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DOI
10.1016/j.cstp.2020.09.007

Publication date
2020

Document Version
Final published version

Published in
Case Studies on Transport Policy

Citation (APA)
van der Veen, A. S., Annema, J. A., Martens, K., van Arem, B., & Correia, G. H. D. A. (2020). Operationalizing an indicator of sufficient accessibility – a case study for the city of Rotterdam. *Case Studies on Transport Policy*, *8*(4), 1360-1370. https://doi.org/10.1016/j.cstp.2020.09.007

Case Studies on Transport Policy 8 (2020) 1360–1370

Contents lists available at ScienceDirect

Case Studies on Transport Policy

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

Operationalizing an indicator of sufficient accessibility – a case study for the city of Rotterdam

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ARTICLE INFO

Keywords:
Accessibility
Equity
Methodology
Operationalization
Assessment
Justice

ABSTRACT

Equity considerations in transportation planning literature have received increasingly more attention in the previous decades. While there have been theoretical suggestions to base transportation planning methods on the philosophical principle of "sufficientarianism" (whereby everyone is entitled to a minimum level of a good or service), the proposed approaches have not yet been developed enough to be usable for policy decision-making. In this paper we aim to bridge this gap by operationalizing in a case study an indicator of equity based on the theoretical work of Martens (2017) which argues for sufficientarianism. The presented formalised methodology can identify and quantify equity issues in transportation, is flexible to different contexts, and is a transparent way to assess equity in transportation. The case study shows that data availability is an important constraint and that careful attention must be paid to various assumptions and choices made.

1. Introduction

Improving accessibility is one of the key aims of transport and land use planning (Geurs and Ritsema van Eck, 2003; Morris et al., 1979; Vickerman, 1974). Since Hansen (1959) introduced the term, accessibility has been defined in many ways. These definitions are mostly concerned with an ability to reach destinations around a place. Van Wee and Geurs (2011) for example consider accessibility the degree to which individuals are able to reach destinations.

Accessibility and improvements to accessibility are not evenly distributed over places and people. Despite the importance of a fair distribution of transport and the usefulness of equity assessments in transportation "if distributive or equity effects are at stake" (Van Wee and Geurs, 2011), current transport planning practice generally ignores distribution effects of transport benefits (Van Wee and Geurs, 2011; Pereira et al., 2017). This lack of attention to distribution effects can be partly traced to the dominant utilitarian approach underlying much of the practice of transport planning, and partly to the lack of clearly defined ways to assess the distribution of benefits (Martens et al., 2012; Martens, 2017; Van Wee and Geurs, 2011; Pereira et al., 2017). In practice "an equity analysis requires making difficult but empirically significant tradeoffs about which there are no established guidelines or standards" (Cambridge, 2002; Karner and Niemeier, 2013). In this paper we aim to contribute to the literature on methods and standards for equity assessments in transport planning practice. We do this by presenting an operationalized approach to equity assessment based on "sufficiency of accessibility" that can be used to understand the extent to which equity effects exist currently (or might be the result of improvements) in accessibility.

"Equity" in philosophy refers to whether the distribution of a good (such as accessibility) can be considered "fair" or "just". Equity concerns not just inequality, but a moral judgment of that inequality, since inequality itself is not inherently problematic. For a moral judgment of inequality, some moral framework must be used and it is important that this is made explicit as many authors argue (Lucas et al., 2016; Pereira et al., 2017; Martens et al., 2012). Equality implies that everyone should be treated equally or receive an equal share of the benefits. Equality is seen by philosophers as the default principle of justice, putting the 'burden of argumentation' on proponents of deviating from equality. A deviation of equality will always imply that some will receive more than

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https://doi.org/10.1016/j.cstp.2020.09.007
Received 4 February 2020; Received in revised form 5 September 2020; Accepted 25 September 2020
Available online 2 October 2020
2213-624X/

others, and this must be justified. Numerous principles of justice have been proposed in the transport literature, although only few of them have been systematically defended based on philosophical reasoning. An alternative to equality that has gained substantial traction in philosophical theory is the principle of "sufficientarianism" (Frankfurt, 1987). It poses that everyone is entitled to a minimum level (a "threshold") of a good or service. Injustice then occurs when some share of the population finds themselves below this threshold value. This principle has also been proposed in new approaches for transport planning, sometimes as part of a broader egalitarian approach (e.g. Lucas et al., 2016). To our knowledge, fully formalized approaches (i.e. defined in formal math) that take sufficientarianism as a starting point and aim for a practical application have not been investigated in detail before.

The work of Martens (2017) provides a strong theoretical basis for equity assessments that takes sufficientarianism as its guiding principle. With this paper we therefore formalize the approach of Martens (2017) and apply it to a case. We focus on formalizing all steps needed for assessment with an existing approach that has up until now only been developed theoretically. We have chosen in this paper to not just formalize Martens' theory mathematically but to apply our formulas in a concrete real-life case (the city of Rotterdam) as well. By doing so we were able to test if our approach is indeed directly applicable, and whether or not it leads to insightful results for policymakers. It also enabled us to explore which methodological and data-related issues the approach might lead to. Our hope is that these investigations provide useful insights and tools for future research towards operationalizing and standardizing ethical approaches for transportation policy making.

Similar to Pira et al. (2016), we explain the theoretical background, our methodology, and then apply it to a case to find out what limitations and difficulties arise when attempting to put the formalization to practice. Section 2 briefly discusses Martens (2017) approach on which our formalization is based. In the subsequent Section (3) we define and formalize the steps in the assessment. We then apply (in Sections 4 and 5) the methodology to a case study for the city of Rotterdam. Finally, we reflect on the operationalization process and the resulting approach in Section 6.

2. Martens' notion of sufficient accessibility

Martens (2017) combines accessibility indicators with the moral framework of sufficientarianism mentioned above into a transport planning approach strongly rooted in "principles of justice". He suggests defining and measuring the equity of transport systems based on the idea of "sufficiency of accessibility". A transport and land use system is fair "if, and only if, it provides a sufficient level of accessibility to all under most circumstances" (Martens, 2017, p. 215). Low levels of accessibility restrict the range of available opportunities and thus increase the risk of transport-related social exclusion. Sufficiency in the context of transportation thus refers to a level of accessibility below which people experience a lack of opportunities. The precise determination of sufficiency (the threshold value) is an explicitly normative process, and the results of that process are and should be dependent on the specific context. This is intentional: by making these choices explicit and a central part of the process, they can be made transparent and more easily discussed, instead of being hidden in (technical) assumptions. For people below the threshold, improvements are either preferred ("weak sufficientarianism") or necessary ("strong sufficientarianism") (Lucas et al., 2016). Weak sufficientarianism can be employed in conjunction with egalitarian indicators, for example giving priority to people experiencing accessibility poverty but also striving for an overall increase in accessibility (as captured by, for instance, a reduction in Gini-coefficient). Strong sufficientarianism implies that transport policy should be based on preventing accessibility shortfalls first and foremost.

