This summary is also available in Dutch in Appendix **??**

Executive Summary

Introduction

In recent decades, ethical considerations in transport planning have become more and more critical. Ethics concerns itself with moral judgements based on values. One ethical consideration that has garnered more attention recently is the role of fairness or *equity* in transportation. It often refers to the "just" or "fair" distribution of transportation benefits over people and places.

A few authors have explored the concept of fairness in transportation (e.g. Karen Lucas and Karel Martens). It can be argued that Martens' 2015 book *Transport Justice: Designing Fair Transportation Networks* is the most comprehensive and theoretically underpinned proposal for incorporating fairness in transportation planning. In it, Martens argues that transportation planning should focus on accessibility and develops a new "fairness indicator" based on accessibility and mobility indicators.

However, his proposed approach has not been operationalised beyond an explorative proof of concept. Considering the potentially broad implications for policy when incorporating fairness in transportation planning, operationalising and assessing the proposed approach with a case study represents a scientific and societally relevant challenge. The goals of this research are thus to detail, challenge, formalise, and implement the proposed approach and to reflect on its usefulness, with the City of Rotterdam as a case study.

This has been translated into the research question: *"What are some of the benefits and issues of incorporating fairness in transportation policy evaluation when applied to a case for real-life agents?"* To answer this, firstly the literature and the developed methodology are explained. Then, the results are presented, along with the sensitivity of the developed methodology to two suggested improvements. Finally, the resulting benefits and issues are discussed, as well as some recommendations.

Literature

Hansen (1959) characterised accessibility as the "potential of opportunities for interaction". More specifically, accessibility indicates the spatial distribution of opportunities around a point corrected for the decreasing desire of opportunities further away (Hansen, 1959). Accessibility is around a point, so this can be considered around individuals or around places. Indicators are called "people-based" or "place-based" respectively. Because equity and fairness concern itself mostly with people and not with places, only people-based accessibility indicators are relevant.

Various indicators have been developed over the last decades to represent the spatial distribution of opportunities, ranging from blunt and straightforward indicators to complex and highly constrained indicators. A simple indicator is the minimum travel time or distance to the closest opportunity. A somewhat more advanced, but much more widely used indicator is to count all opportunities that are reachable within a certain time or within a certain generalised travel cost (called the "cutoff value"). These are called "cumulative" accessibility indicators. More advanced "gravity-based" indicators reduce opportunities that are further away using various "distance-decay functions". The most advanced accessibility indicators attempt to estimate what opportunities are reachable when constrained in time and space by activities like work, shopping and sleep.

Accessibility indicators thus quantify the spatial distribution of opportunities. Equality describes how similar the accessibility indicators are when comparing different places. For example, inequality in accessibility can be observed when comparing a city to a rural town. *Equity* describes not just (transportation) equality, but also a moral judgement of that equality. In other words, are those observed inequalities in transportation *fair*? Two kinds of equity are essential for transportation: spatial equity and social equity, referring to equity between locations (e.g. city / rural town) and equity between socio-economic and demographic groups (e.g. higher/lower incomes) respectively.

In short, equity in transportation matters between *people* and between *places*. Policy makers are interested in creating transportation policy that incorporates these kinds of equity, but the lack of proper methodologies and indicators inhibits this. Equity indicators should not only be advanced enough to capture the phenomenon but should also be easy to communicate and implement.

When making a moral judgement, it is vital to be explicit about which values are used to assess equity. Multiple authors suggest that when equity matters, utilitarian methods (i.e. benefit-maximising and cost-minimising) should be replaced or improved with methods based on so-called "sufficientarianism". Sufficientarianism refers to the idea that everyone is entitled to a minimum level of service that is sufficient. Below this "sufficiency threshold", improvements are necessary, while above this threshold improvements are not necessary.

Martens suggests developing an indicator of fairness based on this idea of sufficiency thresholds. First, he sets two sufficiency thresholds: one threshold for accessibility, and one threshold for the quality of the transportation network. The people who experience insufficient accessibility *and* insufficient transportation require improvements. If people experience insufficient accessibility but have sufficient transportation, transportation policy is likely not the solution to the accessibility problem (land use is). Thus, setting these thresholds and determining the people that fall below both thresholds allows policymakers to find the people who need transportation improvements.

