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DOI
10.1016/j.jtrangeo.2022.103511

Publication date
2023

Document Version
Final published version

Published in
Journal of Transport Geography

Journal of Transport Geography 106 (2023) 103511

Contents lists available at ScienceDirect

Journal of Transport Geography

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

Differences in levels of accessibility: The importance of spatial scale when measuring distributions of the accessibility of health and emergency services

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ARTICLE INFO

Keywords:
Accessibility
Equity
Spatial aggregation
MAUP

ABSTRACT

This paper explores to what extent inequalities in travel times, measured via the Gini index, depend on the spatial scale at which (average) travel times are measured. By using the new concept of Dedicated Accessibility Points, for the Netherlands we calculated average travel times at four spatial levels, ranging from virtually individual addresses to the level of municipalities. Travel times by car and bicycle to three medical points of interest are calculated: pharmacies, family doctors, and hospitals, as well as travel times by car from three other points of interest: ambulance stations, fire stations and police stations. At the level of individual addresses the errors made due to spatial aggregation is absent, but at higher spatial scales it plays a role. The results show that the Gini index is heavily influenced by the spatial scale at which the indices are calculated, with smaller indices at higher spatial scales. We discuss the implications of these differences for research and policy.

1. Introduction

Providing access to spatially dispersed activities is the primary aim of transport policy, and also some land use policies aim to contribute to that aim. An important question is: when are policies in general, but also those that aim to improve accessibility, 'sound'? In the policy analysis literature it is emphasized that sound policies should (at least) meet three criteria: they should be effective, efficient and fair (Young and Tilley, 2006). Until roughly 2010 fairness was largely ignored in transport policy documents and research, exceptions being social exclusion (e.g. Lucas, 2012), and debates on which value of time to use for Cost-Benefit Analyses (CBA), resulting in the proposal to ignore income differences and leading to the use of the 'equity value of time' (Mackie et al., 2001). Since about 2010 the literature on fairness (and equity, terms that are often used interchangeably) in the context of transport policy has grown rapidly. Extensive debates can be found in books written by Van Wee (2011), Martens (2016) and Banister (2018). The literature sometimes has a normative (e.g. Martens, 2016), a methodological (e.g. Lucas et al., 2016; Lucas et al., 2019), a theoretical (e.g. Van Wee and Roeser, 2013) and/or an empirical (e.g. Cooper and Vanoutrive, 2022) focus.

Dominant positions in the normative debates and literature are first that differences in levels of accessibility for different (groups of) people matter, a position that has its roots in egalitarianism, and secondly that the focus should be on those who are worse off (and might face social exclusion), a position rooted in sufficientarianism (Lucas et al., 2016). In addition, there is agreement on the fact that not all candidate origins or destinations matter from an equity perspective. From now on we refer to destinations to which people travel, and origins of services that could drive to people, such as the fire brigade (fire stations), as Points of Interest (POIs). Some POIs are more vital for people's quality of life than others (see Martens, 2016), examples being schools, shops for (daily) groceries, basic medical services, and jobs, a position that matches the concept of 'primary social goods' introduced by Rawls (1971) – see Van Wee and Geurs (2011). In addition to an upcoming focus in the literature is the capabilities of people to travel and have access to POIs, with its roots in the general capabilities literature (Sen, 2009; Nussbaum, 2011), see Vecchio and Martens (2021) for a review of the literature on the capabilities approach in the area of accessibility.

In this paper we assume that for an evaluation of equity effects of candidate (or already implemented) transport and/or land use policies, as far as accessibility is concerned, at least differences in accessibility levels are important. This raises the question: at which spatial scale should accessibility levels be calculated and compared? This spatial

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https://doi.org/10.1016/j.jtrangeo.2022.103511
Received 6 July 2022; Received in revised form 4 December 2022; Accepted 8 December 2022
Available online 21 December 2022

scale is relevant for several reasons. First, content wise it is important to know which inequalities in accessibility are relevant. Is it, for example, about inequalities within or between cities? To what extent is it (un)fair that some people/neighbourhoods have better access to medical services than other people / neighbourhoods within the same city? Or is the question more about fairness comparing people living in different cities? This question of course depends on the decision at stake: is it a national authority trying to distribute facilities more or less equally across a country, or is it about a local municipality deciding on the location of new facilities within the city, or the closure of existing facilities, because there are too many to subsidize? Such questions are relevant in themselves, but even more so because there can be a trade-off between improving regional versus local accessibility (Silva and Altieri, 2022), so addressing the 'right' spatial scale of policy interventions is very important. Secondly, and related, the conclusions about inequalities in accessibility levels can be influenced by the spatial aggregation level, but it is unknown to what extent. This is to some extent a manifestation of the Modifiable Area Unit Problem (MAUP). "The MAUP refers to the problem that, in the analysis of spatially aggregated data, the results for some analyses depend on the definition of the areal units for which data are reported (…). The effects of the MAUP can be divided into two components: the scale effect and the zoning effect. The scale effect refers to the variation in results obtained from the same statistical analysis at different levels of spatial resolution. The zoning effect refers to different results arising from the regrouping of zones at a given scale." (Kwan and Weber, 2008: 111). We explore the importance of the scale effect.

To the best of our knowledge an empirical study to shed light on this question is lacking. This paper aims to reduce this knowledge gap. More specifically we are interested in the questions "*To what extent is the outcome of inequality analysis influenced by the spatial scale?*"

More specifically, we are interested in the overall pattern of inequalities that emerges, depending on the spatial scale of aggregation, in related differences between places to and from which people travel, and in related differences between transport modes.

The most important contributions of our paper are first that to the best of our knowledge we are the first to explicitly and quantitatively study the importance of the spatial scale on the outcomes of inequalities in accessibility levels. Secondly we developed a fit-for-purpose methodology to calculate representative travel times between addresses without having to calculate all travel times between all addresses in our study area, departing from the concept of Dedicated Accessibility Point (DAPs - see below).

We consider this study to be a first explorative step relevant for the discussion on spatial aggregation and differences in levels of accessibility. We present a quantitative study for the Netherlands, calculating Gini indices (see section 2). Based on a literature review Van Wee and Mouter (2021) conclude the Gini index is by far the most used indicator to express levels of inequalities in the area of transport.

We base our Gini indices on travel times by car and bicycle between places of residence and a selection of POIs at four different scales with decreasing unit numbers but increasing spatial size: 8,131,689 individual addresses, 13,289 small neighbourhoods, 3924 four-digit postal code zones, and 355 local municipalities -, all covering the full extent of the Netherland.

POIs we include are three medical POIs: pharmacies, family doctors, and hospitals. We assume that individuals will travel by private transport (car, bicycle) from the home address towards these POI. The included emergency services are ambulance, fire department and police. Now we assume that the emergency service travels from its station towards the individual address, hence these latter three POI reflect how well residential locations are accessible.

We select the bicycle and the car because these are by far the most dominant transport modes in the Netherlands. In 2019 (pre corona) the car (driver and passenger have a share of 69% in the number of overland kilometres travelled, the bicycle has a share of 28% in all trips made.[1] For ambulances and fire departments only car travel times are relevant. In the Netherlands police officers mainly travel by car, but especially in (central areas of) cities the bike is also a popular mode. We used travel times as an accessibility indicator, first because this is an easy to interpret indicator. Secondly, more advanced accessibility indicators need, amongst others, travel times and generally ignore the importance of the spatial scale at which travel times are calculated. By zooming in on travel times, we make explicit the importance of spatial scale at which travel times are calculated, for such advanced indicators. Thirdly, because, as we will show, spatial scale has a big impact on inequalities of travel times, the importance of our newly developed DAP method becomes explicitly visible.