For transport planning, it is useful to focus solely on the accessibility shortfalls that transport improvements can actually solve. Low levels of accessibility can not only be caused by insufficient transport network design, but can also be caused by a sub-optimal distribution of land use and corresponding activities. For example, poor accessibility to hospitals by a group of people can be solved by improving transport to hospitals for that group (changing transportation), but can also be solved by bringing hospital services closer to that group (changing land-use). When people in a particular location are enjoying a high level of transport service but a low level of accessibility, it is hard to fix this lack of accessibility with further improvements to transport services. In such a case the problem can be better approached with land-use policies or social policies. Because the latter situation is quite prevalent, Martens suggests also setting a threshold value for a sufficient quality of the transport network. This threshold delineates the role of transport planning; above this threshold, accessibility problems should be approached through other means than transport planning.

By measuring and determining the threshold values for accessibility and the quality of the transport network, the locations where certain people experience insufficient accessibility and an insufficient transport network can be identified. While the identification of these groups of people can already be of use to transport planners, such an analysis does not enable a prioritization between different areas or groups, which is an important part of the transport planning process. To prioritize groups of people, Martens (2017) suggests to compare each group's "severity of insufficiency": the size of the groups below the two defined thresholds, multiplied by how far below the accessibility threshold they fall. This is the basis of what Martens calls the "Accessibility Fairness Index" (AFI). The AFI can help policy makers identify the most severe equity issues, namely the largest groups of people that fall the furthest behind the set thresholds. It also allows policy makers to compare inequities between groups of people: do groups with a particular attribute (e.g. low income) experience more accessibility insufficiency than other groups (e.g. higher income)? These prioritized groups and/or locations could then form the basis of research on the causes of these equity issues and the starting point for transport planners to identify, evaluate and implement possible solutions.

Martens' proposition that sufficientarianism is not only something to take into account, but also something to base transport planning on, is a substantial departure from current practices and would have significant implications for planning practice if systemically applied. The focus on sufficient accessibility is a stark deviation from demand-based approaches used frequently in transport planning. Instead of focusing on the transport network and its performance, the sufficiency approach directs the attention to people and their resources. Rather than looking at actual or predicted behaviour and translating that to the (future) usage of the transport network, the approach focuses on possible behaviour and asks what possibilities for activity participation a transport system confers to people and whether those possibilities are deemed sufficient. The analysis thus does not focus (only) on places, but on population groups, taking into account their resources broadly conceived, including mode availability, travel budget, and physical fitness and impairments, amongst others. While it is not within the scope of this paper to explore the impact of people's entire resource set on accessibility and equity, the methodology presented is inherently people-based and can thus incorporate those aspects in its equity assessment.

3. Formalization

Suggested indicators and methodology by Martens (2017) were used for the here presented operationalization, which aims to be a case-independent, flexible formalization that others can build upon. We would like to emphasize that the operationalization (consisting of not just this formalization, but also the application in the case study later on) is our best effort at implementing best practices as proposed by the theory as it stands now; we realize that various assumptions and decisions can be made differently, and invite others to contribute in this regard.

The methodology in Martens (2017) consists of six key steps:

1. Defining a study area and groups for which this equity analysis is deemed relevant within this area (e.g., different income groups);
2. Assessing the sizes of these groups sizes;
3. Choosing relevant destinations;
4. Choosing and specifying accessibility & potential mobility indicators;
5. Determining sufficiency thresholds for those indicators;
6. Assessing equity for all groups using the "Accessibility Fairness Index";

Each of these steps will be explained and then cast into equations. The above six steps show some similarity to the three steps as outlined by Guo et al. (2020), who identify three steps of population measurement, cost/benefit measurement, and inequality measurement. These correspond to some extent to step 1–3, 4 and 5–6 respectively. A key difference is that Guo et al. remain implicit regarding the most appropriate justice principle(s) for the assessment of accessibility and actually seem to equate equity with equality - a problematic 'shortcut' taken by many other transport researchers (Martens and Lucas, 2018).

Step 1: Equity will be assessed between *groups*, with each group referring to a specific subset of the population defined by attributes. Groups are chosen based on attributes that (might) reflect a significant difference in accessibility. The population is differentiated into groups based on attributes such as residential location (in the form of zones), income, age, gender, ethnicity, and mode availability. Priority should be given to attributes which have been shown in the literature to be related to differences in mobility and accessibility levels for groups of people. Location, mode availability, income, gender and race are examples of attributes that are very relevant (Martens et al., 2019). In the case study below, we use residential location as an attribute in the form of traffic zones from the regional traffic model, and only indirectly relate to transport mode availability because of data availability issues we ran into. If more detailed data are available on people's attributes, a more fine-grained distinction in population groups would be possible. Detailed individual or household level data is ideal, but the method does not depend on it as this data is often not available. It is however required to know, or estimate, the number of people in each possible group. For example, if there are 50 neighborhoods, 5 income levels and 2 modes considered, this results in $50 * 5 * 2 = 500$ groups. Using further disaggregation, e.g. using 500 zipcodes, increases the number of groups tenfold and also requires (in this example) income and mode availability to be known or properly estimated at the zipcode level. Data availability should be kept in mind when selecting attributes in step 1; the aggregation level should be chosen such that all attributes can be accurately estimated. Once this requirement has been met, equity can be assessed not just for all subgroups separately, but also for larger subgroups. For example, it would be possible to assess the situation of groups defined by a single attribute (e.g. income level) *across* all other attributes (all locations and all possible transport modes combinations).

A set of groups G is created for each attribute that is chosen to be relevant to include. Location is incorporated into the methodology here as attribute i, as is common in the literature. Each additional attribute that defines a group gets its own letter $k, l, m, \ldots$. A group is noted as lowercase g with these attributes sub-scripted, e.g. $g_{i,k,m}$. Thus, each group g is a unique combination of those attributes $i, k, l, m, \ldots$. For example, one group can designate a high income group in a specific neighborhood (i_1) having access to a specific transport mode, which can be noted as $g_{i_1,\ \textit{high income},\ \textit{car}}$.

In the formulations from here on forward, only three attributes (i, k, m) are used to differentiate the population, corresponding to the above example of location, income group, and mode as attributes. More distinctions can be added – the methodology is independent of the number of attributes used. For each attribute, the set of all its (discrete) values must be defined. The below formulas assume all attributes have discrete values, as this makes the calculations simpler. Income, for example, is classified and be defined as set K containing the income levels between which equity will be assessed. By using discrete attribute levels subsequent formulas remain easily decomposable; this means that the whole is equal to the sum of its parts, e.g. the total AFI score is equal to the sum of all AFI group scores. It is possible in theory to use continuous values, but for that integrals are needed instead of sums in the below formulas.

- $\mathbf{I} = \{i_1, i_2, \ldots\}$: set of all zones i in which the study area is divided
- $\mathbf{K} = \{k_1, k_2, \ldots\}$: set of all (discrete) values of attribute k *(e.g. income levels)*
- $\mathbf{M} = \{m_1, m_2, \ldots\}$: set of all (discrete) values of attribute m *(e.g. modes)*

The set of all groups $\mathbf{G}$ among which equity will be assessed is then defined as:

$$\mathbf{G} = \{g_{ikm},\ \ldots\}\ \forall\ i \in \mathbf{I},\ k \in \mathbf{K},\ m \in \mathbf{M} \tag{1}$$

Step 2: For *each* group, the total number of people must be known or estimated. For example, if location and income (high/medium/low) are used to differentiate groups, the number of people must be known (or estimated) for each income group in each zone in the study area.