Merely identifying the people falling below those thresholds is already useful for policymakers. However, it is also useful to quantify the *degree* of insufficiency because that allows policymakers to prioritise. Martens thus suggests calculating the *severity of insufficiency*: the number of people (in an area) that fall below the accessibility threshold, multiplied by how far below the threshold they fall. This is what he calls the "Accessibility Fairness Index" (AFI). Thus, Martens' proposal is to consider the severity of accessibility insufficiencies as a quantified indicator of fairness for different people in different places.

In addition to developing this indicator, Martens also proposes a new approach to transportation planning that fully incorporates it in all steps of policy making from analysing the problem to monitoring the results. It first differentiates the population into groups, insofar equity between those groups is a concern (e.g. income, gender, mode dependency). The indicators that follow will be calculated for these chosen groups.Then, it assesses potential accessibility and mobility (which indicates quality of the transportation network) and assesses how fair or unfair transportation is for each of those groups with the "AFI" indicator. This results in a prioritisation, which is the starting point for investigating and implementing solutions. His proposed approach can be summarised with the following ten steps:

1) *Differentiate* the population into relevant groups

2) *Assess* accessibility & mobility for those groups

3) *Select* thresholds

4) *Identify* groups that fall below the thresholds

5) *Assess* fairness for all groups

6) *Prioritise* population groups based on fairness indicators

7) *Identify* causes of the prioritised insufficiencies

8) *Identify* possible solutions to reduce insufficiencies

9) *Assess* effects and benefits of possible solutions

10) *Implement* and monitor selected solutions

Developed Methodology

This summary attempts to explain the developed and implemented methodology without any formulas. For an overview of the formalised developed methodology, Appendix C can be consulted. The ten steps have been simplified somewhat due to time and resource constraints. Selecting the thresholds in step 3 should be a democratic and deliberate process because of the difficulty of defining sufficiency. Here, they will be based on average accessibilities similar to Martens' proof of concept. The focus is on developing steps 1-6. Steps 7 and 8 require additional in-depth research; here, expert judgement will be used for those steps. Two solutions are tested to explore item 9. Despite not covering all steps, it should be noted that this methodology is a significant improvement over the proof-of-concept in multiple ways.

Differentiating the population was done based on three attributes: location, time (peak/off-peak) and mode availability (car, public transportation and bicycling). This resulted in a differentiation based on 1192 zones in the City of Rotterdam, 3 modes at 2 times of the day. Due to the traffic model not distinguishing time differences for PT and bicycling in a significant way, the total number of groups is $4 * 1192 = 4768$. The size of each group has been estimated with demographic data from the Bureau of Statistics. These group sizes allow the Accessibility Fairness Index, which weighs insufficiencies based on group sizes, to be calculated later on. All indicators from now on will be calculated per group, if possible. This "continuity of groups" is an important aspect of the methodology.

Before assessing accessibility, two questions must be answered: accessibility to which opportunities, and with which indicator? For this research, a selection of opportunities is made to reflect the most important activities in daily life. The 18 opportunity types chosen reflect seven important categories: Health, Educational, and Commercial services; Cultural, Recreational, and Sports facilities; and Jobs. A cumulative indicator (chosen to enable comparisons with Martens) counts the total number of opportunities within a certain travel time, the cutoff value. Cutoff values of 20, 30 and 45 minutes are used. A Gaussian (gravity-based) indicator will also be implemented for a sensitivity test.

Measuring mobility is done with an indicator proposed by Martens called the "Potential Mobility Index". For each zone, the indicator divides the average distance to all other zones by the average time to all zones. This index, measured in km/hour, thus indicates the average speed to all other areas. The "PMI" differs for each zone, mode, and time. For the distance, Martens suggests using the planar (also called Euclidean or "as-the-crow-flies") distance. This will be compared with the network distance as a sensitivity.