Because emergency services in practice mostly use motorized vehicles, only travel times by car are included. Off course emergency vehicles are allowed to exceed the maximum speed when running the appropriate sound and light signals, but in the Netherlands the excess speed is restricted to a flat forty kmph on top of the maximum speed, so it has only limited impact on any comparative accessibility analysis and differences in the Gini-indices between the various area types.[2]

The selection of POIs is inspired by the concept of 'primary social goods' of Rawls (1971), and we think that short travel time to and from these POIs are considered to be important for people, if not even vital. Note that people who are extremely healthy and never have to be hospitalized still will appreciate access to a hospital to visit beloved ones that might need hospitalization, or they might appreciate the option to have access to hospitals for the unforeseen future, as expressed by the concept of the option value (Geurs et al., 2006).

2. Methodology

2.1. Data

Transport network data for car and bicycle use were collected and selected by SPOTinfo (www.spotinfo.nl) from Open Street Map (http://www.openstreetmap.nl) in January 2022. The data was made routable by the authors. All POI data were selected by SPOTinfo largely from the Dutch trade register at the chamber of commerce also in January 2022. All administrative boundaries were downloaded as "Wijk en Buurtkaart 2019" from Statistics Netherlands.[3] Individual address locations were downloaded for June 2019 from the Dutch Registration Addresses and Buildings.[4] Figs. 1 and 2 show the locations of the emergency and medical services locations respectively.

2.2. Dedicated accessibility points (DAPs)

Calculating travel times between all individual addresses and POIs can be extremely time-consuming and the use of so-called projection points may also lead to forms of network corruption when too many of these points get very close. As an alternative we used a newly developed method departing from Dedicated Accessibility Points (DAPs); only the POI are projected on the network and starting out from the (projected) POI sites points (DAP) are calculated at regular intervals along both car and bicycle road network. Provided a relatively small interval is used (5 s for cars, 10 s for bicycles) this method is very accurate in almost all cases and substantially reduces calculation times. Appendix 1 describes

[1] https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/personen/hoeveel-reisden-inwoners-van-nederland-en-hoe-

[2] https://wetten.overheid.nl/BRWR0025357/2020-01-18)

[3] https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/wijk-en-buurtkaart-2019

[4] https://www.kadaster.nl/-/kosteloze-download-bag-2.0-extract

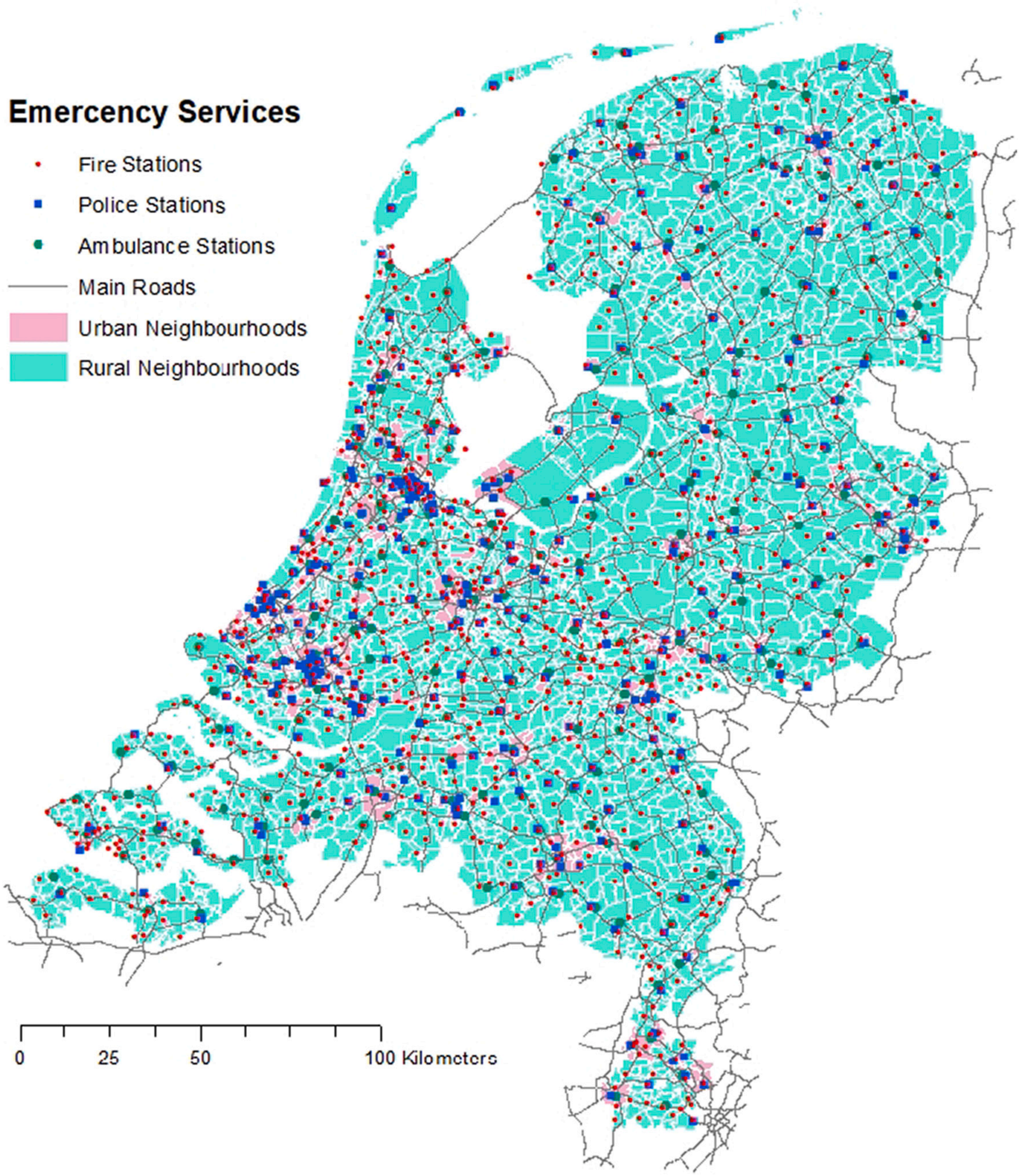

Fig. 1. emergency services locations.

the method in more detail.[5] All individual addresses were then allocated to their nearest DAP thus forming small address clusters with identical travel time to the nearest POI. Next all DAPS were weighted with the number of addresses for which each is the nearest DAP and aggregated average travel times were calculated at all spatial levels and used as basis for calculating the Gini indices.

2.3. The Gini index as a measure for inequalities

Citing Van Wee and Mouter (2021: 110-111) 'The Gini index is a quantitative indicator expressing the level of (un)equality of a distribution. It expresses the index graphically. It sorts the unit of analyses (individuals, regions, …) on the X-axis, based on the unit of the variable for which the distribution is shown. That unit is expressed on the Y-axis, and shows the sum of that indicator up to any point on the X-axis. The graph also shows the Lorenz curve which is the line representing a 100% equal distribution. Assuming an equal length of the X-axis and the Y-axis, that line is the 45 degree line. The Gini index is the surface between the Lorenz curve and the equal distribution curve, divided by the triangle between the Lorenz curve the X-axis, and the right hand positioned Y-axis. The larger the Gini index, the more unequal the distribution. An often used indicator for which distributions are visualized this way and expressed in terms of a Gini index is income. Fig. 3 visualizes this distribution of income and the Gini index.'

We calculate Gini indices for all POI types, spatial aggregation levels, and transport modes as introduced above. Note that the bicycle is

[5] See https://flowmap.nl/Measuring%20service%20accessibility%20using%20Dedicated%20Accessibility%20Points.pdf for more explanation.

