Transportation Research Part D 107 (2022) 103297

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Exploring the potential for sustainable accessibility across settlement types. A Swedish case

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ARTICLE INFO

Keywords:
Sustainable accessibility
Daily amenities
Settlement typology
Small Urban areas
Rural Areas
Modal accessibility gap

ABSTRACT

The potential for residents of smaller urban and rural areas to benefit from sustainable accessibility is an under-researched area. This paper explores accessibility to important every-day amenities within short travel times and how this differs across geography and mode of travel. The analysis draws on a combination of novel open-source data of the transport system and official Swedish register data of the total population of individuals and workplaces geocoded at a 100-meter resolution. The findings show considerable variation in accessibility to everyday amenities by travel mode for different settlement types. While the car provides good accessibility, short trips by bicycle are a very competitive alternative in urban and suburban areas. Access to every-day amenities by active travel modes is limited outside urban areas. Employing accessibility analysis by settlement type offers a powerful policy support tool for planners charged with developing measures to address sustainable accessibility for small urban and rural areas.

1. Introduction

Cities and regions worldwide face the problem of how to manage the growth of population and businesses while meeting policy targets for a sustainable future for all citizens (UN-Habitat 2009). An ongoing challenge is the transition to more environmentally sustainable transport modes (Banister 2008; Curtis, 2020). Technological solutions (low- or non-emitting vehicular transport modes) alone will be insufficient to reach this ambition. Many policymakers now emphasize that increased effectiveness of transport policies towards a zero-emission target also requires land use interventions by planning agencies (see e.g., Swedish Climate Policy Council 2019). Employing an accessibility perspective offers the ability to address both transport opportunities and proximity opportunities, the latter concerning the location of population and everyday destinations (Geurs and van Wee 2004).

Accessibility planning is an emergent planning practice (Silva et al., 2017), seen in the shift from mobility-enhancing to accessibility-enhancing strategies (Curtis 2007, Banister 2008, Handy 2002, 2020). From a regional or local planning perspective this includes integration of an array of spatial planning considerations, including infrastructure, housing, work and healthcare, together with the need to support environmentally sustainable modes of transport including walking, cycling and public transport. A key issue is how to facilitate the transition to sustainable accessibility and also ensure fair levels of access to every-day services across the array of settlement types - from urban cores through suburban to small urban and rural settings.

Sustainable accessibility planning requires a good understanding of the geographical and social distribution of mobility options and

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https://doi.org/10.1016/j.trd.2022.103297
Received 29 December 2021; Received in revised form 27 April 2022; Accepted 27 April 2022
Available online 13 May 2022
1361-9209/

location of every-day activities (Curtis 2007, Elldér et al. 2018, Gil Solá et al. 2018, Silva et al. 2017). Novel micro-level approaches and data availability have enabled increasingly detailed and dynamic accessibility analyses, considering different transport modes and time windows, with high spatial resolution (i.e., 'door-to-door' approaches) (Järv et al. 2018, Stepniak et al. 2019). The social dimension has also received considerable attention, highlighting that accessibility is, as with many other resources in society, unevenly distributed socially and geographically (Lucas 2012, Elldér et al. 2018).

The variation in accessibility across different settlement types, and for smaller urban and rural areas, for a range of journey purposes has received less attention in accessibility research. Understanding these differences is crucial if small urban and rural areas are to achieve sustainable travel. There are studies assessing differences between public transport and car (Niedzielski and Kucharski 2019, Salonen and Toivonen 2013), but only limited studies where accessibility is compared across different cities (Liao et al. 2020) and settlement types. It is rare to find a full range of transport modes included, especially cycling and walking (McCahill et al 2020). Non-urban contexts do not appear to be included at all. Across the range of settlement types a planning agency may have responsibility for, both land-use conditions and transport opportunities vary – they are quite different in dense cities compared to sparsely populated and rural areas. Yet planners are tasked with ensuring inhabitants of all settlement types live sustainably.

Traditionally, accessibility studies have focused on job access, which generally entails regular travel over longer distances since most people do not live close to work. If sustainable accessibility is to be achieved, it is also important to include non-work destinations, especially considering that individuals carry out a range of daily activities, not only work, which influence their mode choice and hence their potential for more sustainable travel behaviour. Travel behaviour research shows that local accessibility to daily amenities can contribute to more walking and cycling (Elldér et al 2022, Handy et al 2006, Næss et al 2019).

This paper explores the extent to which accessibility by different transport modes (car, public transport, bicycle and walk) supports access to every-day amenities, and how this differs across settlement types. The analysis is focused on the region of Västra Götaland, Sweden – a large geographical area for which the regional planning authority has responsibility for and includes a number of different geographical contexts. A settlement typology is developed and applied, classifying the study area along the urban–rural continuum into six settlement types ranging from large city centres to countryside scattered single housing. Exploring accessibility differences required a novel approach aimed at creating the conditions for usability in planning practice. Open-source data and tools are key components, and simplicity in approach is preferred over complexity when developing measures, such that planners can be equipped to address any shortcomings in infrastructure and land use in order to provide the conditions for inhabitants to live sustainably.

The paper is structured as follows. In the next section the research is positioned in the context of the wider research literature. The research approach is reported in section 3. The results are presented in section 4 and discussed in section 5. The final section advances the conclusions.

2. Literature review

Accessibility has long been a key concept for analysing and understanding land use, transportation and daily activity patterns (Hansen 1959, Ingram 1971, Geurs and Ritsema van Eck 2001, Geurs and van Wee 2004). Accessibility can be defined as "the extent to which the land-use transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport mode(s)" (Geurs and Ritsema van Eck 2001, p 36), highlighting transport and land use as its main components. The *transportation* component considers the disutility, most often operationalized as the time or distance a specific transport mode offers between origins and destinations. The *land use* component operationalizes the number, types, variety, quality, etc. of opportunities (e.g., jobs, services or recreation) available at certain destinations *vis-à-vis* the demand at origin locations (e.g., where people live).

The focus of accessibility studies has shifted more recently in both the transport and land use dimensions. First, the heavy focus on the car has been replaced with a growing number of studies now measure accessibility by walk, cycle and public transport (Curtis & Scheurer 2016, McCahill 2018, McNeil 2011, Vale et al. 2016). Second, there has been significant development in increasingly detailed analyses of both space and time. Novel tools and data sources, including OpenTripPlanner (OTP), General Transit Feed Specification (GTFS) and OpenStreetMap (OSM), provide new opportunities for dynamic and micro-level ('door-to-door') analysis of travel times with different transport modes, during different times of day, on a detailed spatial level (Järv et al. 2018, Stepniak et al. 2019). Third, there has been a shift in focus as regards the land use component, most notably away from a narrow focus on job accessibility. Other activities that are important in people's everyday life have gained attention, including grocery stores (McKenzie 2014; Páez et al. 2010; Widener et al. 2015), healthcare facilities (Neutens 2015, Wang 2012), education (Walsh et al. 2015), parks and recreational facilities (Reyes et al. 2014), as well as a wider set of such amenities (Grengs 2015, McCahill 2018, McNeil 2011).

These developments are welcome for several reasons. Job access is central for several key issues including peak-period traffic congestion and the function of the labour market. Also, the commute is, for many people, an essential daily trip. However, in most contexts, commuting to work does not constitute most of the travel, the proportion of non-work travel has increased in recent decades (Grengs 2015). In addition, a narrow focus on job access excludes groups outside the labour market that have traditionally received less attention in transport research and policy, such as the elderly, students, children and the unemployed. In addition, a large proportion of the days of the year are not working days. Of particular importance is the accessibility to various amenities that are central to carrying out maintenance activities that fulfil individual needs and obligations to family members, including activities such as shopping, accessing medical services, and housework. There is a long tradition of travel behaviour research showing how access to key non-work amenities have important effects on mode choice and travel demand (Handy et al 2006, Næss et al 2019, Kitamura et al 1997). Recent research has benefited from geographically high-resolution amenity data. Heroy et al (2022) show how neighbourhood amenities are associated with more walking and less driving in Bogota, Bolivia. In a Swedish context, local access to key amenities such as grocery stores have been found important for increased walking and cycling in daily life (Elldér 2020), but also certain combinations and clusters of daily amenities forming a ‘basic supply’ of essential services (Elldér et al 2022). A key aspect of a sustainable transformation of the transport system is how well walking, cycling and public transport can compete with the car when people carry out daily non-work activities.

Differences between transport modes in their ability to provide accessibility can been described in terms of modal accessibility gaps (MAG), such as between car and sustainable modes (Kwok and Yeh 2004, Yang et al 2017).[1] Empirical MAG-studies have mainly focused on differences between the car and public transport in reaching jobs, for example in Gothenburg, Sweden (Elldér et al., 2012), Detroit, USA (Grengs 2010), Helsinki, Finland (Salonen and Toivonen 2013), Warsaw, Poland (Niedzielski et al. 2020), and Beijing, China (Sun and Zacharias 2020). As expected, these studies generally find that the car provides better accessibility compared to public transport in most settlement contexts. It is only in the city centres and around some public transport nodes that public transport offers a viable alternative (see e.g., Kwok and Yeh 2004, as cited by Benenson et al. 2011, Niedzielski and Kucharski 2019). The study of Yang et al. (2017) is particularly interesting since spatial characteristics and influencing factors of MAG are examined. Results indicate that the difference in access between public transport and car decreases with increasing residential density, land-use mix, bus stop density and metro rail station density. However, there are examples of opposite results. Niedzielski and Kucharski (2019) conclude that in Warsaw the MAG in accessing supermarkets shifts towards public transport with increasing distance away from the city centre due to a long history of public transport investment, and notes that this is the opposite to U.S. cities. Very few studies include active transport modes. Chen et al. (2020) examine MAG to commercial centres between car, public transport and cycling in Nanjing, China. Unfortunately, there is no direct comparison between bicycle and public transport, but the comparisons by car indicate that public transport provides better access than by bicycle. Again, however, the car performs best, although the gaps are smaller in the city centre. Xianteng and Chaolin (2010), measure modal accessibility gaps between bicycle, car and urban transit in the same area, and Li et al. (2019), comparing accessibility by car, cycling and walking to urban parks in Shenzhen, China, also find similar results.