This thesis, as well as the proof of concept done by Martens, does not use a democratic process to derive the threshold values. Instead, the assumption is made that the average accessibility and mobility experienced by car-based groups will be sufficient. Having calculated these thresholds, the groups that fall below the accessibility and mobility thresholds are identified. Then, the deficiency is calculated for those groups as the difference between the threshold and the actual accessibility.

Fairness is then assessed for each group by multiplying this accessibility deficiency with the number of people in each group. This is the "AFI" indicator. With larger deficiencies and larger groups of people, the AFI will also be a larger positive number. (One could argue it should be named the Accessibility *Un*fairness Index.) This AFI is mapped to get a sense of the clustering of unfairness in transportation. Furthermore, Martens also suggests calculating how much each zone contributes to the total unfairness in the study area as well as a ranking of the zones for easy identification of the largest unfairness.

Experts from the City of Rotterdam were consulted to identify areas that experience significant unfairness, and to suggest changes in the network that can alleviate that unfairness. These changes are implemented in the traffic model. The analysis steps are done with the changed models as new inputs, and the resulting changes in AFI are mapped assessed to see what such a change in the network does to the indicators.

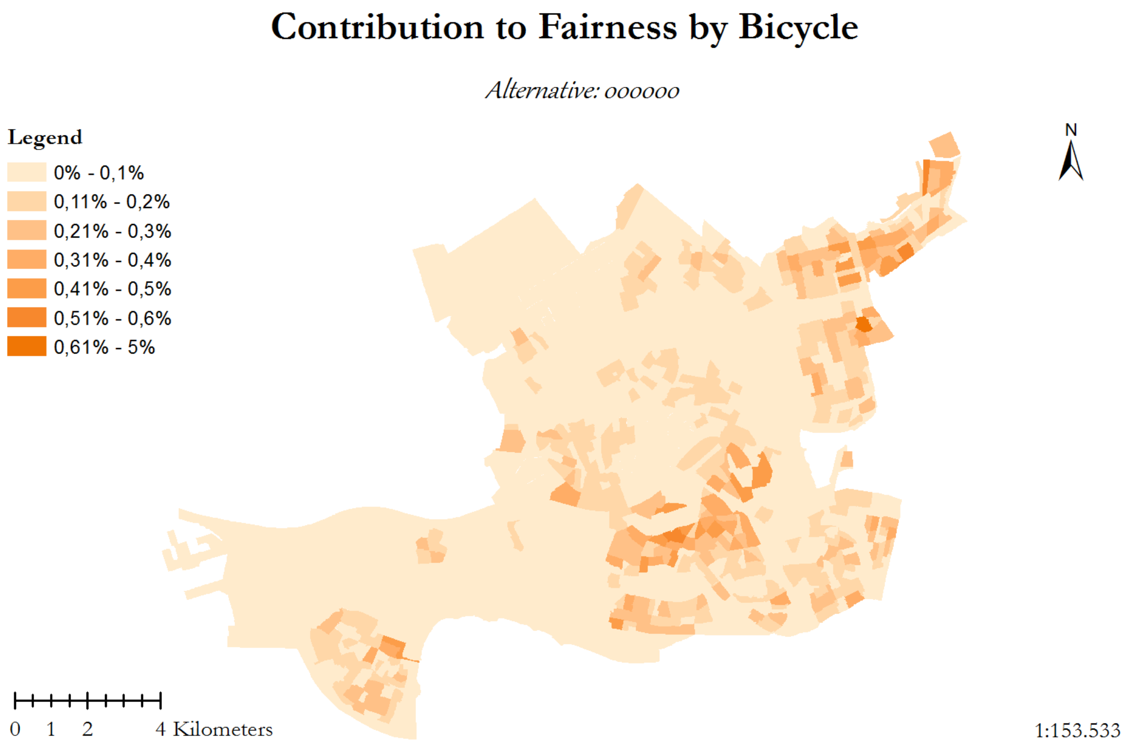

FIGURE 1: Contribution to the Total Unfairness in the Study Area (as Percentage of the Total)