For each of the differentiated groups $g \in \mathbf{G}$, the number of people n in that group must be estimated:

$$n_{g_{ikm}} = \text{the number of people in group } g_{ikm} \tag{2}$$

As mentioned, we use discrete non-overlapping groups in this methodology. This is in contrast to approaches that use multiple indices to generate a composite index to rank neighborhoods, for instance in terms of their need for public transport; see Currie (2010). Here, the sum of all the group sizes equals the total population N:

$$\sum_{i \in \mathbf{I},\ k \in \mathbf{K},\ m \in \mathbf{M}} (n_{g_{ikm}}) = N \tag{3}$$

Step 3: In this step, destinations are chosen that are considered important for the assessment of fairness. Destinations are often called *opportunities* in the accessibility literature to emphasize that they are potential or desired locations, as opposed to locations chosen or visited by people. Because accessibility in the broadest sense of the word is not just about only one kind of opportunity, we suggest choosing a varied and representative set of opportunity types (e.g., schools, hospitals, grocery stores). These "opportunity types" should be chosen such that they properly represent the desired or possible activity patterns of the various groups. If the opportunities or opportunity types chosen in this step are not of equal importance to the experienced accessibility, for example when the set of opportunity types has both jobs (a necessity for some part of the population) and cinemas (a luxury), this step also includes assigning a weight to opportunities or opportunity types.

A substantially large and representative set of opportunities $\mathbf{O}$ of various opportunity types $\mathbf{Y}$ (e.g. schools, hospitals, grocery stores) should be chosen. Defining $\mathbf{Y}$ here is required for the sufficiency thresholds that will be defined later, as those thresholds are opportunity type-specific. As an example, y_1 could represent hospitals, with a set of 5 opportunities ($\mathbf{O}_{hospitals} = \{hospital_1, \ldots, hospital_5\}$). The accessibility threshold could then be set or determined to be 3 for type *hospitals* in step 5.

- $\mathbf{Y} = \{y_1, y_2, \ldots\}$: set of all opportunity types y chosen
- $\mathbf{O}_y = \{o_1, o_2, \ldots\}$: set of all individual opportunities o of type y in the chosen study area

Optionally, a set of weights per opportunity (or opportunity type) can be defined here as well if not all opportunities or opportunity types are of equal importance. This is likely the case when a large and varied set of opportunities are considered. It is also the case when using an absolute measure of accessibility, for example by calculating the number of opportunities reachable within a fixed amount of time. If one were to combine both accessible jobs (a large number) and accessible hospitals (a comparatively small number) into a single measure of accessibility and fairness, then one needs to weigh these types accordingly. An example of such a weighed set of opportunity types can be found in the case study.

Step 4: For every group defined earlier, the chosen accessibility and mobility indicators are calculated. One of the most straightforward indicators of accessibility is the *cumulative* accessibility indicator, which simply counts the number of opportunities that can be reached within a predefined amount of time or travel cost (often called a ’cut-off value’). While this cumulative accessibility indicator has the advantage of being easily explained, it counts opportunities further away just as much as opportunities nearby. This does not reflect actual behavior, which in turn reflects preferences, choices and constraints. Indicators that weigh opportunities less the farther away they are reflect experienced accessibility better. Here, an indicator with a Gaussian curve (also called Bell curve) as a distance-decay function is used as recommended by Bhat et al. (2001) and Ingram (1971) among others. In addition to the cumulative and distance-decay accessibility indicators, a measure of potential mobility is also calculated for each zone. Martens, 2017 suggests calculating the “Potential Mobility Index”, PMI, as an indicator of the quality of transport service at various locations for various groups. The PMI sums for each zone in the study area the travel time and Euclidean distance to all other zones. It then divides the two sums (total travel time divided by total distance) to get a speed-based indicator. At first glance, this PMI seems only location-specific. However, it can also be made group-specific when travel time is calculated differently for certain groups based on the transport modes available to a particular group.

Accessibility indicators A and potential mobility indicator PMI are calculated for each group g. These are the indicators for which sufficiency thresholds will be defined in the next step. Two indicators for accessibility are suggested here as a starting point: one cumulative indicator, and one gravity based indicator with a distance-decay function using a Gaussian curve. The cumulative indicator counts the considered opportunities o of type y (e.g., five opportunities of type ’hospital’) that are accessible within the chosen cut-off value v. This counting is done with function $P(o_y)$, which is 1 if the travel time for that group to that opportunity is lower than the cutoff value v and 0 otherwise. Firstly, note that while travel time is used here, the same formulas apply when considering travel cost, generalized costs or other single-number travel impedances instead. Secondly, note that the travel impedance can be different for different groups even in the same location i due to other group factors k, m, if empirical studies are available and used that can quantify differences in travel impedance between those factors.

In the here presented methodology, there are two ways in which a group attribute can influence the resulting fairness. One is the (relative) size of the group, which is explained in step 7. The other is the degree to which an attribute alters travel time, cost, and accessibility in this current step. For example, when considering multiple travel modes as an attribute, accessibility A by modes can obviously vary in this step. A less obvious, but equally valid way of incorporating attribute differences is to consider how a certain attribute changes travel time or cost; e.g. if various income levels are included as attributes, these levels might have different travel costs or cut-off values. Income may also shape the possible use of parts of the transport system (e.g. toll roads or more expensive types of public transport).

The cumulative indicator for accessibility to opportunities of a group depends on a chosen cutoff value, and on the travel time to opportunities. These are then used in the counting function $P(o_y)$:

- $v =$ chosen cutoff value
- $tt^{o_y}_{ikm} =$ travel time from i with attributes k, m to opportunity o of type y

$$P(o_y) = 1 \Leftrightarrow tt^{o_y}_{ikm} \leqslant v, \text{else } 0 \tag{4}$$

Given those definitions, the cumulative accessibility A for a group g_{ikm} to an opportunity type $y \in \mathbf{Y}$ and cutoff value v is:

$$A^{yv}_{g_{ikm}} = \sum_{o_y \in \mathbf{O}_y} \left(P(o_y)\right) \quad \forall\ g \in \mathbf{G} \tag{5}$$

The “Gaussian accessibility indicator”, here adapted from Bhat et al. (2001), uses a so-called t^* value representing the average travel time (or cost) across all groups. This value determines the inflection point of the Gaussian curve. The Gaussian accessibility indicator also includes a weight W to each individual opportunity. Here, the weight is based on the size of the set $\mathbf{O}$ of opportunities of that type y: if the size of $\mathbf{O}_y = n$, each opportunity gets a weight of $\frac{1}{n}$. The Gaussian accessibility A for all groups g_{ikm} to an opportunity type $y \in \mathbf{Y}$ and average travel time t^* is:

$$A^{yv}_{g_{ikm}} = \sum_{o_y \in \mathbf{O}_y} \left(W(o_y) * \exp\left(- \left(\left(tt^{o_y}_{ikm} / t^* \right)^2 \right) / 2 \right) \right) \quad \forall\ g\ \in \mathbf{G} \tag{6}$$

$$W\left(o_y\right) = \frac{1}{\mathbf{O}_y} \tag{7}$$

The “Potential Mobility Indicator” (PMI) is the indicator used to define the quality of the network, for which a threshold will also be defined. It sums for each location the travel time and Euclidean distance to all other zones $j \in \mathbf{J}_i$. Then, it divides those two sums to get a speed-based indicator. Similar to the accessibility indicator, travel times are group-specific depending on the chosen attributes. The comparison between travel times and shortest-possible distances means that it indirectly reveals inefficiencies in the network, with areas scoring poorly on this indicator when they are geographically nearby other areas but have high travel times to those other areas.