There is a research gap for studies that measure multi-modal, multi-activity accessibility differences by settlement types. We assert that this approach is of keen interest to both transport planners and land use planners charged with investment and development decisions for their region. A multi-scalar, multi-modal, multi-activity analysis is necessary for making critical allocations of scarce resources in the context of sustainability. Notably, all MAG-studies cited above are based in a single city or urban region, and it is unclear how MAG vary between different cities and settlement types. There are, of course, many examples of studies comparing accessibility by one mode across cities and regions. These studies generally find large inter-city differences, including in car access to jobs across Dutch municipalities (Moya-Gómes and Geurs 2020), public transport to jobs in Canadian cities (Deboosere and El-Geneidy 2018), a range of public transport accessibility indicators in 23 cities across the world (Curtis and Scheurer 2016), and accessibility to jobs by walking (Owen et al. 2014) and biking (Owen et al. 2019) in the 50 largest metropolitan areas in the U.S. Another related literature focuses on spatial variations of car dependency beyond larger cities. Wiersma et al (2016) included sustainable accessibility measures when analysing car dependence between and within regions in the Netherlands and found that the bicycle is a strong alternative to the car in cities with over 100,000 inhabitants. In another study, comparing three European mid-sized cities (differentiating centres and suburbs), Wiersma et al (2021) showed that a vast majority of residents in all spatial contexts can reach daily amenities by bicycle or on foot. These studies however only include schools and supermarkets.

There are some notable exceptions where more fine-tuned accessibility analyses include several modes and different types of activities. Levine et al. (2011) estimated four accessibility measures, work-car, work-transit, non-work car, and non-work transit, in a range of US cities, finding that more compact metropolis give greater car accessibility even if travel speeds are slower there. This shows how the land use component can compensate for slower means of transport. Unfortunately, the differences between mode and activities are not commented on to any great extent, although it is noted that car is generally better and that there are large inter-city differences in transit access. Liao et al. (2020) compared travel times by car and public transport in four cities (São Paulo, Brazil; Stockholm, Sweden; Sydney, Australia; and Amsterdam, the Netherlands), finding large differences in favour of the car in all cities and that the gaps are similar across the cities. The analysis is, however, not differentiated by activity. McCahill et al. (2020), compare accessibility metrics for regions in seven states across the U.S. including access to jobs by car, public transport and walking, and access to non-work destinations by walking. Although a close relationship between driving and transit access is found on a general level (car performing better), this relationship also varies within and across regions. Interestingly, walking accessibility, and most significantly to non-work destinations, gives highly different results than public transport and car. McCahill et al. (2020, p 8) therefore concludes that:

> *“a sole focus on access to jobs by driving or even a limited focus on driving and transit access misses important aspects of accessibility and opportunities to leverage information gained from more comprehensive accessibility analysis.”*

This paper takes up this challenge.

In summary, the geographical context, as expected, appears to be of great importance to MAG. There is a general trend where the car is less competitive in denser structures. However, it remains unclear how MAG between all four modes of car, public transport, bicycle and walking vary between settlement types where the conditions for sustainable transport can be expected to vary significantly, comparing, for example, remote rural areas, small towns, different types of suburbs and city centres of different sizes. Note also that most studies use summary metrics for activities, but this aggregation does not offer a clear picture of accessibility. The development of accessibility studies has been very rapid in terms of the transport dimension, where several studies measure travel times with detailed

[1] Related concepts include “Modal (accessibility) disparity” (e.g. Kawabata 2009) and “Modal mismatch” (e.g. Grengs 2010).

'door-to-door' approaches considering important factors such as congestion, different hours of the day, parking times, etc. However, there are several aspects in the land use dimension that have not received the same attention, not least the varying access to various types, clusters, mix and number of amenities important in daily life within and between different settlement types. We assert that this is a crucial dimension in relation to non-work destinations and how MAG vary across different settlement types.

3. Research approach

3.1. Study area

The Västra Götaland region located in western Sweden is selected as the study area. Its diversified geography makes it suitable for comparing accessibility across different settlement types and will enable the focus on smaller urban and rural areas. Approximately 1.7 million people lived in the region, including Sweden's second largest urban region, Gothenburg, with 900,000 inhabitants, as well as several medium-sized cities, including Borås (75,000 inh.), Trollhättan (50,000) and Skövde (40,000), smaller cities (both within and outside a 45-minute commuting distance to larger cities), as well as sparsely populated and remote rural areas. The transport infrastructure differs significantly within the region. Public transport is available in large parts of the region but is better in Gothenburg – offering a well-developed public transport system with trams, buses, ferries and commuter trains (performing well in international comparisons, see Curtis et al. 2019). The regional planning authority has responsibility for the delivery of public transport and works closely with local municipalities on the siting of land use development in the context of transport accessibility.

3.2. Capturing population and amenities

The analysis draws on a unique combination of novel open-source data of the transport system and official Swedish register data of the total population of individuals and workplaces geocoded at a 100-meter resolution. Data from the GILDA database provided by Statistics Sweden captures population and amenities, including data for educational-, income, employment-, and health insurance-registers. Every individual and workplace registered in Sweden is included. Geographical information on place of residence and workplace location are provided with a 100 m resolution. Detailed industry sector codes are provided for each workplace allowing identification of activity type (e.g., restaurant, grocery store, or school). This allows a detailed geographical analysis of the total population of inhabitants and key everyday amenities in Västra Götaland region. This enables the comparison of travel times by transport mode to different types of specific and key amenities such as grocery stores, schools, restaurants, pharmacies and district healthcare centres as well to capture the variety and quantity of amenities reachable within different time thresholds.

The focus is on key everyday amenities needed by a large share of the population. Accessibility is assessed to ten different categories of amenities: grocery stores, liquor stores, other specialized groceries (e.g., bakeries, fruit/vegetable stores), clothing/shoe stores, pharmacies, retailers of other nondurable goods (e.g., florist, chemist, pet stores), district healthcare centres/dentists, restaurants/pubs/cafés, primary schools, and preschools. These are daily amenities and destination points highlighted in previous research as important for everyday mobility decisions and welfare (Elldér 2020, Elldér et al. 2022, Haugen 2011, Larsson, 2020b). By reaching most of these amenities, many people can fulfil their everyday maintenance needs.

3.3. Capturing travel times

It is a challenge to capture travel times on a detailed spatial level in a large and geographically diverse region. The data consists of 135,299 populated 100 m cells as origins and 8,265 cells containing amenities as destinations, i.e., more than a billion OD-pairs to calculate travel times for each of the four transport modes analysed. A combination of data sources were needed; i) OpenStreetMap (OSM), an open-data, crowdsourced spatial dataset with detailed information regarding the road network; ii) the General Transit Feed Specification (GTFS) provided by Västtrafik (official public transport authority in the region), which consists of a collection of files that allows public transport authorities to publish their transportation schedule along with geographical information in a uniform manner; iii) and the Swedish National Road Database (NVDB), which contains detailed information about the geometry and the speed limit of each segment of the road network.

OpenTripPlanner (OTP) was used for walking, cycling and public transport. OTP is an open-source project used for multimodal trip planning and analysis. As input, it requires a set of origin and destinations points, as well as the OSM road network and the public transportation data for the region in the form of a GTFS file. Open Trip Planner makes use of the road network provided by OSM for all trips using roads, e.g. walking, cycling, driving, etc. Each segment of this road network belongs to a distinct link type. For cycling, OTP assigns fixed weights to each link type according to how suitable a link type is considered to be for cycling[2]. For walking we used the average speed of 1,3 m per second (4.68 km/h) and for cycling, the OTP default (11miles/h = 17.7 km/h) was chosen.

Since public transport is time sensitive, the travel time for three departing times were calculated, clustered around 17:00 (16:40, 17:00 and 17:20) in order to get as close to the actual minimum travel time as possible, by assuming that individuals would slightly alter their departing time in order to avoid long travel or waiting time. The specific time was chosen based on the Swedish NTS reported departure times for similar activities. pgRouting was used to capture car travel times – a routing extension for PostGIS.