Results

The results of steps 1-6 of the methodology is the following information for each of the 4768 differentiated groups (1192 zones and 4 mode-time combinations):

1) the number of people estimated for that group

2) the potential accessibility to all 18 opportunity types

3) the potential mobility (PMI)

4) the difference between the accessibility and the thresholds chosen

5) the unfairness experienced by that group (AFI)

6) the group's contribution to the total unfairness in the study area (as a percentage of total AFI)

7) the group's ranking (from largest to smallest AFI)

For steps 7,8 and 9, transportation planners at the City of Rotterdam were consulted. They suggested applying it to a relevant policy subject, namely the unfairness of bike-dependent groups. Figure 1 thus maps the unfairness to opportunities by bicycle within 20 minutes for the study area. Darker colors indicate *more* unfairness. Because opportunities outside the study area are not considered(for data availability reasons), unfairness is expected near some of the study area edges such as Nesselande in the top right. The cluster of darker zones below the centre of the map (Rotterdam-South) was not expected and was thus chosen as problematic.

Two improvements to the bicycling network were implemented in an attempt to reduce this unfairness. In one scenario the bridges over the Maas river, which had been modelled at 5 km/h to represent their geographical barrier, were modelled at 10 km/h instead. (The default modelled bicycling speed is 15 km/h.) In scenario 2, two important bicycling corridors between this problematic area and the large amount of opportunities on the other side of the river were increased to 17.5 km/h to represent a "bicycle highway" type of measure. As a result, the total unfairness experienced in the study area (summed over all groups) decreased by 4.6% in the first scenario and by 16.3% in the second scenario. Most of the improvements occurred in the aforementioned cluster of zones. While it is not explored in this thesis, the decreases in unfairness could also be used in appraisal methods.

Sensitivity

It is unclear how sensitive the end result is to (methodological) decisions made. Two methodological decisions, namely the accessibility indicator and mobility indicator chosen, were altered to assess how sensitive the results are. The methodology allows policymakers to choose certain thresholds, opportunities, cutoff values and groups, so those decisions were varied to explore whether the end results are sensitive to those decisions at all.

The Gaussian accessibility indicator seems to be much more sensitive to the spatial distribution of opportunities, because the variability between opportunity types increases for all modes and types. Because it uses a distance-decay function, most of the opportunities get discounted to some degree, so the accessibility values and the size of the unfairness indicators are lower for all groups. The groups are also more spread out, with more variation in accessibility and mobility values for each mode. This larger spread results in more groups falling below the thresholds.

Changing the PMI from using Euclidean network distances to using network distances reduces the PMI significantly for all modes. Interestingly, the total amount of unfairness in the study area increases when this different PMI is used. Since the accessibility measured doesn't change, this must mean that more areas end up below the PMI threshold.

The developed methodology leaves a few key decisions open to policymakers: it does not dictate which groups to differentiate, which opportunities and cutoff values to choose or which thresholds to set. When those decisions are made, the results should also change. To measure *if* the result changes, the impact of those four choices has been explored:

Groups The results depend on the modes, times and locations chosen. As Figure 1 shows, some groups experience very low accessibility (and thus high unfairness) while others experience high levels of accessibility (and no unfairness). Systemic differences between modes, times and locations are noticeable.

Opportunities The results show a large variability in accessibility between opportunity types. The variability seems to range between -40% and +30%.

Cutoff Value The results depend a lot on the chosen cutoff value for the accessibility indicators. Values 20,30 and 45 minutes travel time show very different accessibilities. At 20 minutes cutoff, all PT and bicycling groups experience unfairness. At 45 minutes cutoff value, only a small amount of groups near the edge of the study area experience some unfairness.

Thresholds The threshold values chosen impacts the result directly, since the accessibility deficiency is based on the threshold values.

Conclusions

This part draws from the above results, from observations made by the author, and from feedback from various transport planners and academics after presenting and discussing the research with them. After the main conclusions are discussed, the part concludes by answering the research question directly with a list of important benefits and issues.