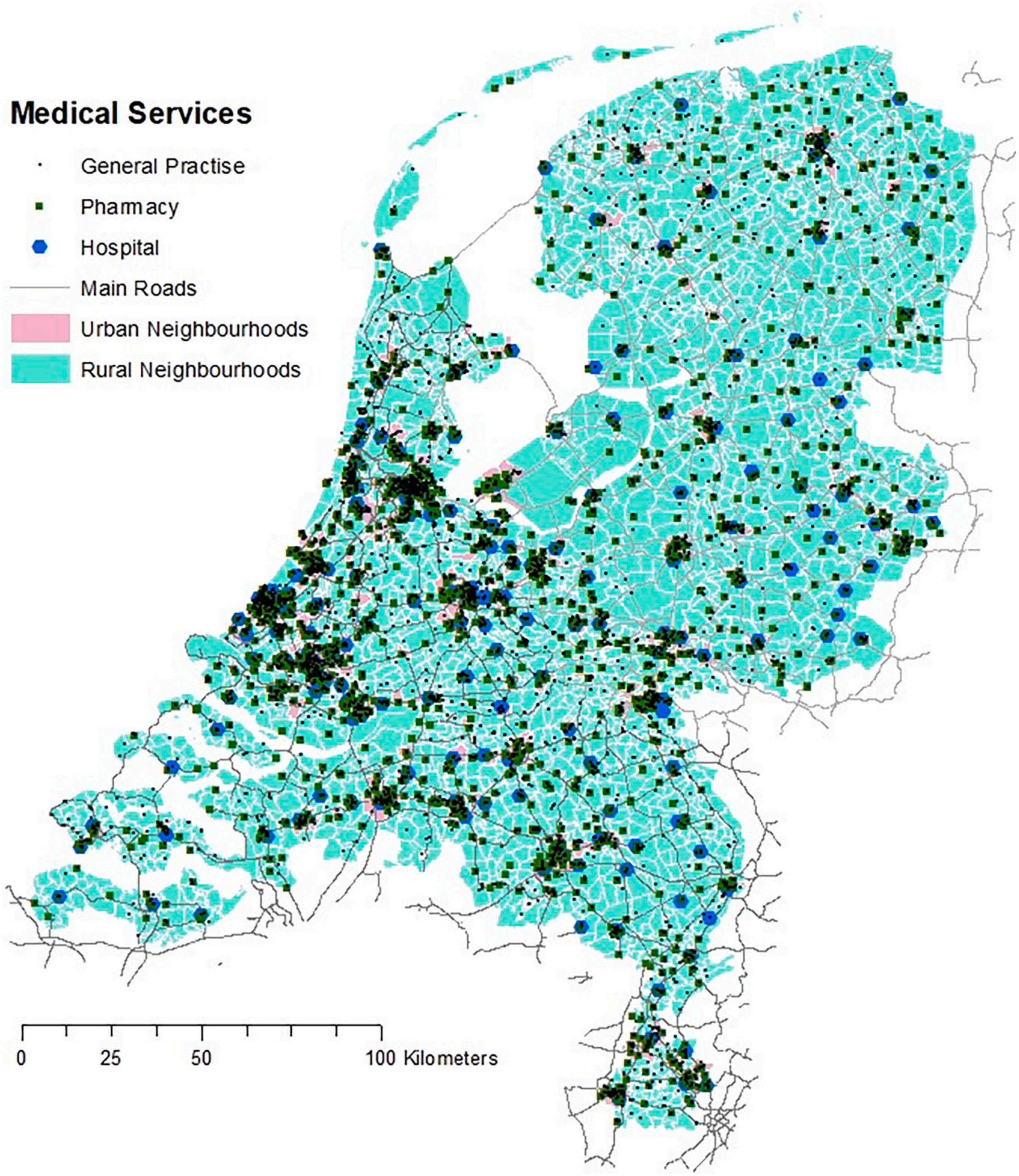

Fig. 2. medical services locations.

particularly important in the Netherlands, and a very inexpensive way to reach not too far away POIs, and cycling infrastructure is of high quality. In other countries this applies to a lesser extent, and public transport could be more important.

2.4. Calculated values of the variable included in the Gini index calculations

We calculated travel times to the nearest POI of each category. Note that this in practice is not always the best option. For example, not all hospitals provide the same medical treatments.

As the variable for the X-axis we use the inverse of travel times (1 / (travel times)) for two reasons. First then in line with the common use of the Gini index lower values express long travel times, so that people facing longer travel times and thus being relatively worse-off are positioned at the left hand side of the X-axis. Secondly, the coefficients are less sensitive to outliers with very long travel times. This because 1 divided by a very long travel time gives a very small value anyway. A doubling of a long travel time then hardly has any impact on the calculated Gini coefficient. This is important because several very long travel times as calculated based on our data are less reliable and relate to transport to and from the Wadden Islands in the North of the country making use of ferries. Our approach makes the results less sensitive to potential errors in calculated travel times.

3. Results

Table 1 presents the results. We first discuss the overall importance of spatial scale for the calculated Gini index, followed by an discussion focusing on difference between modes and POIs.

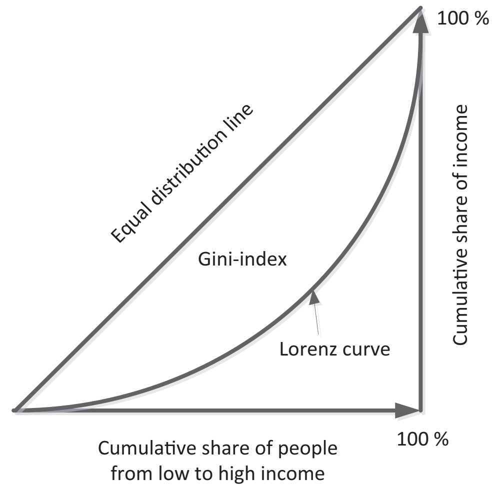

Fig. 3. the Lorenz curve and the Gini coefficient.
Source: Silber (1999).

3.1. Spatial aggregation

We first discuss the magnitude of the problem that results from spatial aggregation. Let us assume the researcher (or anyone interested in the results, such as policy makers) is interested in inequalities between individuals, not in any spatial aggregation and next comparison of zones. Then any spatial aggregation blurs the results due to the spatial aggregation.

In Table 1 the label 'addresses' refers to one or multiple addresses that are linked to the car and bicycle networks at a very disaggregated level.

The right hand column in Table 1 divides the Gini index of spatial units larger than the address level by the address level, for a given POI and travel mode. This differences express the error in the calculated Gini indices due to the spatial aggregation. The results reveal that this problem does exist and is all but negligible. So, a very important conclusion is that the calculated magnitude of inequalities of accessibility heavily depends on the spatial scale at which travel times are calculated and averaged. And a related issue is that if one is interested in inequalities between individuals, problems due to spatial aggregation is significant.

But in many cases the researcher, policy maker or other 'client' of research could have good reasons to not be interested in inequalities between individuals, but at a certain spatial scale, as made explicit above. From here on we assume there are good reasons to be interested in inequalities comparing averages at a certain spatial level. We next dig deeper in the results departing from this perspective. A first and very important conclusion, already presented above, is that the value of Gini index can significantly differ, depending on the spatial aggregation level at which inequalities in the level of accessibility occur. The highest values of the Gini index for a given POIs type and mode are 45–128% higher (see right hand column) than the lowest level, depending on the spatial scale. This conclusion applies to all POIs and modes evaluated in this study. So, if one is interested in comparing zones, it matters a lot how addresses are clustered in zones, and thus how large zones are.