[2] For more details see: https://wiki.openstreetmap.org/wiki/OpenTripPlanner#Bicycle_routing.

pgRouting requires a routable road network and a set of origin and destination points. NVDB was used for calculating the travel times from the closest network node of each origin to the closest network node of each destination travel times by car based on speed allowed on each road segment.[3] For all modes, we also included amenity locations outside of Västra Götaland (within a 50 km buffer), in order to take into account that individuals would also travel outside the administrative boundary in order to fulfil their needs. The travel times were then merged with the GILDA data in order to measure accessibility for each individual living in Västra Götaland at the time of study (N = 1,688,040). Fig. 1 summaries the data processing flow. Apart from the OTP-model for public transport described above, all trips are calculated as direct trips between origin and destination. Trip-chaining and multiple visits to facilities during the same trip are not considered.

3.4. Accessibility measures and analysis

Measuring accessibility to everyday amenities required some thought. First, the travel times are generally shorter than for work or leisure-related travel. Many people need and want to have these types of amenities within close (time) distance from home (Haugen 2011, Larsson 2020b). This particularly applies to key amenities such as grocery stores that are used regularly (Elldér 2020, Elldér et al. 2022). However, most individuals also need a range of different amenity types (representing various everyday needs such as grocery shopping, picking up/leaving children at school), and the choice options (e.g., reaching large numbers of amenities) are important for active travel to seriously challenge the car (Elldér et al. 2022). It is important that accessibility measures take into account, i) the diversity of amenities, ii) the quantity, and iii) that certain types of key amenities are represented within a reasonable travel time from home. It is difficult to capture all these aspects in one general accessibility index or using different types of gravity functions often applied for job or general accessibility measures. In the analysis, closest facility measures were used, as well as different cumulative opportunity measures – together this approach offers a more nuanced and richer picture of accessibility.

The closest facility measure is defined by the following equation:

$$A_i = \exp\left(-\beta \bullet t_{ij}\right), \tag{1}$$

where the accessibility for an individual (A_i) is simply a function of the travel time (t_{ij}) time between the place of residence i and the location where the closest amenity is located j, multiplied by shape parameter β (with $\beta > 0$). In this case, the accessibility A_i has a maximum value of 1, if the traveltime t_{ij} is zero and decreases towards zero with larger travel time t_{ij} due to the negative sign in front of β. The larger parameter β, the faster A_i decreases with increasing travel time. Accessibility to each specific category of amenity uses this measure. Furthermore, the following cumulative accessibility measure is used:

$$A_i = \sum_{j \in \{1,\ldots,J\}} O_j f\left(t_{ij}\right) \tag{2}$$

where A_i is the accessibility from the place of residence i, O_j is the number of amenity opportunities at location j, where J denotes the overall number of amenity locations considered, and t_{ij} is the travel time between i and j. Equation (2) is calculated both when O_j is defined as the total number of amenities and the number of different amenity categories, i.e., $O_j = \sum_{k \in \{1,\cdots,K\}} O_{kj}$, where K denotes the overall number of amenity categories and O_{kj} is the number of amenities of category k at location j. The travel time function $f(t_{ij})$ is defined as follows:

$$f\left(t_{ij}\right) = \begin{cases} 1 if\, t_{ij} \leq t_{\text{threshold}} \\ 0 if\ t_{ij} > t_{\text{threshold}} \end{cases} \tag{3}$$

where $t_{\text{threshold}}$ denotes the travel time threshold which is set to 10 min (one-way). This threshold is a realistic travel time for walking and cycling to everyday activities for many people (Alfonzo 2005, Barton et al. 2012, Elldér et al. 2022, Southworth 1997). However, time thresholds vary for different transport modes, individuals and activities, and some previous studies define time thresholds using average travel times from travel surveys. The objective of this paper is to compare different modes in different settlement types. The same threshold is therefore used in order to ease such comparison, but it is also important to be attentive that the prerequisites for different modes in different contexts differs significantly (discussed later). Note also that the presentation of the closest facility measures includes travel times from 0 to 30 min (one-way).

Finally, the modal accessibility gap (MAG) between to modes of transport for a specific location i is defined by.

$$MAG_i(m_1, m_2) = \frac{A_i(m_1) - A_i(m_2)}{A_i(m_1) + A_i(m_2)} \in [-1, +1] \tag{4}$$

where $A_i(m_1)$ and $A_i(m_2)$ denote the accessibility at location i for modes of transport m_1 and m_2, respectively. The range of this measure is between $+1$ (if only mode m_1 is available, i.e. $A_i(m_2)$ is zero, and -1 (if only mode m_2 is available, i.e. $A_i(m_1)$ is zero. For a practical application of this measure with some results see Fig. 7 and the corresponding discussion.

A systematic exploration of results, visualization and interpretation was employed in three steps involving mapping and plotting of

[3] This resulted in more realistic travel times compared to using OTP.

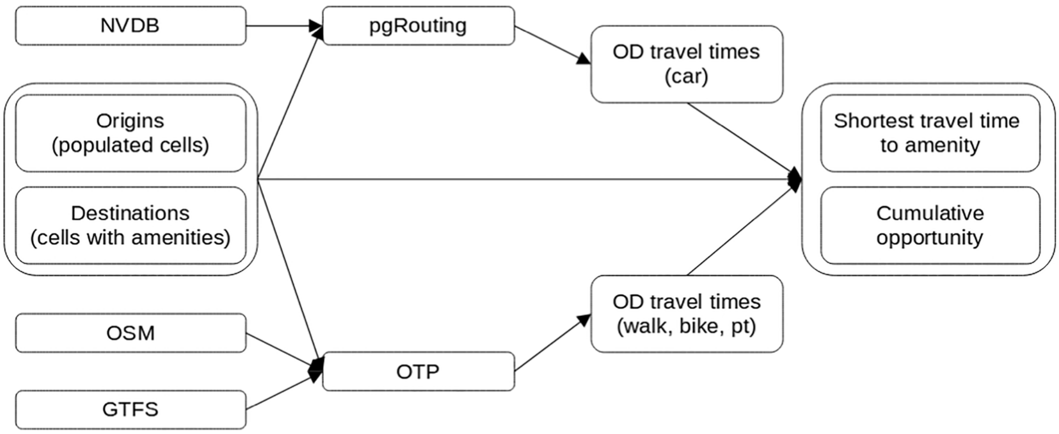


Fig. 1. Data processing flow.

accessibility measures. In a first step, regional modal accessibility gaps were explored by analysing the cumulative opportunity measures for the entire study area. In a second step, a more detailed exploration of how modal accessibility gaps differ across different settlement types used the geography described in the following section. In a third and final step, the analysis by amenity category was differentiated to explore how modal accessibility gaps differs for different types of services.

3.5. *Creating a settlement typology for analysis*

The high-resolution spatial data makes it possible to avoid aggregation to administrative areas that, for example, risk being too large to represent one homogenous type of settlement geography. However, it is important to take careful account of the context in which such a settlement typology is to be defined. Sweden is considerably less densely populated than most other countries. Many widely used definitions of settlement types are based on population density, such as the method used by (Eurostat, 2021). This approach has informed our work, however, given the population density in the case study area, adjustments to the Swedish context were required. A three-step procedure was applied utilizing detailed population data and official Swedish settlement delineations:

i. In the first step, the population density for each 100-meter cell was mapped, including testing different floating catchment areas, selecting a 1 km radius as the best fit.
ii. Second, the population density was overlayed with a combination of official Swedish geographical administrative classifications/typologies in order to support a first matching of the calculated population densities (SKR 2016, Larsson 2020a, SCB 2022).
iii. In the final step the correspondence between population density and land-use type was tested through a series of "spot checks" of 50 one-kilometre cells representing different land-use categories derived from the previous step. Smaller city centres and suburban centres were found to overlap in terms of population density (see Table 1). Therefore, a feedback-loop to step two was needed to divide these two categories. The new national statistical DeSO-areas (Larsson 2020b) were used to identify population centres in small and medium sized (in terms of population) municipalities, while the ones located in large municipalities were classified as suburban. The remaining cells were defined as either countryside near urban (if located adjacent to or between urban areas) or countryside scattered single housing. Photos illustrating the different settlement categories are in Appendix 2.

Of note is that only 13% of the population live in large city centres and smaller city centres/suburban centres (see Table 2). The vast majority reside in settlement structures that are significantly different from the dense urban areas underpinning many of the studies on accessibility and travel discussed in section 2. This spatial divide is further demonstrated in Fig. 2.

4. Results: Exploring spatial and modal accessibility gaps

4.1. *The regional accessibility context*

The general overview of the region for accessibility by transport mode to the everyday activities is shown using ECDF[4]-plots (Fig. 3), where the accessibility measure for each mode of transport as indicated with different colours. Two different measures of activities are shown - the completeness of potential opportunities (left) (i.e., how many of the ten activity categories that are accessible), and a cruder measure of the total number of amenities reached (right). The horizontal axis indicates that this is based on the

[4] Empirical cumulative distribution function.

Table 1
Settlement categories by population density and official classification definitions for urbanized areas.

Population within 1 km	Inside urban area as defined by Statistics Sweden (SCB)	Centre in small- or medium sized municipality by DeSO demarcation.	Adjacent to SCB urban area polygon	Other
7000+	Large city center			
6999–5000	Suburban center	Smaller city centre		
4999–1500	Suburb (dense housing estates)			
1499–250	Suburb (single housing)			
249–30			Countryside near urban	
29–3				Countryside scattered single housing

Table 2
Settlement types and population 2018 for the area of study Region Västra Götaland.