- $\mathbf{I} =$ set of all zones i
- $\mathbf{J}_i = \{\mathbf{I} - i\}$: set of all zones, excluding i
- d^j_i: Euclidean distance from i to $j,\ i \in \mathbf{I},\ j \in \mathbf{J}$
- tt^j_{ikm}: group-specific travel time to $j \in \mathbf{J}$

$$PMI_{g_{ikm}} = \sum_{j \in \mathbf{J}_i} \left(d^j_i\right) / \sum_{j \in \mathbf{J}_i} \left(tt^j_{ikm}\right) \quad \forall\ g \in \mathbf{G} \tag{8}$$

Unlike the cumulative indicator, where opportunities far away are discarded, in a gravity-based model they never truly are as their weight approaches, but does not reach, zero. Opportunities outside of the study area zones defined below as $\mathbf{I}$ should be taken into account at least up to twice t^* from the edge of the study area. Beyond that 2x threshold, it cannot influence results by more than a few percentage points.

Step 5: Having assessed accessibility and potential mobility for each group, a threshold (or set of thresholds) that delineates sufficiency for those indicators must be chosen. This not only allows policymakers to focus on the groups that suffer insufficient accessibility and potential mobility, but is also needed for the fairness indicator in the next step to work (since it calculates the difference from this level of sufficiency). Ideally, these thresholds are supported by a deliberative and democratic process due to the contentiousness of any single definition of sufficiency. However, more pragmatic solutions to define thresholds are possible. For example, one might use descriptive statistics like averages, standard deviations or percentiles for a particular attribute (e.g., considering 50th percentile accessibility or potential mobility of car users as sufficient). When various opportunity types are considered in assessing accessibility (as suggested), thresholds should be set for each specific type.

- $\mathbf{X} = \{x_{y_1}, x_{y_2}, \ldots\}$: set of chosen accessibility thresholds x, one per opportunity type $y \in \mathbf{Y}$
- z: chosen potential mobility threshold

Step 6: In this step the proposed equity indicator, the Accessibility Fairness Index, is calculated. It is a normalized weighted sum indicator of the shortfalls below the set thresholds, in line with Foster et al. (1984). The index is first and foremost defined for the entire study area, but for additional analysis into the spatial distribution it is useful to calculate the AFI for each group in the study area. Formulas for both the overall AFI, and the group-specific AFI, are given below.

For groups that fall below the thresholds for accessibility and potential mobility, the AFI calculates how far below the threshold of accessibility each group falls. This accessibility deficiency is weighed with the size of the group as determined in step 1, and normalized with that same group size so that values fall between 0 and 1. Higher values of the AFI thus indicate that a lot of people experience a high level of insufficiency. It is a relative value without a unit. After calculating the AFI for each group, a ranking can be made from the groups with the largest unfairness to least unfairness (i.e. high to low group-AFI), which can subsequently be used by policy makers to set priorities across groups and to investigate the primary causes and solutions for these unfairnesses.

Only groups that fall below accessibility and potential mobility thresholds, are relevant for the AFI scores. Function $Q(g_{ikm})$ in Eq. (9) is a simple binary function that returns 1 only when accessibility $A^{y}_{g_{ikm}}$ is below the accessibility threshold x_t *and* potential mobility $PMI_{g_{ikm}}$ is below potential mobility threshold z, otherwise it returns 0. Because all AFI scores in Eq. (10) are multiplied by Q, the function thus sets the scores of groups above the thresholds to zero, with those that do fall below the thresholds multiplied by one and thus left unchanged.

$$Q(g_{ikm}) = 1 \Leftrightarrow A^{y}_{g_{ikm}} < x_t \Lambda PMI_{g_{ikm}} < z, \quad 0 \ otherwise \tag{9}$$

The *AFI* is calculated over all groups $g \in \mathbf{G}$, all opportunity types $y \in \mathbf{Y}$, and all accessibility thresholds $x_y \in \mathbf{X}$ that are specific for each opportunity type. For each group, it calculates the difference between accessibility $A_{g_{ikm}}$ and threshold x_t and weighs it according to group size $n_{g_{ikm}}$. The result is then normalized over the total population size N.

$$AFI = \sum_{g\in \mathbf{G},\ x\in \mathbf{X},\ y\in \mathbf{Y}} \frac{\left(\left(\left(x_t - A^{t}_{g_{ikm}}\right)/x_t\right)^2 * n_{g_{ikm}} * Q(g_{ikm})\right)}{N} \tag{10}$$

The group-specific AFI ($AFI^{y}_{g_{ikm}}$) is calculated for all groups g, to opportunity type y, with accessibility thresholds $x_y \in \mathbf{X}$ that are specific for each opportunity type. For each group, it calculates the difference between accessibility $A_{g_{ikm}}$ and threshold x_t and weighs it according to group size $n_{g_{ikm}}$. By removing the group size from the equation, it becomes a normalized indicator regardless of which accessibility indicator is used.

$$AFI^{y}_{g_{ikm}} = \left(\left(x_t - A^{t}_{g_{ikm}}\right)/x_t\right)^2 * Q(g_{ikm}) \ \forall\ g \ \in \ G \tag{11}$$

4. The case of Rotterdam

To apply the formalized approach the city of Rotterdam, the Netherlands, was chosen as study area. We chose this case for two main reasons. First, transport poverty is becoming an important policy topic in Rotterdam (Gemeente Rotterdam, 2016) and policymakers at the City of Rotterdam have expressed interest in developing policy to make their transport networks more equitable. Secondly, the City of Rotterdam facilitated this research by providing access to their traffic model and expertise.

The city of Rotterdam is the second largest city in the Netherlands with nearly 640,000 inhabitants, with the agglomeration of Rotterdam ("Stadsregio Rotterdam") having 1.2 million inhabitants. The transport system in the region is characterized by a well-developed bus network, a tram network that covers the city centre and some suburbs, and a train & subway system that connects suburbs and neighbouring cities to Rotterdam. Compared to other Dutch cities, Rotterdam has a more extensive road network throughout the entire city with higher capacities. This difference is due to the lack of a dense, car-averse historic city center. In 2014 within the municipality of Rotterdam 30% of all trips inside the city were made by car, 10% by bus, tram and subway and 27% by bike (the remainder were mostly walking trips) (De Graaf, 2018).

Each of the six steps as outlined at the beginning of Section 3 were performed for this case study. For selecting the study area, traffic zones within the municipality of Rotterdam were used, which can be seen in Fig. 1. The Rotterdam traffic model ("RVMK") consists of 5791 traffic model zones in total and 1192 within the municipality. We chose to use these zones as the aggregation level in our study for their high level of granularity, for being directly able to use its travel times, and for existing population and job data estimates being most precise within the municipality at that level. The RVMK traffic zones are smaller than neighbourhoods and larger than housing blocks. For more details on the model, Li et al. (2010) can be consulted. The analysis in this case study only assesses equity for population groups living within the municipality of Rotterdam. The resulting AFI and PMI scores, which are both relative measures, are thus only relative to the traffic zones within the municipality. However, an important note is that destinations were not (and should not be) limited to this study area, as destinations outside the study area will contribute to residents' accessibility significantly.