This thesis has formalised and operationalised most of the steps proposed by Martens. The developed methodology firstly assesses potential accessibility and mobility. When this assessment is combined with chosen sufficiency thresholds, the "accessibility fairness indicator" as proposed by Martens (2015) can be used to assess both social and spatial equity in transportation. The resulting fairness indicators can be used to identify problematic areas. It can also be used to assess the impact on equity of some transportation and land-use policies. The developed methodology can be based primarily or entirely on public datasets.

By operationalising the proposed ten-step methodology and implementing it in a case for the City of Rotterdam, the gap between Martens' (2015) proof of concept and a useful methodology has been reduced. The developed methodology has been formalised (see appendix C) and can serve as a good starting point for further research, for example research into more advanced assessments. The developed methodology is already generalised and flexible enough to be applied in various cases, policy contexts and purposes. The combination of accessibility, mobility and equity assessments of the developed methodology was deemed interesting and valuable by planners and decision makers at the City of Rotterdam. It provides a good starting point for solving difficult transport-related social problems that politicians seek solutions for, e.g. social exclusion. For planning practice, the developed methodology is already considered useful by planners and decision makers as an instrument to assess equity and measures that have a large impact on equity.

It is however unclear how much of the aforementioned research gap has been closed. Various methodological decisions made in Chapter **??** and 4, such as the chosen aggregation size and study area, could be chosen differently. Originally, the intention was to include income as an attribute to differentiate groups with - even experimenting with income-specific opportunities - but this was not achieved due to insufficient data available. It also took more time and effort than expected to make the implemented methodology simultaneously flexible and robust to accommodate the four choices and two sensitivities mentioned in the previous part. While the theoretical foundation under the proposed approach by Martens appears sound, it does not provide any answers to the difficult questions that the operationalising process posed. There is thus still room to improve fundamental parts of the here developed methodology, for example by including factors common in accessibility research such as competition and spatial self-selection, or by using more advanced (activity-based) indicators and models.

The role of the used value system is also important for contextualising the results. Unlike other methodologies used in transportation planning, it places a value judgement at the very center of the methodology by requiring threshold(s) to be set for sufficient accessibility and mobility. This idea (called "sufficientarianism") is already operational in other policy fields and for other public goods. Policymakers expressed interest in applying this idea to transportation planning but were also worried about the political implications and difficulty of setting those sufficiency thresholds. The proposed ideal process of making this value judgement includes a democratic and transparent process leading to a consensus among relevant stakeholders. There are however three issues that can stand in the way of implementing this ideal process for thresholds. One, it is difficult to create and maintain such a process. It is not clear for example which stakeholders should be included in this process. Two, the precise role of the thresholds themselves is not yet clear. Is any insufficiency something which must be enacted upon? Martens (2015) proposes using more thresholds to reduce the importance of any single threshold, but this does not make the process of setting thresholds easier. Three, because the thresholds can be based on averages (or can simply be determined by policymakers), it is entirely possible that the intended deliberative process is sidestepped out of pragmatism when used in planning practice.

The results are very sensitive to the chosen accessibility indicator, are not very sensitive to the chosen mobility indicator, and are sensitive to variation in cutoff values, opportunities, thresholds and groups chosen. One of the difficulties of interpreting the results of the developed methodology is that the number of methodological decisions made is quite large, with the effects of those decisions on the results largely unknown. The decisions and sensitivities tested aimed to tackle the largest unknowns that were apparent, but it is by no means comprehensive enough to reduce all unwanted effects. As mentioned, due to choices made in choosing the study area and the data available, a strong "edge effect" is visible in the results. This effect can however easily be conflated with actual unfairness - because the center of the study area is also the center of the city of Rotterdam, areas near the edges are prone to experience unfairness because of their large distance from the center.

To answer the research question *"What are some of the benefits and issues of incorporating fairness in transportation policy evaluation when applied to a case for real-life agents?"* the major benefits and issues below have been identified. The issues identified can also be seen as recommendations for further research.