Settlement type	Population within 1 km	Total population	Percent
Large city center	7000+	95 125	6%
Smaller city centre or suburban center	6999–5000	123 011	7%
Suburb (dense housing estates)	4999–1500	597 337	35%
Suburb (single housing estates)	1499–250	525 588	31%
Countryside near urban	249–30	202 641	12%
Countryside scattered single housing	29–3	144 338	9%
Total		1 688 040	100%

principle that 10 min (one-way) is a realistic travel time for non-car-based mobility to everyday activities[5]. The vertical axis indicates the cumulative share of the total population within the region. For example, reaching 5 different amenity categories within 10 min is possible for almost the entire population using the car and 75% can reach the same supply with bicycle.

A substantial share of the population (about 40%) cannot reach a supply of more than three every-day activities within 10 min through walking or using public transport. If the diversity of supply is increased to include all of the 10 activity groups, the car still provides good access for two-thirds of the population while walking (<5 %) and public transport (<10 %) lose their potential. The bicycle, however, is still a potential option for almost 40% of the population. For the region overall, the analysis illustrates how walk and public transport provide relatively lower level of access compared to bicycle and car.

Figs. 4a and 4b compare accessibility by walk, bicycle, public transport and car by visualizing the two cumulative opportunity measures for the entire region on a map. The car, as expected, provides the overall best access in terms of geographical coverage – both in terms of diversity of amenity categories and in number of amenities. Interestingly, the bicycle provides access to a wider range of activity categories than public transport offers. It has far better reach than public transport for 10-minute trips in the larger cities. This is partly explained by the fact that public transport in most places has been planned primarily for commuting to work rather to service short local trips. Still, the maps illustrate a significant advantage of cycling in the spatial pattern of access to a large supply of different services.

Turning attention to the inaccessible areas on the maps, it is only in the larger cities that residents can carry out a diverse range of daily activities using sustainable means of transport within 10 min from home. Access to every-day amenities for large parts of the region is only possible by car. From a planning perspective this poses several challenges. For example, how should sustainable accessibility policies address locations where new development is clearly dependent on the car. This is further developed in the next section where different geographical contexts in the form of settlement categories are introduced.

4.2. Uneven access and settlement structure

The results so far highlight how accessibility is related to the interaction of population structure, mode of transport and the type(s) of amenity(s), demonstrating that every location in the region does not provide the same potential for the use of sustainable mobility options in pursuing everyday activities. This section focuses on accessibility gaps by settlement type. Fig. 5 shows an ECDF plot for the cumulative opportunity measures discussed above for each of the six settlement types described in section 3. Each column represents one accessibility measure while each row relates to one settlement type, the densest settlement types at the top with diminishing population density downwards.

Large cities (in this case Gothenburg) together with *suburban- and small city centres* are characterized by the high level of bicycle access that, in principle, is equal to the car. Those living in the large city centres have the potential to reach the full range of amenity categories as well as more than 250 amenities within 10 min both with car and bicycle. Public transportation provides lower potential access within 10 min of travel and is more comparable to walking in dense urban settings. However, a majority of people in the large

[5] Note, however, that the detailed plots in Fig. 6 and Appendix 1 shows travel times 0–30 min (oneway).

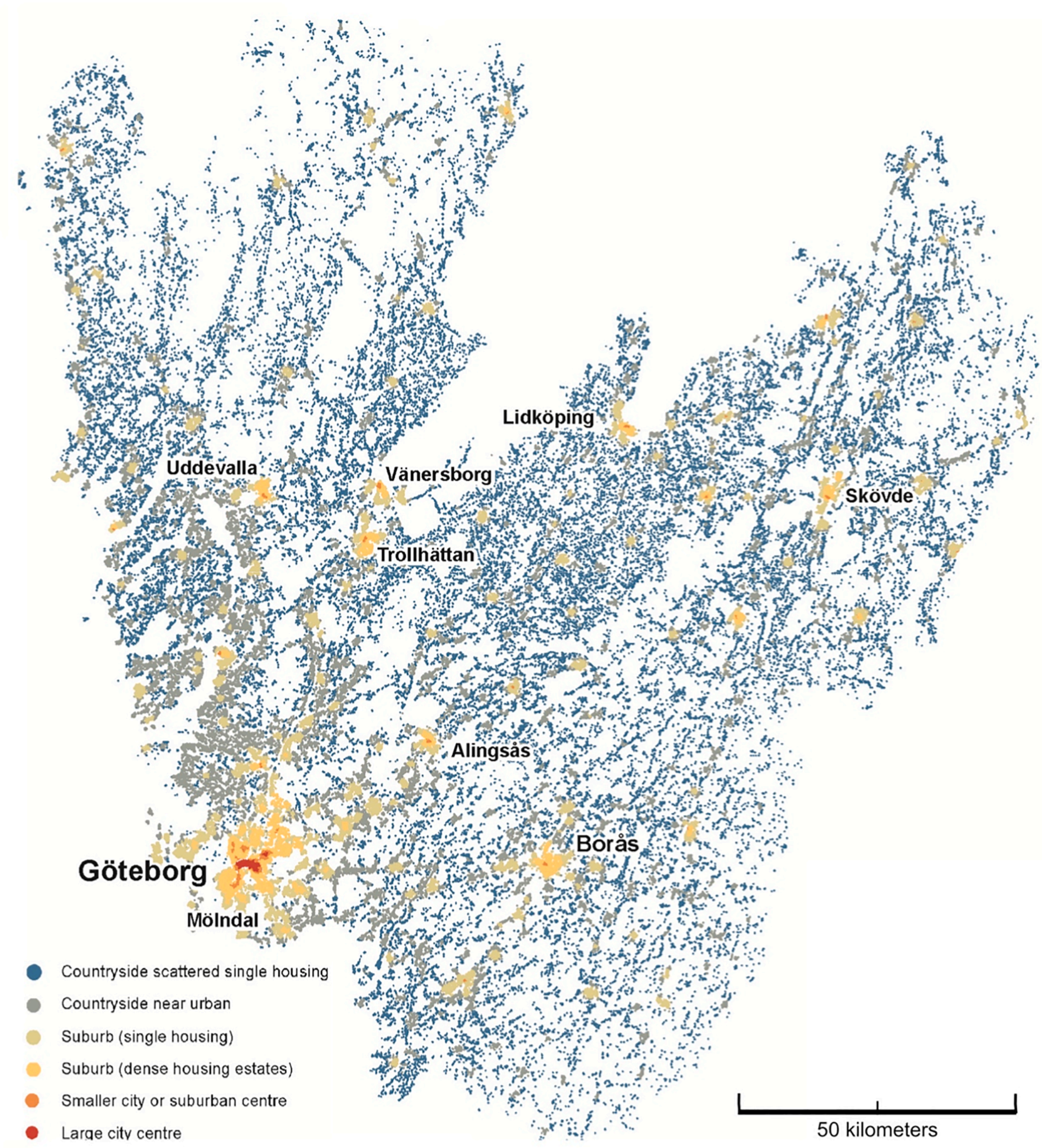


Fig. 2. Map of Västra Götaland region study area and settlement typology definition.

city centres, independent of transport mode, have the potential to reach 7–8 different amenity types within 10 min. It is mainly specialized amenities such as pharmacies and liquor stores that are less accessible within short travel times, while key amenities often used on a daily basis such as groceries and schools see small differences between car and cycle accessibility (see the detailed diagram in Appendix 1).

Dense suburban areas follow the pattern of the city centres due to their relatively high population density. One observation is the threshold between *dense suburbs* and the next category, *single housing suburbs,* where the car is now the dominant mode for achieving high levels of access. Cycling retains second place and follows the pattern of the car more closely compared to public transport and walking. For some basic amenities such as grocery stores, restaurants, and pre-schools, walking and public transport still provide access within short travel times for a majority of the population. However, few people reach more than four different amenity types with these travel modes.

Single housing suburbs represent not just suburbs adjacent to the large urban centre around Gothenburg, but also a variety of smaller

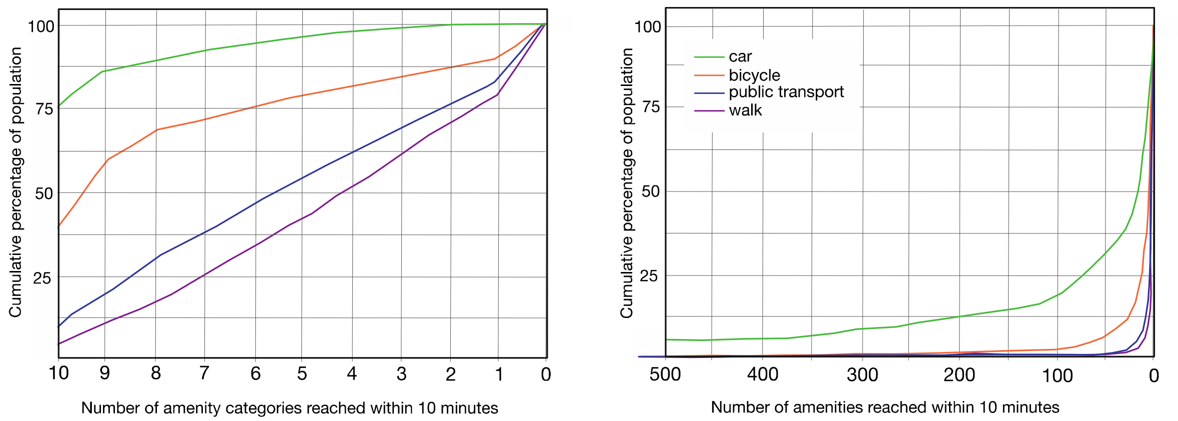


Fig. 3. ECDF plots of cumulative opportunity measures by transport mode within 10 min travel time.

towns and populated places across the region. The results suggest that people living in these are dependent on the car in order to access more than a basic supply of every-day amenities.