Inequalities are higher at lower spatial scales. This also applies to all POIs and modes. In other words: levels of accessibility comparing small neighbourhoods differ more across these neighbourhoods, than that they differ comparing municipalities. This implies that if the aim is to reduce general inequalities across all people, regardless of the specific policy question at stake, the focus should primarily be on at least smaller geographical areas, and to what extent policies could reduce difference in accessibility.

Table 1
Gini coefficients per POI, mode and area type.

POI	Travel mode	Area type	Gini coefficient	Gini addresses/ Gini area type
Pharmacy (*N* = 1672)	car	individual address	0.33	1.00
		small neighborhood	0.27	1.25
		4 digit postal code	0.23	1.45
		municipality	0.18	1.86
	bicycle	individual address	0.42	1.00
		small neighborhood	0.32	1.31
		4 digit postal code	0.27	1.54
		municipality	0.24	1.75
family doctor (*N* = 4705)	car	individual address	0.31	1.00
		small neighborhood	0.23	1.38
		4 digit postal code	0.19	1.67
		municipality	0.14	2.28
	bicycle	individual address	0.43	1.00
		small neighborhood	0.28	1.52
		4 digit postal code	0.23	1.83
		municipality	0.20	2.17
Hospital (*N* = 187)	car	individual address	0.32	1.00
		small neighborhood	0.31	1.05
		4 digit postal code	0.29	1.09
		municipality	0.22	1.45
	bicycle	individual address	0.42	1.00
		small neighborhood	0.40	1.06
		4 digit postal code	0.38	1.12
		municipality	0.27	1.56
Ambulance (*N* = 236)	car	individual address	0.30	1.00
		small neighborhood	0.28	1.06
		4 digit postal code	0.27	1.13
		municipality	0.16	1.84
fire station (*N* = 992)	car	individual address	0.28	1.00
		small neighborhood	0.24	1.18
		4 digit postal code	0.20	1.39
		municipality	0.19	1.46
police station (*N* = 337)	car	individual address	0.35	1.00
		small neighborhood	0.32	1.09
		4 digit postal code	0.29	1.18
		municipality	0.21	1.65

3.2. Differences between POIs

Especially the Gini index for POIs that are relatively nearby, family doctors and pharmacies, is influenced strongly by aggregating from the address level to larger areas. For other POIs for which people in general need to travel further because they are less nearby (in other words, there are fewer of those available in a city or town), as expected, the Gini index is less sensitive to spatial aggregation.

Looking at the three emergency services included in our analyses we see that the differences at the municipality level are relatively small, but at the level of small neighbourhoods, they become somewhat larger. Spatial scale matters most for ambulances, then for police stations, and finally for fire stations.

3.3. Car versus bike

We also see a systematic pattern that for the bicycle the impact of spatial aggregation is larger than for the car, for all POIs for which Gini indices for both modes are calculated. We see two possible explanations. The first is at the 'within city' level, and the second is at the 'city versus rural areas' level. First, a possible explanation is that the bicycle networks in the Netherlands are more uniform than those for cars. In central urban areas and neighbourhoods around centres several roads are closed for cars or are unidirectional for cars, but not for bicycles. This means that the detours for bicycles in such areas are smaller than for cars. In addition, in such areas the speeds of cars are lower than in the outskirts. This trend probably also applies to bicycles, but to a lesser extent. The result of this pattern is that for cars the advantages of having POIs nearer by than further away is partly compensated by the lower average speeds on shorter distance and the longer detours, but for bicycles this is less the case. In other words: distance matters more for bicycle trips than for car trips because of differences in car speeds across the network. Secondly, focusing on urban versus rural areas, an explanation can be that speeds for cars are way higher outside urban areas than in urban areas, but this hardly applies to bicycles. The higher speeds for cars reduce inequalities in travel times, whereas this does hardly apply for bicycles. Again: distance matters more for bicycle trips than for car trips because car speed difference.

3.4. Do speed differences between modes matter for inequalities?

To explore if our explanation with respect to the impact of speeds of cars versus bicycles makes sense we present the results of a sensitivity analyses. We assumed car speeds to be 15 km/h throughout the network, equal to those of bicycles. This analyses implies that differences between travel times and next Gini coefficients are the result of network difference only, not of speed. Table 2 presents the results.

Table 2 shows that the Gini coefficients for car now are higher than for the bicycle. This implies that network characteristics lead to a more equal distribution in travel times to POIs for the bicycle than for the car. The higher values for the Gini index as found in Table 1 indeed are the results of differences in car speeds throughout the network.

Spatial scale matters more for cars than for bicycles, certainly for pharmacies and family doctors, but less in case of hospitals. A possible explanation for this difference between these POI could be that there are fewer hospitals in a city/town than pharmacies and family doctors. So, hospitals are generally further away than both pharmacies and family doctors. Therefore, the principle 'distance matters more for bicycle trips than for car trips', as explained above, is more relevant for hospitals than for pharmacies and family doctors.

Comparing these results across modes and POIs an overall conclusion is that the results differ per POI type and mode. This means that analyses of inequalities in accessibility should be fine-tuned to the (policy) question at stake.

Table 2
Gini coefficients per POI, mode and area type, assuming 15 km/h for car and bicycle.

POI	Travel mode	DAP interval	Spatial Unit	Gini coefficient	Gini addresses / Gini area type
pharmacy	car variable speed	5 s	individual address	0.33	1.00
			small neighborhood	0.27	1.25
			4 digit postal code	0.23	1.45
			municipality	0.18	1.86
	car uniform speed 15 kmph	10 s	individual address	0.46	1.00
			small neighborhood	0.34	1.38
			4 digit postal code	0.28	1.65
			municipality	0.23	1.97
	bicycle uniform speed 15 kmph	10 s	individual address	0.42	1.00
			small neighborhood	0.32	1.31
			4 digit postal code	0.27	1.54
			municipality	0.24	1.75
family doctor	car variable speed	5 s	individual address	0.31	1.00
			small neighborhood	0.23	1.38
			4 digit postal code	0.19	1.67
			municipality	0.14	2.28
	car uniform speed 15 kmph	10 s	individual address	0.46	1.00
			small neighborhood	0.29	1.58
			4 digit postal code	0.24	1.95
			municipality	0.19	2.46
	bicycle uniform speed 15 kmph	10 s	individual address	0.43	1.00
			small neighborhood	0.28	1.52
			4 digit postal code	0.23	1.83
			municipality	0.20	2.17

4. Conclusions, policy implications, discussion and avenues for future research

4.1. Conclusions

As explained above, this is a first exploratory study into the sensitivity of the inequality index (in our case: the Gini index) for spatial aggregation. Our main conclusion is that the value of Gini index can significantly differ, depending on the spatial aggregation level at which inequalities in the level of accessibility occur. This conclusion applies to all POIs and modes evaluated in this study. The highest value of the Gini index can be as much as 128% higher than the lowest level, depending on the spatial scale, for a given POI type and mode. This implies that the assessment of inequalities in accessibility the choice of the spatial aggregation level should be made carefully.

Next we conclude that the newly developed DAPs methodology has shown to be an efficient way to create relatively small clusters of addresses at the same distance to their nearest POI with only a very marginal loss of accuracy in calculated travel times. Its application virtually brings the individual address level into play and hence reduces the problems due to spatial aggregation to almost zero.

An important consideration for choosing the 'right' spatial aggregation level is that the distribution of POIs is spatially quite different between POIs. Whereas pharmacies and family doctors can be found throughout cities and towns, this does not apply to hospitals (or theatres, or swimming pools, ….). For POIs that are limitedly available in each city or town, from an accessibility inequality perspective both 'within city' inequalities matter, as 'between cities' inequalities: location choice ideally should be influenced by both forms of inequalities.