Originally, we also intended to couple demographic data to these granular traffic zones, such that income and ethnicity would be possible to include as attributes. We unfortunately ran into data availability issues and were not able to gather this data at that level of granularity during the research. Groups are thus defined largely by mode of transport instead of more socially relevant attributes. For the case study, groups are defined with all traffic zones (i), for all modes in the model (m, car/public transport/bicycle) at different times (k, peak/off-peak). We know the number of people and modal split in each zone and use that to estimate the mode usage per zone. The size of each group g (step 2) was estimated with population data from the traffic model. Modal split estimates and car ownership data were derived from Statistics Netherlands (CBS). The number of jobs and the number of residents were known for each zone in the RVMK, with the jobs dataset originally coming from the LISA Foundation dataset of employment statistics.

As per step 3, a substantially large and comprehensive set of various destination types were chosen, with the aim of reflecting the most important activity types in daily life. Because the number of opportunities as well as their comparative relevance is not equal between types, a weighing between opportunity types was applied. This prevents the problem of, for example, 10 grocery stores counting as much towards accessibility as 10 hospitals. A simple hierarchical approach was applied, with equal weight given to every subcategory:

- Service
  - Health: hospitals, pharmacies and nursing homes
  - Educational: elementary schools, high schools and higher education (2 types)
  - Commercial: supermarkets and clothes stores
- Leisure
  - Cultural: theatres, museums, libraries, and cinemas
  - Recreational: playgrounds, recreational areas
  - Sports: swimming pools, tennis courts, multi-sport centres

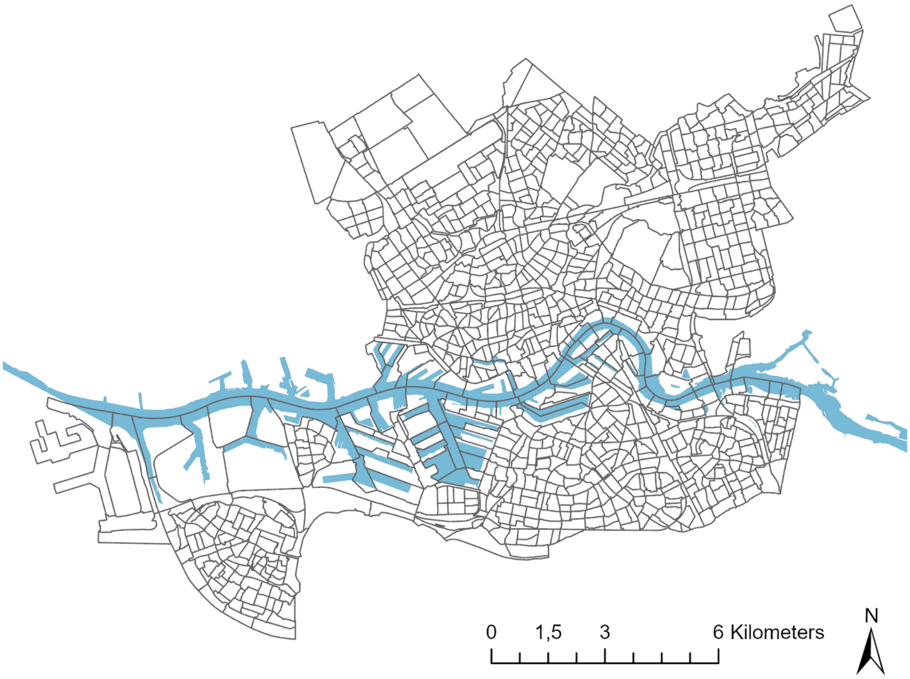

Fig. 1. The study area of Rotterdam chosen for this case study, with each of the 1192 traffic zones shown.

- Employment
  - Jobs

Employment, services and leisure were chosen as the top level categories, each thus contributing 1/3rd to the total accessibility score over all destinations; so accessibility score to jobs weighs as much as accessibility to services for the total accessibility of a group. Within each of these main categories, selected opportunity types were considered to be of equal importance. So all "Services" opportunities will contribute with 100%/3 = 33% to the total accessibility; Health, Educational and Commercial opportunities each contribute with 33%/3 = 11%; hospitals contribute with 11%/3 = 3,7% to the total. This weight based and hierarchical approach should be seen as a suggestion - it can easily be adapted to different cultural contexts and policy goals.

Accessibility and potential mobility to each opportunity type is then assessed in step 4. The travel times that form the basis for these assessments were derived from the RVMK, which is a static traffic assignment model with simultaneous mode choice and trip assignment. This assignment calculates mode and trip choices for freight transport, car transport (both peak and off-peak), public transport and bike trips. The PT and bicycle assignments do not take network loads into account and are thus an all-or-nothing assignment based on the number of people that do not choose car as their primary mode of transport. This means that there is little to no discernible difference in travel times in peak and off-peak for those two modes. The two accessibility indicators were calculated for each group, to each opportunity type. Because the cumulative indicator is an absolute indicator and the Gaussian indicator is a relative and normalised indicator, the cumulative accessibility is normalised.

To set accessibility and potential mobility thresholds (step 5), the suggestion by Martens (2017) is to collaborate with relevant stakeholders in a democratic process whose end product is a set of those thresholds. While that could be the most appropriate method for this inherently normative step, it is a time-consuming process which is outside of the scope of this research. Instead, this research makes two pragmatic decisions in this regard: to use a descriptive statistic for setting the sufficiency threshold, and to base that statistic on a group that we consider to have sufficient accessibility, without doing further research into precisely what relevant stakeholders consider sufficient. We leave the exploration of practical normative discussions about sufficiency to be further discussed in other papers.

We set two accessibility thresholds with a percentage of the average accessibility of people travelling by car at peak times: 100% and 50% as a high and a low threshold. This is in line with methods of income poverty research (Martens et al., 2019). In other words, with the high threshold, the average accessibility by car at peak hours in Rotterdam is considered 'sufficient' in the analysis. Every group (including those using different modes) is compared to this level of sufficiency in the next step. With the low threshold, half of this peak accessibility is considered sufficient; so if the average car driver can reach 4 hospitals during peak hours, the sufficiency is set at 2 hospitals for all groups. With a high threshold, more insufficiencies becomes visible, assigning more responsibility to transport planners for solving insufficiencies, and treating groups in a more egalitarian way; with a low threshold, the focus is squarely on the largest poverties.

Finally, with the accessibility and potential mobility indicators calculated for each group, the AFI has been calculated (step 6). The results for the case study will now be detailed.

5. Results of the case study

For all groups in the case study, the following has been calculated: the size of each group, the accessibility and potential mobility of that group, and the "fairness" (AFI) score of each group with two accessibility thresholds. These results are now briefly described, with some notable observations made.