The non-urban contexts, c*ountryside near urban* and *countryside scattered housing* offer poor accessibility compared to the previous settlement types. Appendix 1 shows that if the travel time is increased from 10 to 15 min one-way, more than half of the population in these areas are still unable to gain access to any of the amenities without a car. Even for the most accessible amenities such as groceries, non-durables, restaurants and schools, both cycling and public transport require at least 30 min travel time to provide access for the majority of people living in the *countryside near urban* category.

4.3. The impact of amenity types

The detailed data enables the identification of specific amenity types. This allows for a more sensitive analysis of differences in access due to specific use of activities and destinations. Fig. 6 includes separate ECDF-plots for the shortest travel times to the closest of each amenity type. It illustrates that at least one grocery store, other non-durable goods, pre-school or school are accessible within 10 min from home for at least 50% of the region's population even by the slowest mode of transport. Common to these services is that they are used daily by many people. However, more specialized amenities that are used less frequently, such as pharmacies, liquor stores, specialized grocery stores, clothes stores and district healthcare centres are accessible by a lower share of the population based on a 10-minute one-way trip. These less accessible amenities also show greater accessibility difference between modes. These patterns suggest a concentration to fewer locations where the longer average travel times support car-based access and hence accentuate differences between modes. These amenities generally require a larger population base, and prevail under different location principles (e.g., concentration in retail agglomerations). In some cases, the city/suburb is not large enough to include even one single alternative of some specialized amenities. Interestingly, in these cases of spatially scattered concentrations of supply within the region, public transport becomes more competitive and, in some cases, provides a slightly better alternative than the bicycle for travel times around 30 min (e.g. pharmacies and liquor stores). These results become even clearer when the ECDF-plots for the shortest travel times to the closest of each amenity type are differentiated by settlement typology (see Appendix 1).

4.4. Mapping the modal accessibility gaps

Fig. 7 maps the relative differences between pairs of modes in the number of amenity categories that can be reached within ten minutes. The darkest purple identifies areas where the first mode dominates, and dark green illustrate the opposite situation with a domination of the second mode in the comparison. The maps confirm the car-dominated pattern, however there are new observations apparent - the bike can compete well with the car across the region in most urban areas.

It is only in the most densely populated areas of central Gothenburg, however, that walking and public transport provide an alternative to the car. The differences between public transport and bike further underscore the ability for the bike to provide good access over short distances, although in absolute terms large parts of the region are coloured grey which indicates no access at all within 10 min with either bike or public transport. It is also evident that better public transport access is restricted to the corridors of the network outside of the more densely populated centres.

5. Discussion

5.1. Sustainable accessibility across settlement types

The intent of this paper is to explore measures of accessibility from the viewpoint of the reality of individuals and their complex daily activity needs with a focus on the differences between settlement structures.

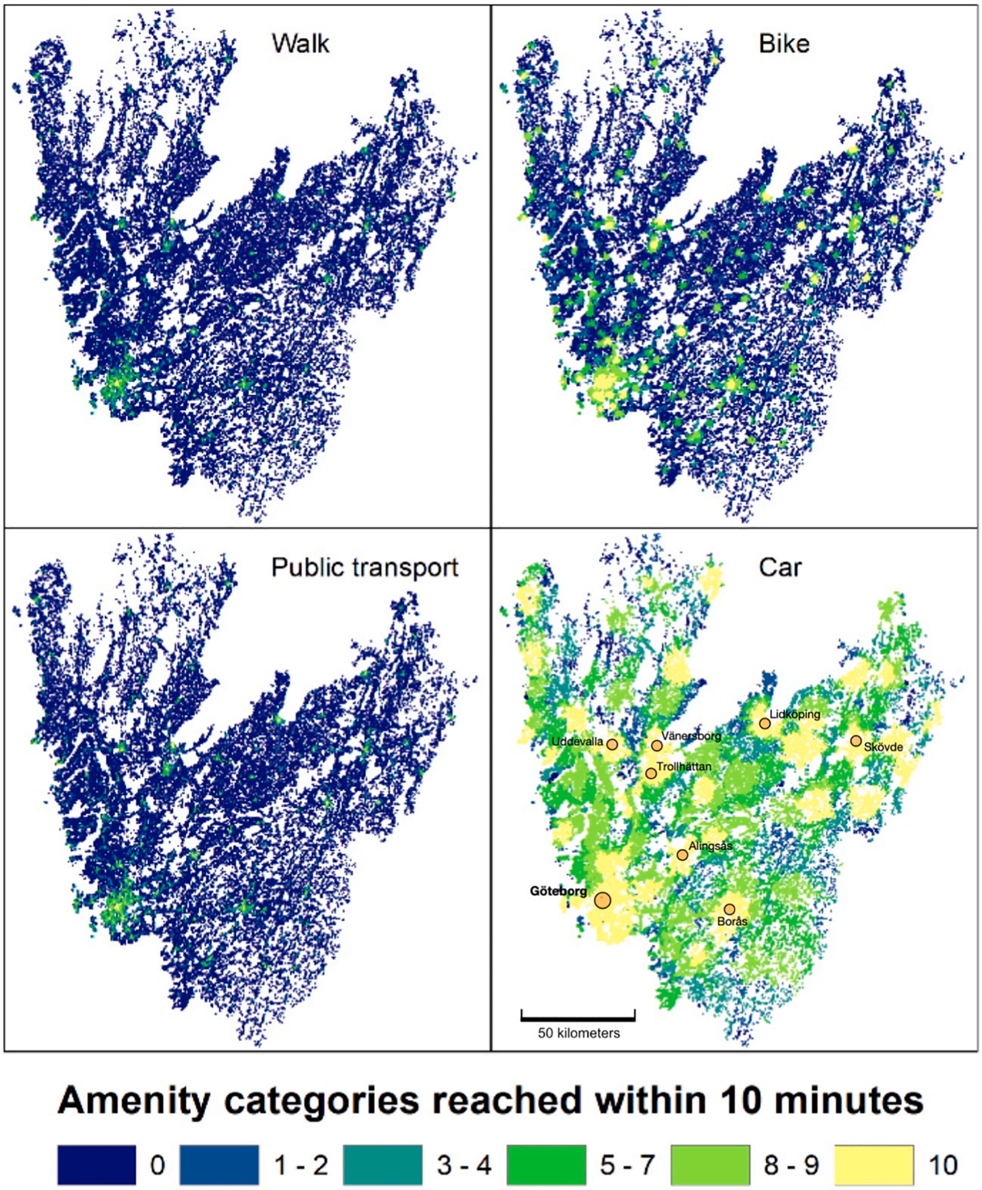


Fig. 4a. Maps of cumulative opportunity measure indicating the diversity of amenities accessible within 10 min by transport mode. Location of largest cities in the region indicated on the car map.

In general, large modal accessibility gaps are found. Due to its speed, the car provides the best potential accessibility alternative in all settlement types. The bicycle shows the best potential to challenge the car, and in many contexts provides an equivalent alternative for shorter trips. Public transport and walking, however, generally provide significantly poorer accessibility compared with the bicycle. Public transport is slightly better than walking, although these modes are generally equivalent alternatives.

Beyond these general results, a more detailed picture is offered by displaying important geographical differences and also major differences between the amenity groups that can be reached based on our assumption that ten minutes travel one way put focus on the potential for non-car-based access.

When it comes to the possibilities of reaching specific amenities that residents use daily, the differences between the car and the sustainable modes of transport are significantly smaller than the average. An important explanation is that these activities are more common and are more often located in residential areas. These include grocery stores, pre-schools and restaurants. However, when it comes to more specialized amenities such as pharmacies, it becomes more difficult for the slower modes to compete with the car. This indicates that planning for sustainable and equal access is not just a question of mobility but also a question of the geography of supply. The issue of supply become even more accentuated if we consider that people often want to choose from more than one alternative. However, having the potential to access a large number and a wide range of amenity categories within a ten-minute one-way trip from