Finally we conclude that inequalities in travel times for the bicycle are larger than for the car, and the difference is mainly explained by network characteristics.

4.2. Policy implications

For policy makers the most important message is that if they are interested in spatial inequalities in accessibility they should specify the spatial scale of their interest. This because, as we have shown, for all POIs and modes evaluated in this study the value of Gini index can significantly differ, depending on the spatial aggregation level at which inequalities in the level of accessibility occur, but the extent to which the spatial scale influences the Gini index, varies strongly between POIs. For example, are they interested in differences between cities, between neighbourhoods, or at the individual level? Next, they should ask researchers to make the calculations of inequalities at that level. Especially if they are interested in the individual level, they should ask for analyses at the (near) address level. The newly developed DAPs methodology makes it possible to calculate Gini indices efficiently. Another policy implication is that there are probably more policy options to reduce inequalities in travel times for the bicycle, than for the car, first because the Gini indices for the bike are larger than for the car, and secondly because adding bicycle infrastructure is relatively inexpensive compared to adding infrastructure for cars.

4.3. Discussion

One could think that the conclusion that inequalities are higher at smaller spatial scales could be drawn analytically beforehand, without doing any research. After all, at smaller spatial scales, additional heterogeneity is added. But the extent to which this applies can be very context specific. Take the hypothetical case of a country with many largely equally sized towns, half of them having a hospital, the other half not having one. Travel times to a hospital are short for all people living in a town with a hospital, and long for all others. The Gini index comparing towns will then not differ a lot from the Gini index calculated at the level of individual addresses. Now let us assume a city with 20 neighbourhoods, equally large, with comparable networks, and all having a family doctor at a central location. Then the Gini index comparing average travel times between those neighbourhoods will be small (average travel times to the family doctor will be about the same), but the Gini index comparing travel times at the address level will be way larger because of the difference in travel times to family doctors within each zone. So, in the first hypothetical case the Gini index is not strongly influenced by the spatial scale of measuring accessibility, but in the second example it is. But these are hypothetical situations only. If the logic behind the examples would be plausible we would expect a stronger impact of the spatial scale on the Gini index if there are more POIs of a certain type. Table 1 shows this is the case. There are 4705 family doctors in the Netherlands, and this number is over 10 times more than the number of municipalities. The Gini index at the address level divided by this index at the municipality level is 2.28 for the car and 2.17 for the bicycle, and these values are larger than for all other POIs. For pharmacies, the POI with the second largest number, the values of 1.86 and 1.75 for the car and bike respectively, and these values are higher than for the other POIs that are less densely distributed across the Netherlands. But the values are not continuously declining with the number of POIs in the Netherland, suggesting that also the locations of POIs matter, not only the number of POIs, which seems plausible.

4.4. Limitations and future research

Our study has several limitations which provide interesting avenues for future research. First, we only calculated one accessibility measure. Future research could first of all explore the impact of the accessibility measure selected (See Geurs and van Wee, 2004, for a discussion accessibility measures). Geurs and van Wee explain which indicators for accessibility do exist, and that these indicators are based on (a selection of) the land use, the transport, the individual and the temporal component. They also discuss the pros and cons of using different indicators, a major challenge being that easy to communicate indicators have important scientific limitations, whereas more advanced indicators are more difficult to interpret. It is beyond our aims to further discuss accessibility indicator selection. Rather we zoom in on a few choices we made. In this study we only looked at (the inverse of) travel times to the nearest POI. In applied accessibility analyses it is common to include several POIs of one type in the analyses, and to apply the principle of distance decay implying that nearby (in time and/or distance) POIs are more important than those further away. This leads to the importance of distance decay functions. For example, distance matters more for primary schools or supermarkets, than for theatres of recreation parks. And distances (as an indicator for travel costs) to jobs are more important for people with low wages than for those with higher wages. Giannotti et al. (2022) conclude that distance decay functions can differ a lot between groups of people, and it really can matter if such functions include only travel times or (also) costs. So it is not at all straightforward to include the importance of distance decay in the assessment of accessibility of key POIs, which is especially relevant for assessing inequalities in accessibility. Future research could explore the importance of heterogeneity in people, and the impact of distance decay on access to important POIs.

Secondly we selected only two transport modes, six POIs, limited ourselves to the Netherlands and a few available datasets, and ignored time-of-day, and heterogeneity of people. Future research could include all these ingredients that matter for accessibility: more modes (walking, public transport), other POIs (like schools, shops, and recreational facilities), other countries/regions, other data sets, time of day variability in accessibility (time tables of public transport, opening hours of POIs), and heterogeneity of (groups of) people based on socio-demographics and preferences/attitudes. We expect the message that spatial matters a lot will remain robust, but the extent to which this applies could depend on the accessibility indicator(s) used.

Finally we only included one index for inequalities, the Gini index, so it is an option to calculate other indices. See Van Wee and Mouter (2021), for a literature review. As explained above, they conclude that the Gini index is by far the most used indicator to express inequalities in transport. They speculate that the reason for this is the fact that this indicator is easy to interpret and communicate. Other indices they discuss are the Suits, the Palma, the Theil and the Atkinson index, the percentile ratio, and the coefficient of variation.

Author statement

Bert van Wee: idea, lead author.
Tom de Jong: development DAP methodology, calculations, writing.

Data availability

Data will be made available on request.

Acknowledgement

We thank two anonymous reviewers for their helpful suggestions.

Appendix 1. Measuring service accessibility using Dedicated Accessibility Points (DAP)

The accessibility of services is often expressed in terms of travel distance by a particular mode of transport to the nearest service location (POI) from the centre points of statistical or administrative spatial units like wards, neighbourhoods, postcode zones etc.… This is relatively crude method as questions can be raised about the representativeness of that centre point for the whole spatial unit also in relation to the compactness of the spatial units.

Nowadays most of these questions can be overcome by using individual residential address locations instead of a single centre points per spatial unit. The idea is to first calculate the travel distance to the nearest service location from all individual sites and to average the results the any spatial unit afterwards. However, the calculation of the travel distance to the nearest service location from individual sites may present some practical problems. A few street blocks in the city of Lochem in the Netherlands will be used to illustrate these problems.