Important benefits:

Useful — The developed methodology already provides useful insights into accessibility and equity.

Interesting for policy — Policymakers want to include equity in their process, but until now the lack of proper methods has prevented this. They indicate that the developed methodology can identify equity issues and aide finding solutions for a variety of transport-related policy goals.

Flexible — The methodology can be applied to many types of opportunities, groups, spatial scales and policy topics.

Generalisable — The methodology is not specific to a given case, culture, traffic model, or mode of transport

Important issues:

Research Gap — It is hard to say how much the research gap has been closed, despite that being one of the main research goals. What is needed from a scientific and policy viewpoint to make this methodology used?

Assumptions/Choices Made — Methodological choices and assumptions, like which study area size or opportunities to incorporate, have a direct effect on the outcome. It is not clear if the currently chosen approach is the "right" one.

Sensitivity — The sensitivity of the results is explored but still not very well understood.

Values — Setting thresholds is a value-judgement, and it is done halfway in the methodology. This is unlike current practice and can thus pose a significant challenge.

Appendix A

Formal Definition of the Methodology

A.1 Differentiating Groups

This appendix summarises the generalisable methodology explained in Chapter 3 and the changes made when implementing this methodology in Chapter 4. Parts A.1 - A.4 cover the formal definition of the methodology both the generalisable (case-independent) formulation as well as the implemented (case-specific) formulation. For all methodological considerations that went into this method, the Chapter 3 and 4 should be consulted.

The methodology aims to assess the "fairness" or *equity* of transportation networks. It does this by assessing equity between *groups*, with each group referring to a specific subset of the population. Groups are differentiated based on *attributes* chosen, such as income, age, gender, or mode availability. The attributes chosen should reflect a significant difference in accessibility. Each attribute gets its own letter $k, l, m, \dots$ To assess spatial equity, location is incorporated into the methodology as attribute i. Each group g is thus a unique combination of those attributes $i, k, l, m, o, p, \dots$ (j and n are reserved). In the generalisable formulation below, only three attributes (i, k, m) are used to differentiate the population.

Generalised Formulation:

$\mathbf{I} = \{i_1, i_2, \dots\}$: set of all zones i that are in the study area

$\mathbf{K} = \{k_1, k_2, \dots\}$: set of all discrete attributes k considered

$\mathbf{M} = \{m_1, m_2, \dots\}$: set of all discrete attributes m considered

Given the above three attributes, the set of groups $\mathbf{G}$ between which equity will be assessed is defined as:

$$\mathbf{G} = \left\{g_{ikm}, \dots\right\} \ \forall \ i \in \mathbf{I}, \ k \in \mathbf{K}, \ m \in \mathbf{M} \tag{A.1}$$

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

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

If the chosen attributes are discrete non-overlapping groups, the sum of all these group sizes equals the total population in the study area N:

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

Case-Specific Formulation:

$\mathbf{I} = \{1, 2, \dots, 1192\}$: set of all 1192 zones i in the chosen study area

$\mathbf{K} = \{peak, offpeak\}$: set of all times k considered

$\mathbf{M} = \{car, PT, bicycling\}$: set of all modes m considered

$\mathbf{G} = \left\{g_{ikm}, \dots\right\}$ set of all groups $g \ \forall \ i \in \mathbf{I}, \ k \in \mathbf{K}, \ m \in \mathbf{M}$

Because *potential* accessibility is calculated, it is assumed that the number of people n is equal for $k =$ peak and $k =$ offpeak. Estimating the amount of people n in each group is thus not done for all $k \in \mathbf{K}$.