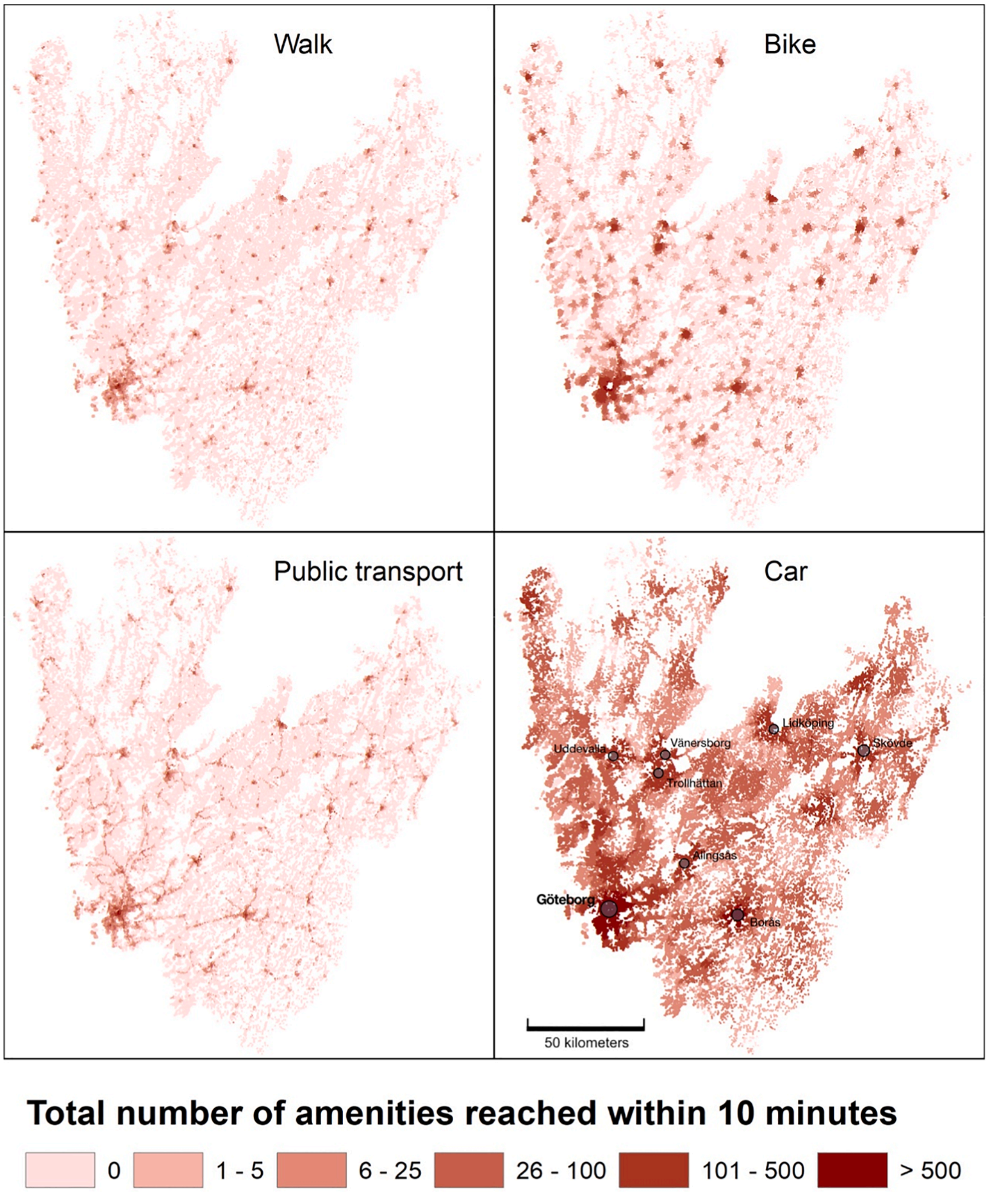


Fig. 4b. Maps of cumulative opportunity measure indicating the total number of amenities accessible within 10 min by transport mode. Location of largest cities in the region indicated on the car map.

the home reinforces the gap between different modes of transport in favour of the car.

A focus on settlement type in the analysis indicates that in the larger city centres and in densely built suburbs, the differences between transport modes are generally small, while in less dense settlement types it is much more difficult to challenge the car. However, it is important to point to the fact that most of the population in the case area live in different types of suburban settings. These areas are less homogenous than city centres or rural areas and seems to be a sort of transitionary belt around city centres concerning accessibility to every-day services. These are also the areas where new developments often take place, further emphasizing the importance of alternatives to city-based studies and models.

When it comes to the generalizability of our findings, there is unfortunately limited previous research suitable for direct comparison, not least when it comes to specific amenities, detailed settlement types and walking/cycling access. However, similar to previous research we find that the car generally outperforms public transport (e.g. Liao et al. 2020, Salonen and Toivonen 2013) and that the differences decrease when the density increases (Yang et al. 2017). When it comes to walking and cycling, our results are in agreement with Wiersma et al (2016, 2021) who also found that a majority of residents in mid-sized cities in the Netherlands and Europe could reach schools and grocery stores by bicycle or on foot. Asian studies also concluded that MAG between active transport modes and the car are smaller in central areas (Li et al 2019, Xianteng and Chaolin 2010). However, it is also important to remind that

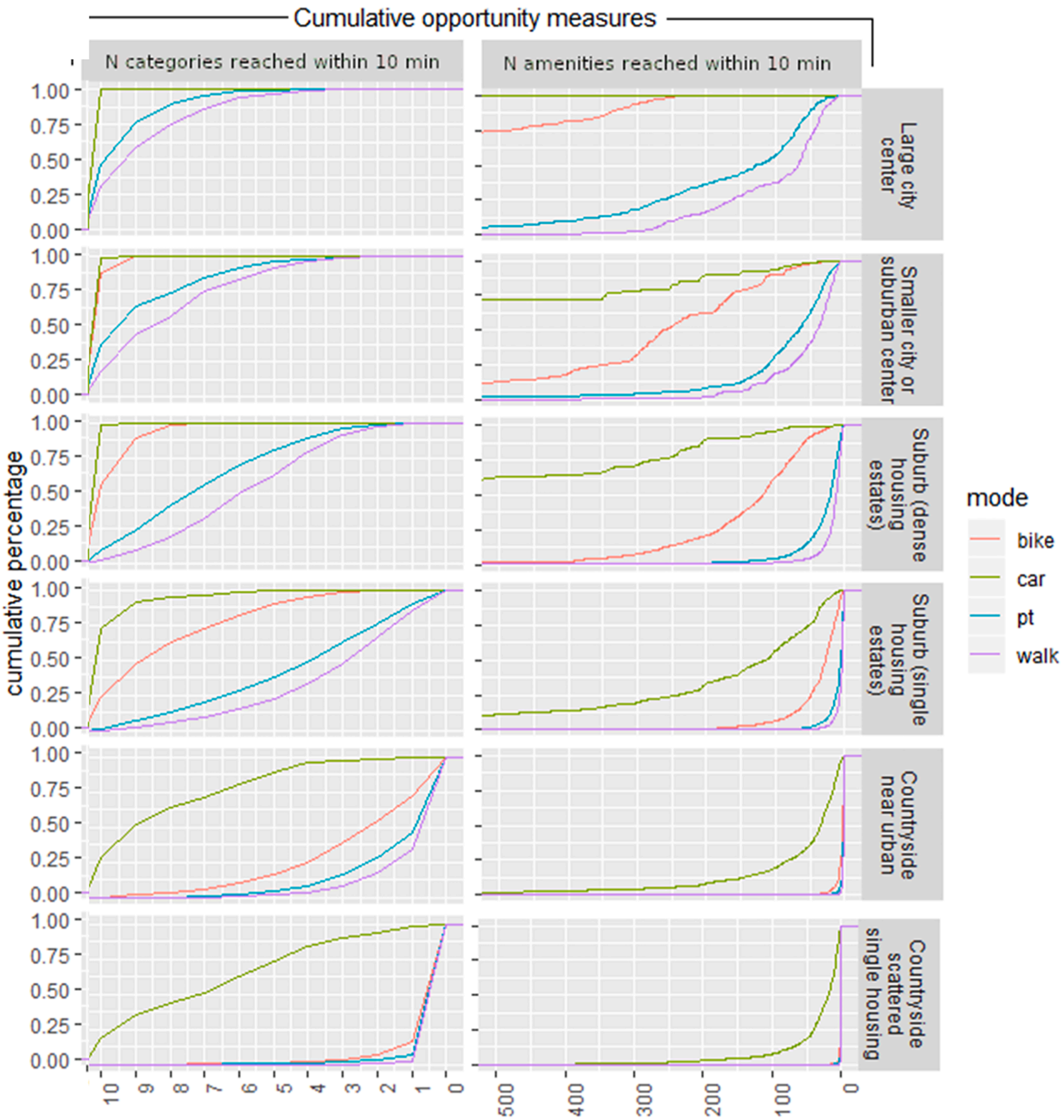


Fig. 5. ECDF plots of cumulative opportunity measures. Share of population by transport mode within each settlement type.

our results based on the specific geographical context of Region Västra Götaland, which is characterised by a large urban core in one “corner” and large areas of low population density along the “outer edges” with smaller towns in between. Regions with a more homogenous structure and higher population density may see less spatial variation (depending on prior investment decisions made by planners).

5.2. Implementation in planning

New high-resolution data, which is both rich and spatially-detailed, offers a platform to explore accessibility as a multi-faceted and hence more realistic input for planning strategies. In this way it can directly and holistically relate to the interests of planning practice in relation to sustainable transport investment and development decisions. The visual mapping and plotting provide an output of appeal to land use planners (te Brömmelstroet et al. 2016). The opportunities to interrogate the detailed data to understand why there are differences (by settlement type, by amenity, by transport mode) offers benefits in tailoring planning approaches and investment decisions, but there are also challenges, as discussed in this section.