Accessibility has been calculated in two ways; once with a cumulative indicator, and once with a distance-decay indicator. Fig. 2 depicts accessibility for all groups with those two different indicators. In the figure, 30 min is chosen as the chosen cutoff value. To allow for comparisons, half of the cutoff has been chosen as the $t*$ value, so the average travel time is 15 min, which means close to 90% of the decay happens within 30 min; in other words beyond 30 min most of the points are decayed to such a degree that results should be comparable to using a cutoff value. The cumulative accessibility indicator has been normalized using the total number of destinations per opportunity type - if all

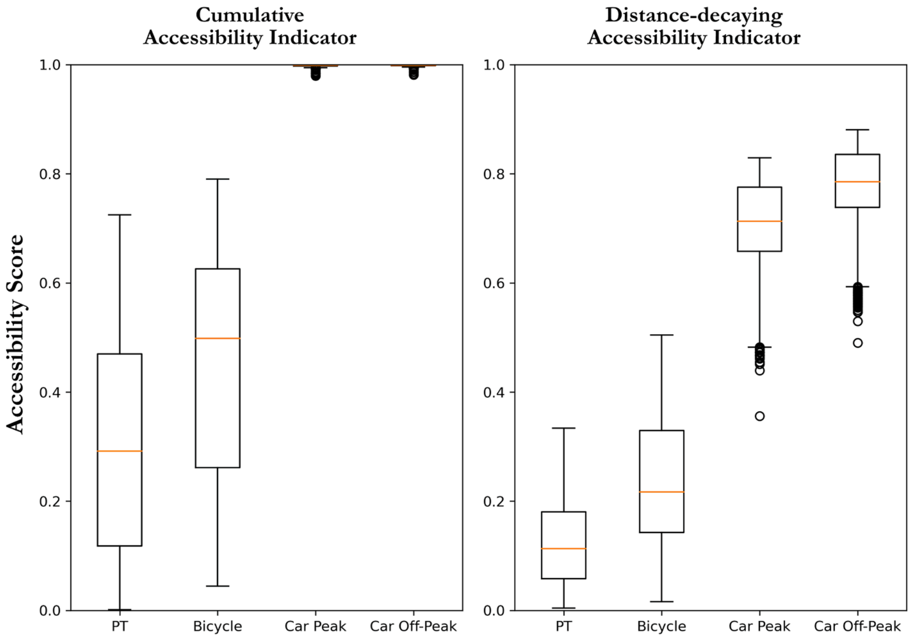

Fig. 2. Left: Accessibility using a cumulative indicator with 30 min as the cutoff. Right: Accessibility using a distance-decay indicator with 15 min as the average travel time (t*).

destinations can be reached within the cutoff time, the score is 1. The distance-decay indicator already gives a result between 0 and 1, with 1 representing perfect accessibility: all destinations are zero minutes away.

As expected, car users (both in and off-peak) have a much higher accessibility than public transport and bicycle users. The most notable (and expected) difference between the two graphs is the vertical shift that each dot makes. When the Gaussian accessibility indicator is used instead of the cumulative accessibility indicator, destinations further away contribute less to accessibility. A perfect score of 1 is much 'easier' to attain with a cumulative indicator than with a distance-decay indicator. Somewhat contrary to expectation, accessibility is noticeably better when travelling by bicycle than by public transport. This is due to the relatively low time of 30 min, which is short enough for access/egress/wait times to be a significant part of any PT journey. When the same analysis is done for an average travel time of 25 instead of 15 min, the accessibility score for many public transport groups increases to a level equal or higher than bicycle groups, as can be seen in Fig. 3.

The reason PT does not overtake bicycling easily is because the main advantage of PT is over longer distances, which are discounted when using a distance-decay Gaussian indicator in a fairly small urban area. In other words, because the Gaussian indicator puts more emphasis on destinations that are close in terms of travel time, the disadvantage of PT in travel time for short trips means a much poorer score for groups dependent on PT.

Fig. 4 shows the same y-axis and four groups as the middle figure in

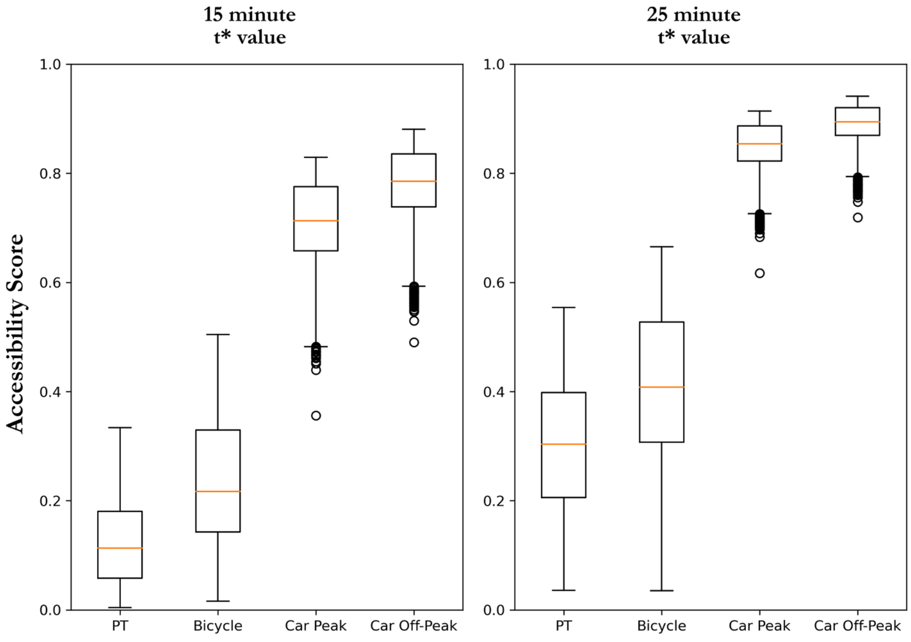

Fig. 3. The Gaussian indicator calculated for two different average travel times: 15 and 25 min.

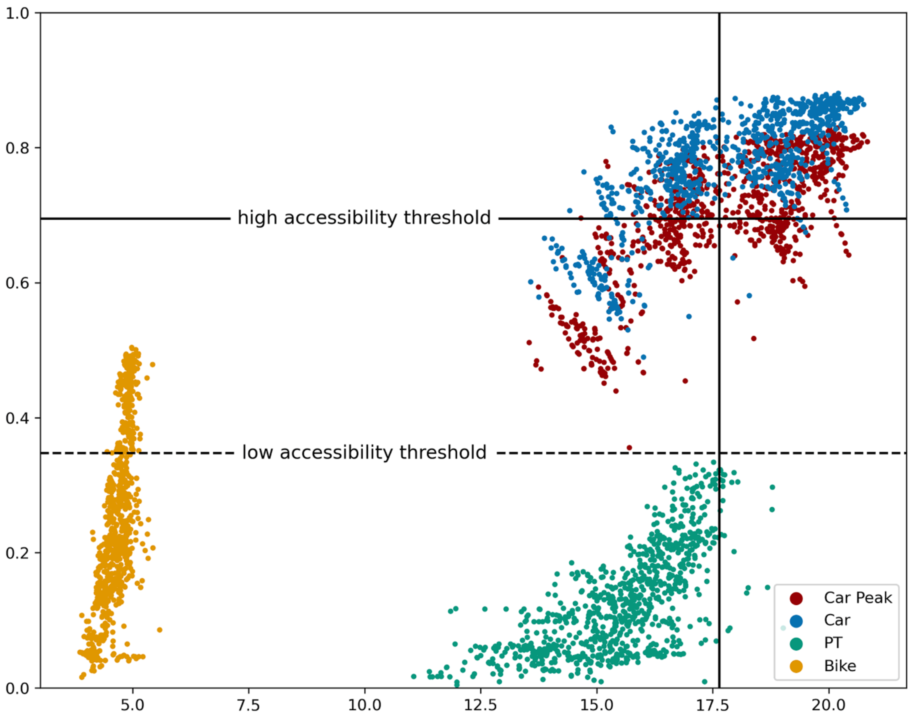

Fig. 4. Accessibility (y-axis) vs. Potential Mobility Index (x-axis) in line with Martens (2017). Black lines indicate thresholds (average accessibility and potential mobility for peak-time car users), black dotted line indicates half of the accessibility threshold.