First, the share of people travelling by car ($m = car$) is estimated for each zone i with a simple linear function $C(i)$ based on the number of cars per household for that zone. The values 3 and 0,2 are chosen based on known modal split variation.

$$n_{g_{i,k,car}} = n_i * C(i) \quad \forall \ i \in \mathbf{I} \tag{A.4}$$

$$n_i = \text{total number of people in zone i} \tag{A.5}$$

$$C(i) = \left(\frac{(\text{cars per household})_i}{3}\right) + 0,2 \tag{A.6}$$

The remaining share is divided over PT and Bicycle according to the known modal split in the case study, i.e. respectively 65%/35% of non-car travellers.

$$n_{g_{i,k,PT}} = (n_i - n_{g_{i,k,car}}) * 0,65 \quad \forall\, i \in \mathbf{I} \tag{A.7}$$

$$n_{g_{i,k,bike}} = (n_i - n_{g_{i,k,car}}) * 0,35 \quad \forall\, i \in \mathbf{I} \tag{A.8}$$

A.2 Accessibility Indicators

The accessibility indicators A are calculated for each group specifically. For the generalisable formulation, a simple cumulative accessibility indicator is suggested as a starting point. A more advanced gravity-based indicator (based on a Gaussian distance-decay curve) is introduced later. The cumulative indicator counts the considered opportunities op of type t in set $\mathbf{O}_t$ that are within the chosen cutoff value v with function $P(op_t)$:

Generalised Formulation:

$\mathbf{T} = \{t_1, t_2, \dots\}$:	set of all opportunity types chosen (e.g. $\mathbf{T}$ = {Schools, Jobs, ...})
$\mathbf{O}_t = \{op_1^t, op_1^t, \dots\}$:	set of all individual opportunities in the chosen study area, with one set $\mathbf{O}$ for all $t \in \mathbf{T}$
$tt_{ikm}^{op_t}$:	group-specific travel time to op_t
v:	chosen cutoff value

Given those definitions, the cumulative accessibility A for all groups g_{ikm} to an opportunity type $t \in \mathbf{T}$ and cutoff value v is:

$$A_{g_{ikm}}^{tv} = \sum_{op_t \in \mathbf{O}_t} \Big(P(op_t) \Big) \quad \forall\, g \in \mathbf{G} \tag{A.9}$$

$$P(op_t) = \begin{cases} 1 & \text{if } tt_{ikm}^{op_t} \leq v, \\ 0 & \text{otherwise} \end{cases} \tag{A.10}$$

The "Gaussian accessibility indicator" uses a so-called t^* value, representing the average travel time, which determines the inflection point of the Gaussian curve. Its value is assumed to be $\frac{1}{2}$ the chosen cutoff value v. The Gaussian accessibility indicator also gives 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 t: if $\mid \mathbf{O}_t \mid = n$, each opportunity gets a weight of $\frac{1}{n}$. The Gaussian accessibility A for all groups g_{ikm} to an opportunity type $t \in \mathbf{T}$ and cutoff value v is:

$$A_{g_{ikm}}^{tv} = \sum_{op_t \in \mathbf{O}_t} \left(W(op_t) * \exp\Big(- \big((tt_{ikm}^{op_t}/t^*)^2\big)/2 \Big) \right) \quad \forall\, g \in \mathbf{G} \tag{A.11}$$

$$W(op_t) = \frac{1}{\mid \mathbf{O}_t \mid} \tag{A.12}$$

$$t^* = \frac{1}{2} v \tag{A.13}$$

The case-specific formulation leaves the above indicator definitions mostly unchanged. The only minor change to the above notation is that instead of choosing one v value, the analysis was done for a set of three cutoff values $\mathbf{V}$, i.e. 20, 30 and 45 minutes. For set $\mathbf{T}$, 18 opportunity types are chosen. These 18 types (hospitals, schools, etc.) aim to reflect the most important activities in the case study:

Case-Specific Formulation:

$\mathbf{T} = \{1, 2, \dots, 18\}$: set of all 18 opportunity types chosen: i.e. hospitals, pharmacies, nursing homes, elementary schools, high schools, MBO & ROCs, HBO & universities, supermarkets, clothes/fashion stores, theatres, cinemas, libraries, museums, recreational areas, playgrounds, swimming pools, sports centers, tennis/squash centers.