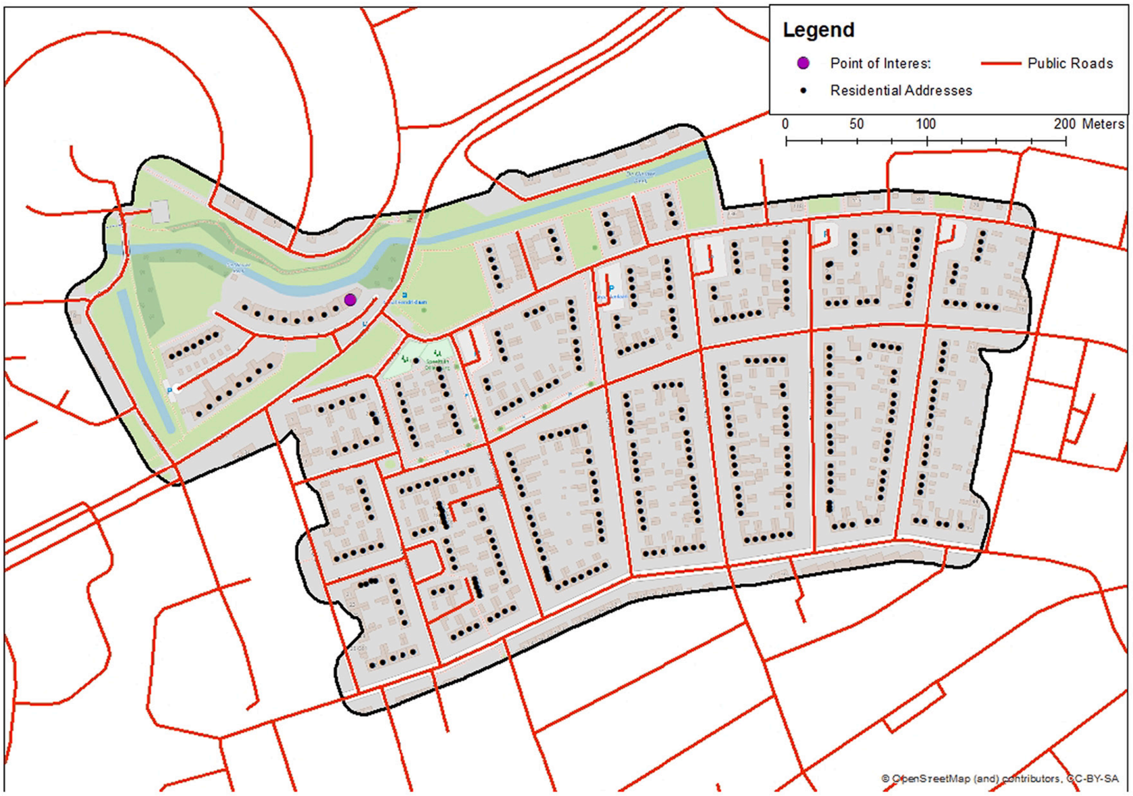

Fig. 1. Location of POI and residential addresses with respect to the road network.

Neither the POI nor any of the residential addresses are located exactly on top of the road network (Fig. 1). Normal procedure to facilitate network distances calculation is therefore to project POI and addresses on the network at the nearest opportunity, split the roads at the projection points and add a so-called "feed link" from each POI/address to its projection point (Fig. 2). Next, regular quickest / shortest path analysis can be applied to calculate the distance from each residential address to its nearest POI. Optionally the feed link can be skipped by using the projection point instead of the actual residential location, for instance when the projection point is seen as the place where the car is parked in the street or in case a very high percentage of residential addresses is close to the network.

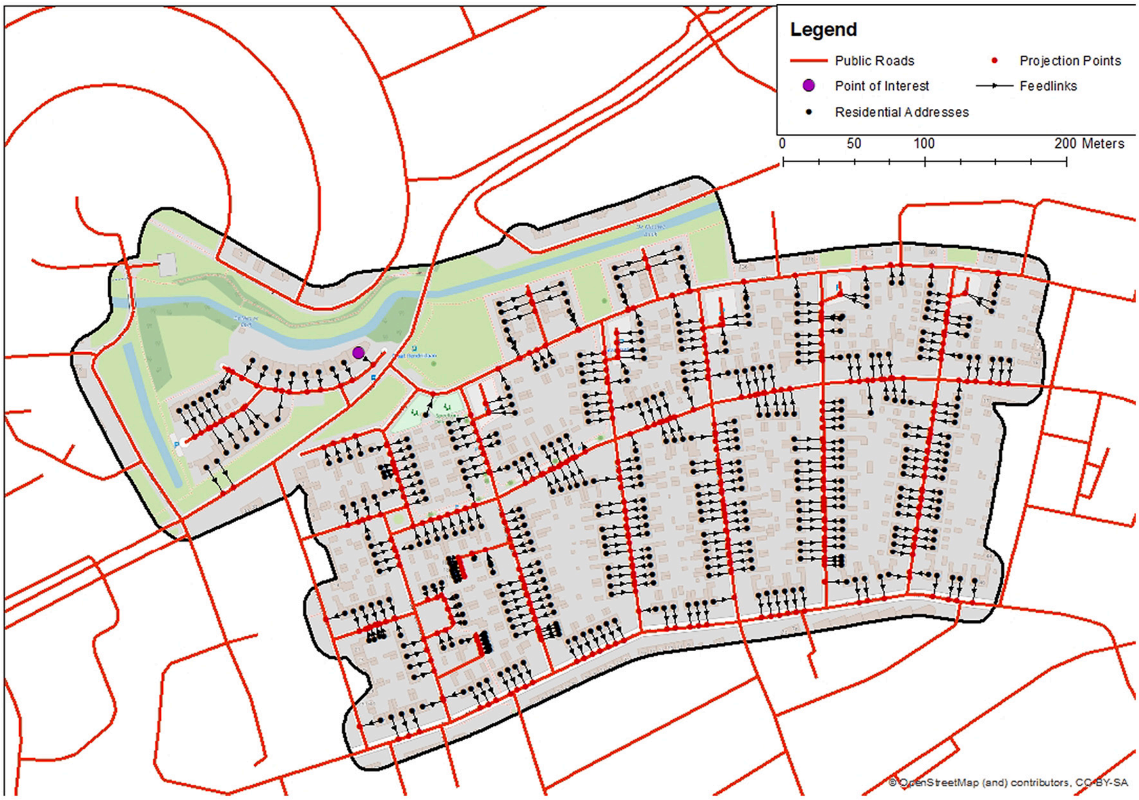

Fig. 2. Connecting POI and residential addresses the road network.

For relatively small areas this procedure works fine but at the Dutch national level (over 8.1 million residential addresses and over 2 million road segments) two types of problems are encountered. Firstly a concentration of very closely situated projection points may lead to corruption of the digital transport network due to rounding errors even at a high level of coordinate precision. The odds of this happening are very slim, but may occur when the network is split at over eight million projection points. Secondly, the identification of the projection points on the transport network is relatively slow procedure compared, for instance, to a point-to-point search or a point in polygon search as some of the usual preselection filters are not applicable in this case.

At any spatial level there will be an unbalance between the number of residential addresses and the number of POI of any type; the residential addresses easily outnumber the POI by a factor of one thousand or more. The concept of dedicated accessibility points (DAP) therefore aims to overcome the above problems by not projecting the residential addresses on the transport network and replacing the traditional method with a two-step approach. In the first step only the (relatively few) POI are projected, integrated with the transport network and the full network is traversed outwards from the POI. On the way outwards point markers are created at regular intervals (Fig. 3), containing apart from coordinates only the network travel distance to the nearest POI. These are the so-called Dedicated Accessibility Points or DAP. The word 'Dedicated' refers to the fact that each type of POI will have its own set of DAPs.