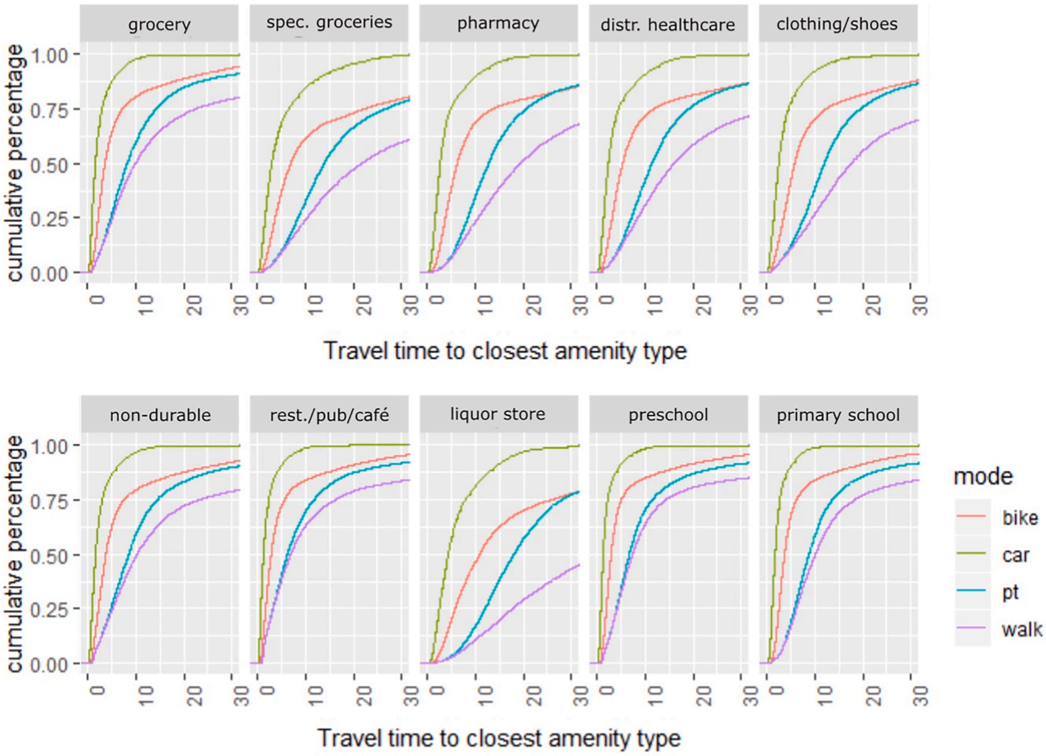


Fig. 6. ECDF plots travel time to closest amenity type.

The findings for accessibility by transport mode and activity category provide a useful overview for planners in assessing how well the transport supply offers the potential population to access everyday amenities. This could be developed further into a heuristic for policy targets towards sustainable accessibility.

The findings on accessibility by amenity type raise important questions as to what amenities should be available in which location types, and as well as considering diversity, it is possible to question how many of these amenities should be considered sufficient. This shifts the discussion in the direction towards relative measures where careful calculation and statistical rigour need to be combined with issues of equality and policy goals (Silva & Larsson 2018). The current discussion on accessibility and social justice offers one potential avenue for further development (Lucas et al. 2016, Pereira et al. 2017). Indeed, the interpretation of accessibility measures and its planning implications are intimately related to a wider understanding of the role of mobility in society. Transport planning has traditionally taken increasing economic development and better access through private cars as a tacit goal. However, in the light of resource scarcity, sustainability transition and claims for equality, other ways of valuing mobility need to be taken onto consideration (Cattaneo et al. 2022).

As regards the settlement typology, the contribution of this work is in its potential for analysis beyond pre-defined administrative areas while still incorporating the transport dimension with all four modes. It provides a basis for understanding flexible regional functional networks and relations (consistent with how inhabitants live their lives) as a complement to the more static administrative geography. The high geographical resolution lends itself to aggregation of results into other geographical entities. The findings for accessibility by settlement type open a discussion for planners about the overarching settlement strategy, especially within the context of sustainable development goals. It prompts a range of questions around expectations of provision in non-urban locations, such as if it is reasonable/affordable to service non-urban locations with sustainable transport. These and other such questions are again set in a much wider context that requires accessibility measures to be multi-modal, multi-activity, multi-scalar.

The aim in this paper has been to explore an approach where presentation and analysis is made open and accessible to users in order to avoid the problems of "black box" modelling output. The problem of communicability is to a larger extent linked to the level of abstraction and simplifications in models and calculations of indicators. This raises the issue of the tension between scientific rigour and communicability of accessibility measures (te Brömmelstroet et al. 2016; Papa et al. 2016; Silva et al. 2017). We assert that detailed data as such does not necessarily lead to increased complexity, nor impede the understanding of results. Using fine-grain and reliable data, shown here, is one way to safeguard a geographically grounded discourse around these problems and potential solutions. Providing MAG-maps can offer a powerful diagnostic tool for planners and policymakers based on a straight forward comparison between two modes of transport. In the same vein, the ECDF-plots offer an efficient way capture the multi-dimensionality of the data without hidden modelling assumptions.

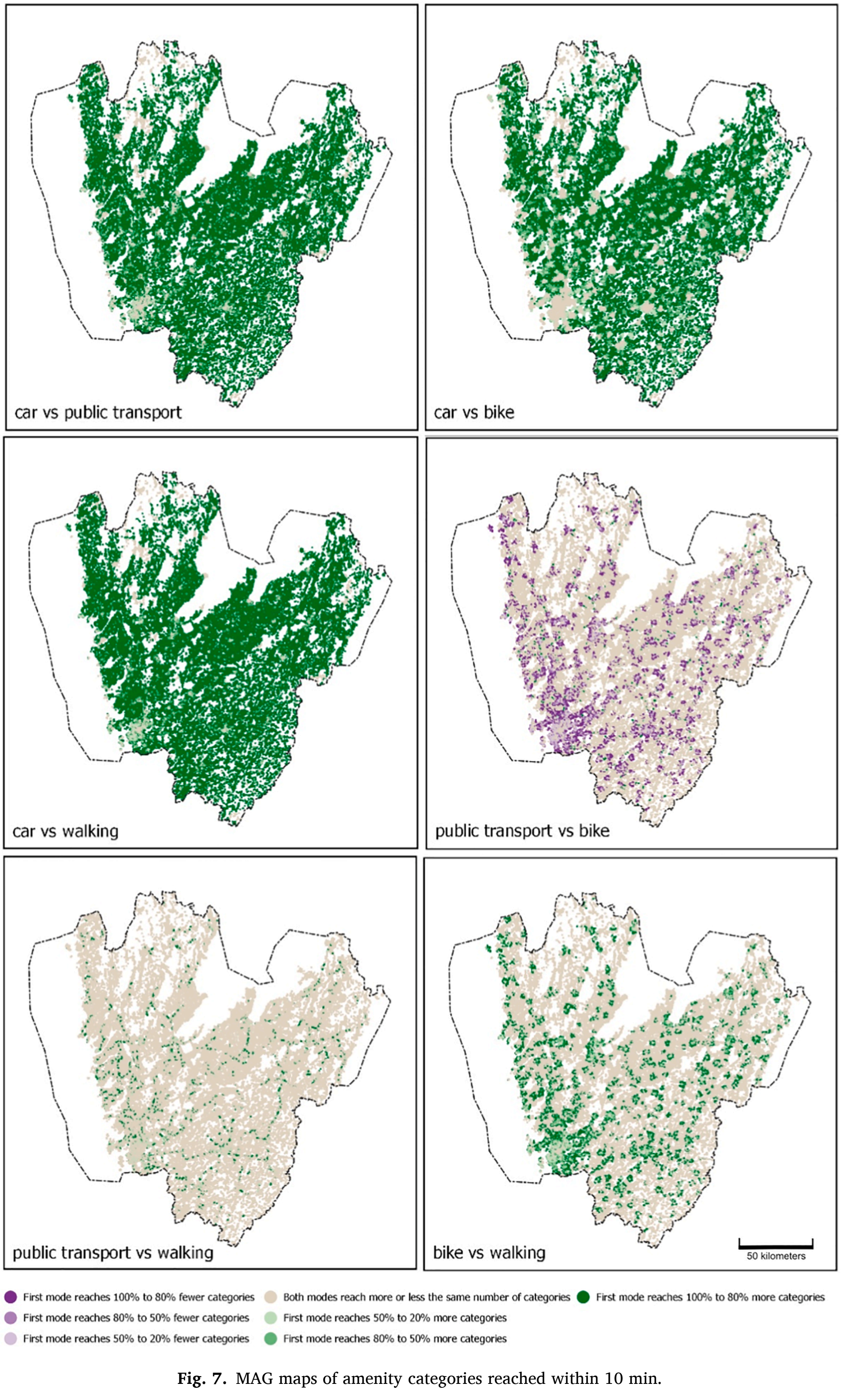


Fig. 7. MAG maps of amenity categories reached within 10 min.

5.3. Critical assessment of data, measures and results

One reflection concerns the underlying assumption of substitution, that all amenities within the same category are treated equal in the analysis. Some amenity categories have wide variation in supply and quality (e.g. restaurants and grocery stores), which risk being hidden by the 'closest facility' measure. Our interest in sustainable accessibility, such that people's needs and opportunities for being served closer to home, suggests that the significance of size of amenity is less useful than simply being able to access a shop. The disbenefit of including size as an attraction means it will favour car and public transport access since larger supermarkets are fewer and often located distant from homes. A related aspect is how to identify and measure the importance of the co-location of several amenity categories. Research shows that certain combinations of amenity types – i.e., a 'basic supply' of different amenities that allows a locally oriented everyday life – have important effects on mode choice (Elldér et al 2022).