Fig. 3 (i.e. 15 min t* value), but each group is plotted individually and on an additional x-axis representing the Potential Mobility Index calculated. Groups that are further to the right score higher on the potential mobility index, which means that the average travel speed to all other areas in the study area is higher. The average potential mobility and accessibility for car users off-peak is shown by the two continuous black lines. The dashed horizontal line depicts the low threshold, at half of that average; in other words, most bicycling and all PT users cannot reach even half the (distance-decayed) destinations within 30 min in the city that car users can reach.

A large variance can be seen in the PMI scores for car users in particular, with those living near the ring highway entrances or centrally in the city scoring highest, and those groups living in the peninsula-like (former) harbors scoring much lower. The best PMI scores for the PT users were found along the stops of the subway system, which forms a strong and highly frequent backbone throughout the city center, leading in some cases to better PMI scores for public transport than for car users. It may seem counter-intuitive that PT users have a better PMI score but a worse accessibility score than bicycle users - one would expect those to be correlated, increased potential mobility leading to increased accessibility. In this specific case however, the fact that the PMI is an average and that the study area is small (compared to regional analyses done by (Martens, 2017)) leads to this result. Because the PMI is the average speed to all other zones and the study area contains various geographical barriers (with the Maas river often doubling travel times in the traffic model), almost no bicycle group has a PMI that comes close to the other modes. For future research, we would recommend a broader study area at the metropolitan or regional level, even if this means the available zones are less granular.

PT users have significant speed advantages over longer distances, but due to wait times being modeled have significant disadvantage to other modes at short distances. So when considering travel times to *all other zones*, which is what the PMI does, public transport does almost as well as car-based groups. But when considering *only the most important* destinations, which is what the distance-decaying accessibility indicator measures, the focus is on centrally located short-distance destinations. Accessibility to destinations farther away might be good, but because those destinations are distance-decayed, they don't contribute much to accessibility. As a result, bicycling provides more accessibility to the set of destinations used in this research than PT, despite being on average a slower mode of transportation.

While these graphical representations are useful for analysing the results, the practical application of the methodology benefits more from the spatial distribution of these results. Where do insufficiencies take place in the city? Fig. 5 depicts the share of insufficiency that each traffic zone contributes to the total insufficiency across all groups ($AFI_g/\sum_g AFI$). Darker shades of red thus indicate where "unfairness" for that mode is clustered, and areas with these darker shades should form a higher priority for policy makers aiming to reduce unfairness in the study area. White areas with a black outline have no insufficiencies because they fall above the threshold values; they are above and to the right of the lines in Fig. 4.

A first observation is that insufficiency is highest further away from the center. The city center, which is just above the Maas river at the center of the map, contains the most destinations and jobs. The further away from the center, the lower the accessibility to these destinations is and the larger the AFI score will be. It should be noted here that the mapped colours are percentages *per mode*; so the dark red areas in the bottom two graphs indicate that what little unfairness there is for car users during peak hours is highly clustered at the furthest edges of the study area. It does not indicate that those areas score worse for car users than for other modes, which the previous figure already showed. An important conclusion that policymakers could draw is that almost all residents with a car experience a sufficient level of accessibility, which implies that investments might do more good in transportation solutions that don't cater to car drivers. This conclusion is further reinforced by the previous figure, which already showed that car-based groups Another conclusion is that most areas near the city center and along the subway lines do very well, which points to the importance of good, frequent and well-connected major connections in public transportation. That said, they are not always free from inequities, which implies that there is still more work to be done for transportation planning.

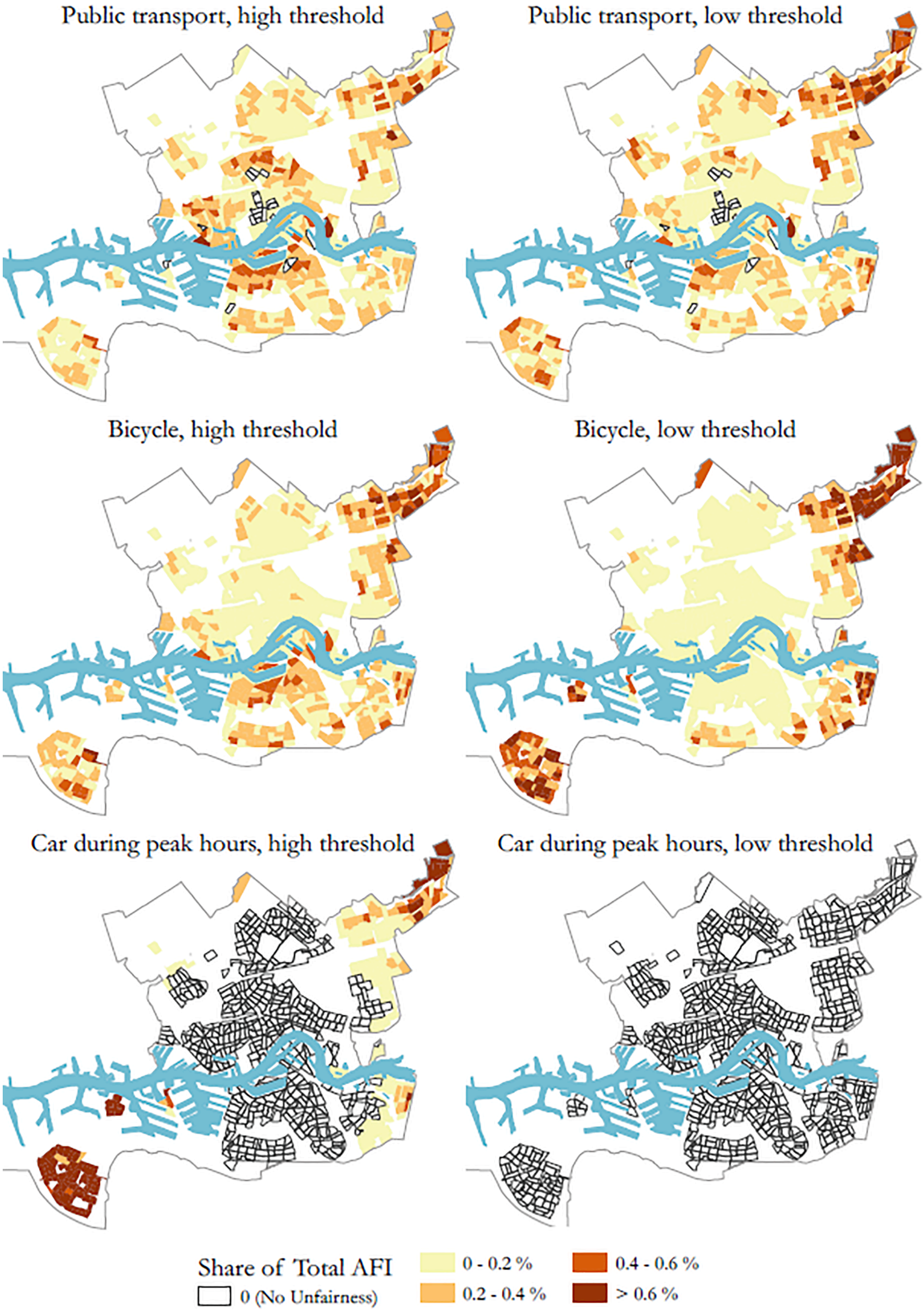

Fig. 5. Percentage that each zone contributes to the sum total of "unfairness" (AFI) for their mode (PT, bicycle, car-peak), with a high and a low threshold of accessibility (100% and 50% of the average accessibility of car-peak groups.).

