. Part of the effects of differences in mass transit provision are therefore probably absorbed by our destination accessibility variables. Street *design* was not investigated separately, but in the qualitative interviewee this was not at all mentioned as a built environment characteristic that matters to travel. Neither was *demand management* a topic of this study, but according to earlier studies, the toll cordons in Oslo have suppressed car driving somewhat (Lian, 2004). Finally, our study shows, in line with numerous other studies, that socio-*demographics* influence driving distances, particularly income and age.

We consider the main results of the study as generalizable particularly to the Nordic countries (Scandinavia, Finland and Iceland), but also to other North and West European countries. The present study and our earlier studies have shown surprisingly high similarity in individuals' rationales for activity location and travel mode choice across the widely differing contexts of Copenhagen, Hangzhou, Oporto, Oslo and Stavanger. This suggests a high degree of generality in the basic mechanisms through which urban form influences travel behavior, at least for cities with high levels of affluence and job specialization. The magnitude of the effect of each built environment characteristic will of course vary with the specific city context, as we can also observe when comparing the results from Oslo with those from Stavanger.

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