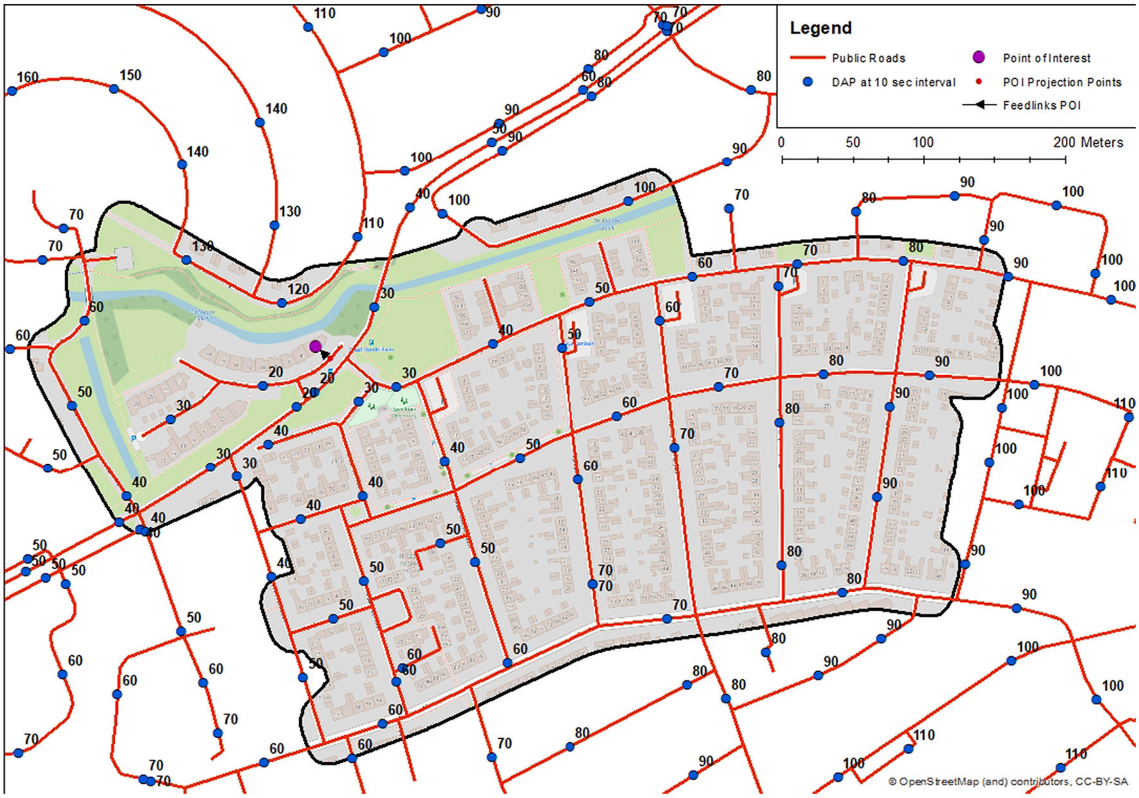

Fig. 3. Dedicated Accessibility Points (DAP) for car travel to nearest POI at 10 s intervals.

In the second step the transport network itself is no longer needed and with a simple point to point search the residential addresses are allocated to the nearest DAP (Fig. 4) and the travel distance can be transferred from the DAP to the address.

In case an average travel distance per spatial unit is required, researchers can simply weigh the travel distance of the DAPs within each spatial unit with the number of addresses for which a particular DAP is the nearest DAP. For most purposes the interval accuracy of 5 or 10 s, depending on average travel speed will do the job (see also Tables 1 – 2). Allocation lines should ideally not cross the roads enclosing the building block that contains the residential address to ensure maximum accuracy. In seven cases (marked with a dark green line in Fig. 4) one or more allocation lines cross a street to connect to a DAP in a road that does not enclose the building block containing the residential address involved. But there is no additional loss of accuracy as long as that road is directly connected to the roads encircling the building block with the residential address. However, in two cases (marked with a red line) this last requirement is not met. The red line indicates where two addresses jump a canal and double their expected travel time. The pink line indicates where another two addresses short cut a detour in the network and halve their expected travel time.

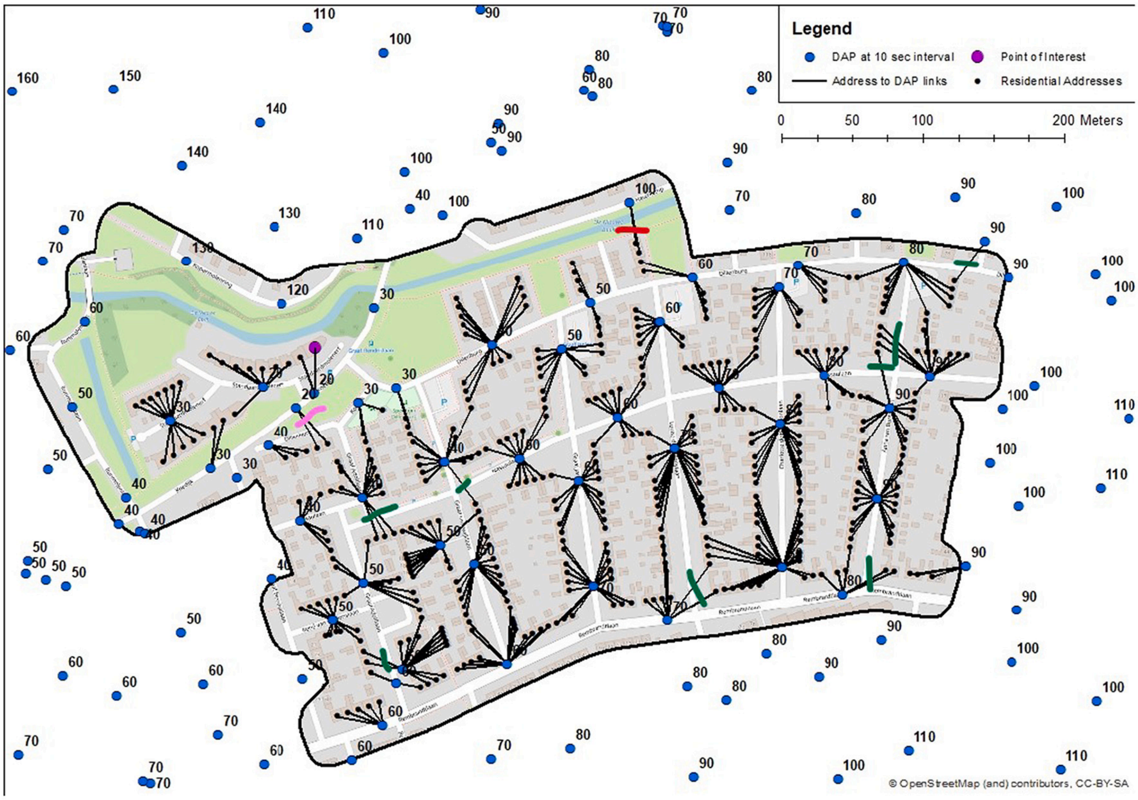

Fig. 4. Linking residential addresses to nearest Dedicated Accessibility Point (DAP).

Particularly linear shaped obstacles in space may lead to detours in the transport network and cause DAPs with very different values to be situated relatively close to each other values. Most often these linear features are canals, railroads and highways where legal crossings are restricted to a limited number of bridges, viaducts and tunnels and are effectively impassable for traffic in between. But also, two parallel one-way streets can have the same effect provided they run in opposite directions and are not frequently interconnected. Whether or not a linear obstacle comes into play ultimately depends on the position of the POI, in case the POI are close to a passage there will be very limited effects. Effects will be maximal when POI are situated close to linear features, but exactly in between passages like the POI in the 30 s example above.

When comparing the effects of straight (air-)line allocation to the nearest DAP at different time intervals (Fig. 5) it can be noted that at the short five second interval there are no more dubious allocations but at the thirty second level several dubious allocations (red lines) can now be observed close to the POI crossing the canal and there by raising the expected travel time from fifteen seconds to two minutes.