The structure of the transportation network is visible in the results. For public transportation, the zones that are served well by the dense subway and tram network show low AFI scores. Particularly near the city center, a few traffic zones have a high enough level of potential mobility to not even receive an AFI score. It is also remarkable that the most southwestern part of the City scores relatively well despite its geographical distance. This is in no small part due to two subway lines that cross the city terminating there. Still, it is striking that they fare better than some areas just south of the river that are not as well-connected to the subway line there. This hints at potential significant improvements for those areas south of the river.

The geographical barrier that the river forms is very visible in the bicycling results; areas south of the river score much worse than areas an equal distance to the north of the river. Another geographical barrier is found in the northeast. There is a large park between that area and the rest of the city, the detour leading to significantly worse accessibility results. The impact of these barriers could be taken into account and resolved when planning for bicycling infrastructure improvements. For example, the city of Amsterdam has a similar geographical barrier with the IJ river, but has a lot of frequent bicycle ferries there that can greatly reduce the geographical barrier.

6. Conclusion and Discussion

By operationalizing the work of Martens (2017) and implementing it in a case for the city of Rotterdam, we aimed to reduce the gap between the theory and an applicable methodology to include fairness in transport planning using sufficientarianism as a starting point. Our results showed noticeable differences in accessibility between population groups when distinguished by travel mode availability, time of day and location, suggesting an equity analysis is warranted. The resulting AFI scores, maps and figures allow policy makers to identify equity issues which can help them in the transport planning process in prioritising policies for groups of people who face some kind of unfairness. Our formalization is flexible in its geographical scale, attributes, indicators and travel impedance, which means it can be applied to many different cases and contexts.

The approach presented has various advantages and disadvantages that became apparent whilst doing this research. Firstly, it provides a fairly straightforward approach to assess equity in transport planning. The methodology and its assumptions are simpler to explain than the often complex current planning practices involving key assumptions hidden in traffic model design and parameters. The presented methodology uses only a handful of relatively easily communicable assumptions, such as the thresholds set and the destinations chosen. While we did use travel times from the Rotterdam traffic model, the impact of various traffic model assumptions via travel times on the results were negligible. Direct comparisons between places, cities and regions are possible, if assumptions are held constant, although there might be difficulties that we could not yet uncover in this research. A difficulty is that threshold values and distance-decay functions are likely context-dependent, but these difficulties can be resolved by setting thresholds as a percentage of an average performance of accessibility and by incorporating comparative empirical research into distance decay parameters. An advantage is that the approach is quite flexible: changes to the chosen groups, destinations, or functions can be made if there is data available for them. The granularity of the approach may also come with a risk. Very selective choices could be made by policy makers: e.g. they only want to consider a handful of groups or destinations. By doing so, they negate the goal of the methodology which is to enable a comprehensive and inclusive analysis of fairness.

Various assumptions about the study area, data quality requirements, granularity, destinations, accessibility indicators, and the precise role of the thresholds were made in this study. While these assumptions have been made with the greatest care, the impact of certain choices on the results are not always fully understood which may hinder the use of this new approach. It should be noted that similar key assumptions are also made in traditional approaches to transport planning and are influenced by pragmatism in similar ways, so this is not unique to this methodology. Our view is that it will take time before a consensus about key decisions for this new methodology will emerge and best practices will have been created. Key decisions that need to be considered are: which transport modes to include (walking trips and bicycle trips have typically been excluded in transport planning practices, even in the Netherlands, despite their importance in providing accessibility against low costs), the size of transport zones used for analysis, the days of the week and hours of the day to include in the analysis, and the weighing method of the destinations. With this research, simplicity and pragmatism were important factors in all of those decisions. We implore anyone to be very transparent about these decisions - assumptions are unavoidable, so the better they are communicated the better they can be tested and challenged.

The sufficientarian principles that are at the heart of the methodology have a large impact on the results. By drawing a line, priority can be given to those who suffer the largest insufficiencies. Regardless of the process of determining these thresholds, this is an inherently normative step in the planning process since it by definition deprioritises groups of people above the sufficiency threshold. Comparing this approach to the status quo however, it can be argued that the current planning process already deprioritises (and even excludes) groups of people as reflected in the significant body of literature on equity issues and transport-related social exclusions. Comparing this approach to the proposal in Lucas et al. (2016) of including sufficientarianism in an egalitarian approach, it can be argued that a sufficientarian-based approach is preferable since it counters the deprioritising nature of egalitarian approaches by explicity prioritising groups of people, namely those who are suffering from the largest insufficiencies. Regardless of the combination of equity-based methods that are used, the explicit inclusion of such a moral framework in a planning process that did not have that a moral compass before is a major political and societal challenge. Providing a grounding in the philosophical literature will clearly not be enough. At the same time, lessons can be learned from other policy domains which are firmly based on such a moral compass, such as housing, basic education or income policy. We also recommend considering with political actors as to their view on this different approach.

We realize that in its ideal form the assessment of equity is based largely on the attributes of individual people, instead of using group attributes. The case study showed that data availability is a very important constraint - estimating group sizes is a necessity for the methodology, and the desired group attribute data cannot always be received. This, however, does not negate the usefulness of the methodology, as equity concerns will always become visible when population groups are based on attributes that indicate significant differences in accessibility. For example, despite not knowing precisely for each person or household whether they have the ability to use a car (which matters significantly, as shown in the results) we can say something about equity and accessibility for the group of people who do not own a car and what that might mean in terms of accessibility in an area in the city. These are precisely the assessments that policy can be based on. It would be best to have data on individuals, but the lack of such data does not preclude interesting conclusions and assessments. While there are still more aspects of Martens' approach that can be added, we think that the proposed methodology can provide a foundation on which further scientific research towards operationalising theoretical ethical approaches for transport policy-making can be based.

Further research could improve the developed methodology by looking at various indicators for accessibility and transport network quality (e.g. exploring utility-based indicators), could expand on the threshold setting process, or could explore the robustness of the developed methodology and the impact of various assumptions made. Another important point is that the direct relation between groups, and the included travel impedances, could be further investigated. As an example, generalized costs could be used, and these could be made larger or smaller based on which groups people fall in, based on empirical research. This could result in a more realistic view of accessibility issues compared to looking solely at travel times as impedance. The application and integration of this methodology into the ex ante transport planning process, where it could be used to evaluate the beneficiaries of new policies that reduce travel times and/or costs, is also an interesting path forward. We also leave the exploration of more inclusive group attributes and more sophisticated cost factors to further research.

CRediT authorship contribution statement

Anne S. van der Veen: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Jan Anne Annema:** Conceptualization, Writing - review & editing, Supervision. **Karel Martens:** Conceptualization, Methodology, Writing - review & editing. **Bart van Arem:** Methodology, Writing - review & editing. **Gonçalo Homem de Almeida Correia:** Writing - review & editing, Supervision.

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