Cumulative opportunity measures are predicated on a 10-minute travel time (one-way), this is based on the assumption that this is a realistic indicator for local living based on use of active transport modes. A further consideration relates to whether all modes should be treated equally as regards travel time – and this provides insights into whether car travel times should be impeded through use of travel demand management measures. Engagement by policy makers in agreeing such assumptions is a key aspect of learning and gaining new insights from using accessibility measures in planning practice.

The calculation of car travel times may be underestimated in certain settlement types since parking time, congestion, stop lights, and other attributes of denser urban areas that slow car travel have not been accounted for. As public transport timetables include such delays this disadvantages public transport in terms of estimated travel times.

Public transport travel times are calculated based on afternoon peak hours when public transport supply is at its highest. Local travel surveys revealed this time these activities are most commonly accessed. However, many amenities are also reached off-peak when public transport supply is lower. Also, public transport risks appearing less competitive when the threshold is set at 10 min due to access and egress times. However, we calculated travel times up to 30 min for the closest facility measures and found that the bicycle was still a faster alternative in most cases. Furthermore, e-bike and multimodal options (including walk/bike-public transport combinations) were outside the scope of this paper. Recent research from the Netherlands shows large potential, not least in medium-sized cities and suburbs (Wiersma 2020). It is also important to mention the declining trend of brick-and-mortar outlets with the rapid rise of e-commerce. Virtual accessibility is an additional way to access certain daily amenities (e.g., clothing/shoe stores) and is becoming increasingly important to consider in future research and policy.

The findings in this paper show that essential factors for increased cycling, proximity and short travel times, are already fulfilled in many contexts in relation to grocery shopping, restaurant visits and childcare. However, the bicycle mode share does not correspond to its demonstrably good accessibility. Many people do not feel safe enough or have the physiology to cycle with, for example, children and heavy grocery bags. There is often also a lack of cycling infrastructure in the form of, for example, lighting, winter road maintenance, accessibility, and safety. Moreover, non-work travel is not always independent of commuting to work, for example when car commuting is necessary. Acquiring and using a car for commuting risks being habit-forming and resulting in spill-over effects when reaching non-work destinations. A number of factors come into play influencing whether individuals take advantage of sustainable accessibility opportunities but the critical point in this paper is the demonstration of the supply of accessibility rather than the demand (the latter determined by e.g., travel behaviour). However, it is an important task for future travel behaviour research to detail when, where and why sustainable accessibility translates into sustainable mobility. The long tradition of built environment-travel studies could be an important departure, not least recent studies that utilize microdata of amenities geocoded at the neighbourhood level (Elldér et al 2022, Heroy et al 2022).

6. Conclusion

The policy imperative to achieve sustainable travel has gained in importance given the need to decarbonise travel in the face of the climate emergency. Knowledge of the effect of settlement type is, however, focused on large urban areas with dense city centres. There is scant understanding of the potential for sustainable travel in smaller urban and rural areas, yet these are the homes for a significant proportion of the population. Key to understanding the potential for sustainable travel is in the use of multi-scalar, multi-modal, multi-activity accessibility analysis. This can highlight accessibility shortfalls which create barriers for the achievement of sustainable travel – these may be in relation to transport infrastructure and/or the location of the amenities that support an inhabitant's daily needs.

By examining accessibility to daily amenities by a full range of transport modes, this research finds important differences in accessibility between settlement types. What sets smaller urban and rural areas apart from larger and more dense urban areas is the reliance on the car in order to reach a daily amenity. Dense urban areas and the adjacent suburbs provide good opportunities by sustainable modes of transport to reach a basic supply of daily amenities. The bicycle in particular is a very competitive alternative to the car in urban and suburban areas. Public transport and walking, however, generally provide poorer accessibility on a 10-minute travel time (one-way). In single housing urban sprawl and smaller towns and settlements, alternatives to the car are largely uncompetitive.

The findings point to the importance of integrating multiple metrics in the study of accessibility in three main aspects:,: *i)* the measurement of accessibility for all modes of transport, *ii)* the detailed geographical variation of modal accessibility gaps across settlement types, and *iii)* the need for in-depth consideration of the land use component of accessibility in terms of different activities/ amenities. The latter had less priority in the many important advances made in accessibility research in the last decade. By utilizing the unique Swedish register data and applying a mix of accessibility measures that capture the potential to reach several specific amenity-types as well as the variation and quantity, a richer image of accessibility emerges. This approach offers a useful input to planning practice.

Funding

This work was supported by the Swedish Energy Agency [grant number 44499-1] and Region Västra Götaland as part of the project "Accessibility Planning Lab" [grant number KTN 2017–00124].

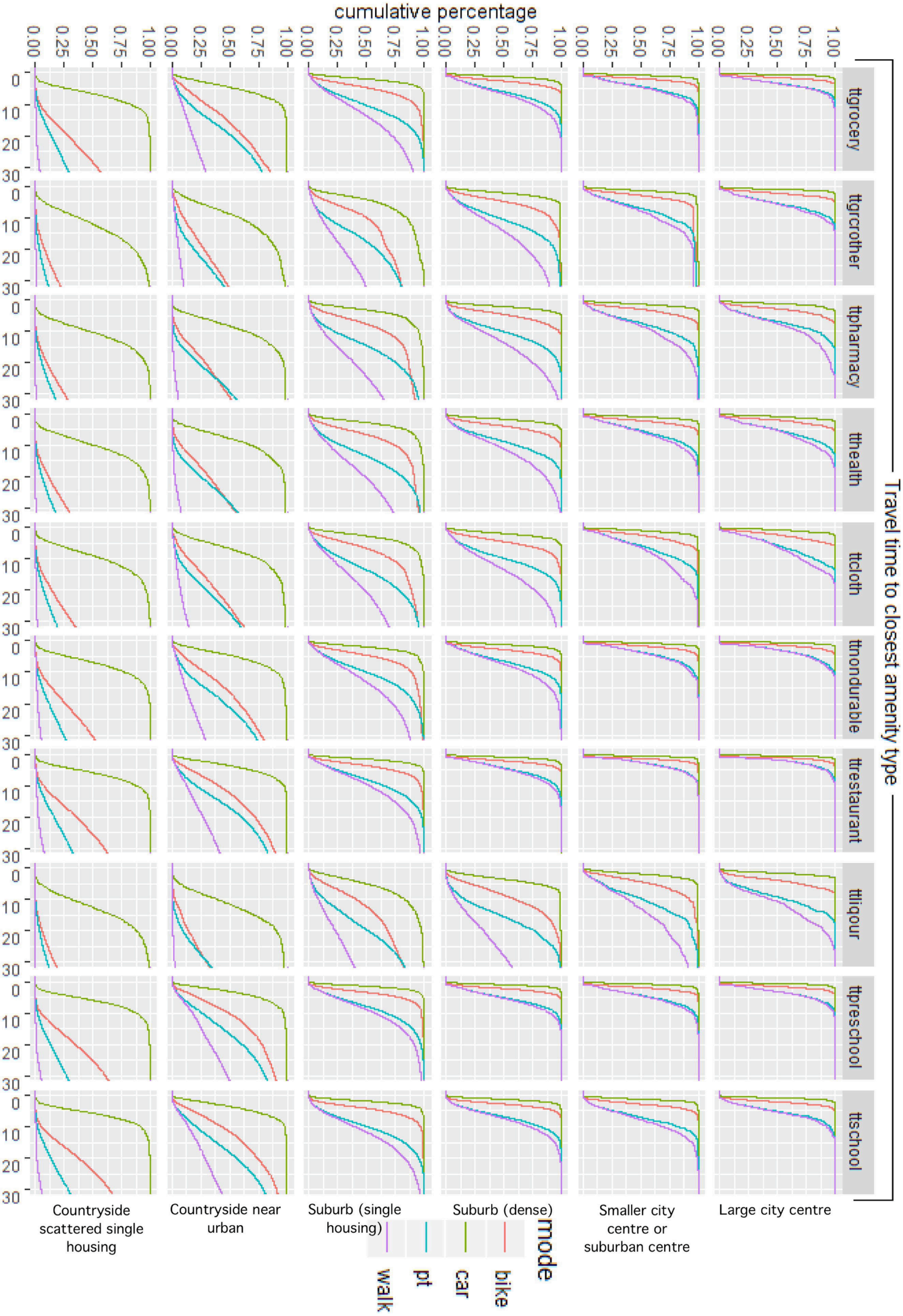
CRediT authorship contribution statement

Anders Larsson: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Project administration. **Erik Elldér:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Evangelos Vafeiadis:** Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Carey Curtis:** Conceptualization, Writing – original draft, Writing – review & editing. **Albert Steiner:** Software, Validation, Writing – original draft, Writing – review & editing.

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.

Appendix 1. ECDF plot showing accessibility measured as travel time to the closest amenity differentiated by mode of transport, settlement type (ranging from countryside scattered housing in the left column to large city centers in the right column) and type of amenity (rows).



Appendix 2. Illustration of settlement types in the context of the case study region.

Large city centre

Smaller urban- or suburban centre

Suburban dense housing estates

Suburban single housing

Countryside near urban

Countryside scattered housing

Photos: Authors

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