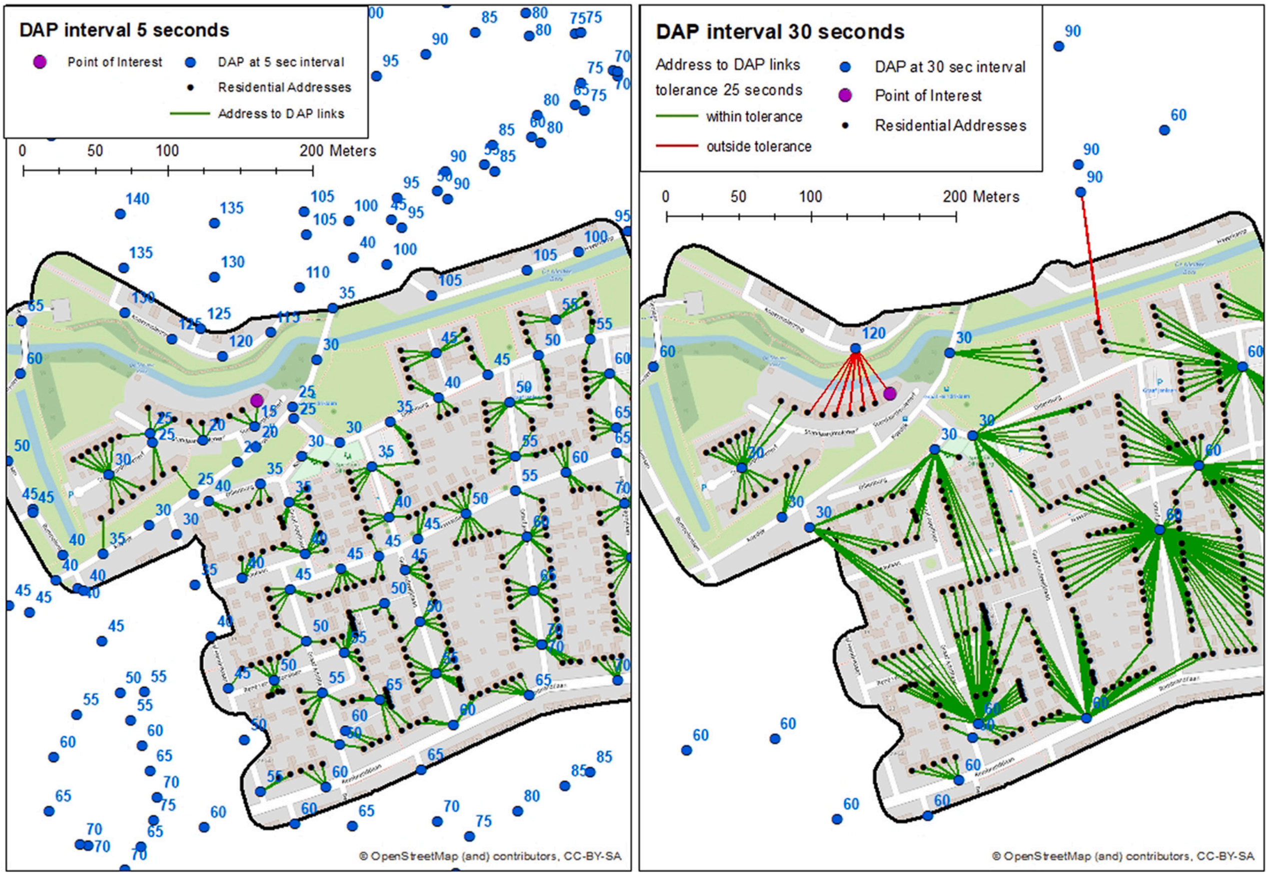

Fig. 5. Comparing allocation lines of Dedicated Accessibility Points (DAP) at different intervals.

The notion is off course that a shorter interval will lead to better results but will cost more processing time.

Table 1
Quality of travel distance prediction at increasing DAP-levels.

	observed travel distance in seconds by car				absolute travel distance prediction error in seconds	
	average	minimum	maximum	standard deviation	to best 95% of addresses	to best 99% of addresses
single center point	53.93	53.93	53.93	0		
individual addresses	63.84	14.46	95.75	18.28		
DAP 5 s interval	62.11	15	95	18.16	4.7	5.6
DAP 10 s interval	61.72	20	100	18.31	7.7	15.6
DAP 15 s interval	62.37	15	120	19.05	10.4	47.0
DAP 20 s interval	61.62	20	100	18.98	15.5	42.0
DAP 25 s interval	61.25	25	100	19.59	17.2	42.9
DAP 30 s interval	63.97	30	120	20.91	18.0	99.9
DAP 35 s interval	63.58	35	105	21.62	24.0	57.4

When comparing several intervals (Table 1) the first impression is that positive and negative prediction errors largely cancel each other out so that at all DAP levels the predicted average travel distance is just over one minute which is very close to the number obtained based on individual measurements at the address level. For smaller areas the travel distance from each individual address (projection point) can also be calculated the traditional way and relevant statistics can be obtained. The travel distance prediction error is then calculated by subtracting for each address this actual travel distance from the travel distance recorded at the nearest DAP. At the five second DAP level 95% of all addresses have their travel distance predicted with an error of no more than 4.7 s and this number steadily increases with the interval size. But at 99% of all addresses the effect of dubious allocation becomes noticeable with a jump from 15.6 to 47.0 s already at the fifteen second DAP level. This leads to the preliminary conclusion that when one is interested in the average travel distance per spatial unit a relatively large (and quick) interval can be chosen. But when interested in the best predictions at the individual address level in this case an interval level of 10 or less seconds is called for.

The above results are based on a very small area and serve illustrative purposes largely. To get more insightful results the municipality of Houten in Utrecht province was selected.[6] Houten municipality is not only traversed by motorways, major canals and railways, but by design the new town also

[6] For a full version of this appendix that also discusses results for other municipalities and other POI see: "https://flowmap.nl/Measuring%20service%20accessibility%20using%20Dedicated%20Accessibility%20Points.pdf".

has a poorly connected car road network; in order to promote the use of the bicycle there is no way for cars to cross the two town centres. To get from one neighborhood to the other cars must always use the eight-shaped ring-road. So, for car travel neighborhood boundaries in Houten are also potentially acting as linear obstacles; if the DAP concept works here it should work anywhere.

To evaluate the DAP concept's suitability for quantifying the accessibility of service delivery by pharmacies the traditionally calculated car travel distance to the nearest pharmacy for all (over 22,000) individual Houten addresses was compared with DAP predictions at several interval levels to evaluate DAP concept suitability for service delivery by pharmacies (Table 2).

Table 2
Quality of travel distance prediction at increasing DAP-levels in Houten for pharmacies.

Houten / Pharmacy (6)	Travel distance by car in seconds to closest facility					Worst case absolute travel distance prediction error in seconds		
Calculation method	average	minimum	maximum	standard deviation	Average absolute error	to Best 95% of all addresses	to Best 99% of all addresses	to All addresses
Municipal gravity point	328.5	328.5	328.5	0.0	118.0	201.0	271.6	300.9
All individual addresses	250.3	11.9	737.4	119.9	0.0	0.0	0.0	0.0
DAP 5 s interval	245.0	15.0	730.0	119.1	6.5	10.3	28.6	371.2
DAP 10 s interval	244.0	20.0	730.0	119.0	8.6	14.9	58.1	376.2
DAP 15 s interval	246.0	15.0	720.0	119.3	9.7	19.0	74.0	371.2
DAP 20 s interval	244.1	20.0	720.0	119.7	11.6	24.2	117.8	379.9
DAP 25 s interval	243.9	25.0	725.0	120.2	13.4	30.9	119.4	371.2
DAP 30 s interval	243.6	30.0	720.0	119.7	15.4	37.5	146.2	376.2
DAP 35 s interval	241.6	35.0	735.0	120.1	17.7	46.5	170.9	384.9
DAP 45 s interval	241.4	45.0	720.0	119.5	20.1	57.3	177.4	432.6
DAP 60 s interval	239.0	60.0	720.0	119.1	28.0	91.7	296.4	376.2

Mostly to illustrate its unsuitability to handle variations within a municipality also similar statistics are provided based on the travel time from a single municipal gravity point instead of all municipal addresses. Unlike the single gravity point the DAP methods at essentially all intervals very closely reproduce the variation in the actual data at the address level in terms of average, minimum and maximum values and standard deviation and the resulting averages can therefore be used as a good proxy for the actual average travel distance in each municipality. When it comes to prediction of travel distance at the individual address level again the patterns are very similar; the average error steadily creeps up and at the DAP shorter intervals remains under an acceptable 30 s even for up to 99% of the addresses.

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