$\mathbf{O}_t = \{op_1^t, op_2^t, \dots\}$: set of all individual opportunities in the chosen study area, with one set $\mathbf{O}$ for all $t \in \mathbf{T}$

$\mathbf{V} = \{20, 30, 45\}$: chosen cutoff values

$tt_{ikm}^{op_t}$: group-specific travel time to op_t

Everything else remains unchanged from the generalisable formulation.

A.3 Mobility Indicators

An assessment of the quality of the transportation network is done using an indicator of potential mobility suggested by Martens (2015). This aptly named "Potential Mobility Indicator" (PMI) sums for each zone 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. The PMI is also group specific.

$\mathbf{J}_i = \{\mathbf{I} - i\}$: set of all zones, excluding i

d_i^j : Euclidean distance from i to j, $i \in \mathbf{I}$, $j \in \mathbf{J}$

tt_{ikm}^j : group-specific travel time to $j \in \mathbf{J}$

$$PMI_{g_{ikm}} = \sum_{j \in \mathbf{J}_i} (d_i^j) / \sum_{j \in \mathbf{J}_i} (tt_{ikm}^j) \quad \forall\, g \in \mathbf{G} \tag{A.14}$$

There is no difference in the case-specific formulation. In addition to the above Euclidean-distance-based PMI, a PMI based on the network distance is also tested. It is identical except for the d, which becomes group-specific:

d_{ikm}^j : network distance from i to j, $i \in \mathbf{I}$, $j \in \mathbf{J}$

A.4 Fairness Indicator

For the fairness indicator, the Accessibility Fairness Index ("AFI") as proposed by Martens (2015) is used. It requires threshold values to be determined for both accessibility and mobility. For groups whose accessibility and mobility scores (from A.2 and A.3) fall below the determined thresholds, it calculates the size of the accessibility deficiency. This deficiency is weighed with the group's size as determined in A.1. Large values of the AFI indicate that a lot of people experience a lot of insufficiency. The AFI values thus indicate how large *un*fairness is for a particular group. It is a value without a unit.

The AFI is calculated for groups g, to opportunity type t, with accessibility thresholds $y_t \in \mathbf{Y}$ that are specific for each opportunity type (e.g. a threshold of 5 for $t =$ hospitals). It calculates the difference between accessibility $A_{g_{ikm}}$ and threshold y_t and weighs it according to group size $n_{g_{ikm}}$. Function $Q(g_{ikm})$ returns 1 only when accessibility $A_{g_{ikm}}^t$ is below the accessibility threshold y_t *and* mobility $PMI_{g_{ikm}}$ is below mobility threshold z, meaning that only groups with insufficient accessibility and mobility are given an AFI score.

Generalised Formulation:

$\mathbf{Y} = \{y_{t_1}, y_{t_2}, \dots\}$: set of chosen accessibility thresholds, one threshold per opportunity type $t \in \mathbf{T}$

z : chosen mobility threshold

$$AFI_{g_{ikm}} = \left((y_t - A^t_{g_{ikm}})/y_t\right)^2 * n_{g_{ikm}} * Q(g_{ikm}) \; \forall \; g \; \in \; G \tag{A.15}$$

$$Q(g_{ikm}) = \begin{cases} 1 & \text{if } \; A^t_{g_{ikm}} < y_t \wedge PMI_{g_{ikm}} < z, \\ 0 & \text{otherwise} \end{cases} \tag{A.16}$$

The suggested formulation by Martens sums the AFI over all groups in one area (here, that would sum over $k \in \mathbf{K}$ and $m \in \mathbf{M}$). The above notation is a group-specific unfairness assessment, instead of an area-specific one.

For the case-specific formulation, the 19 thresholds (18 y and 1 z) were not based on a deliberative process due to time and resource constraints. Instead, they are based on the average accessibility ($\bar{A}^t$) and mobility ($\overline{PMI}$)by car off-peak for each opportunity type. It is assumed that this is a sufficient level. (50% of this average has also been tested, see Chapter 6.) Thus,

Case-Specific Formulation:

$\mathbf{Y} = \{\bar{A}^{t=1}, \dots, \bar{A}^{t=18}\}$: set of chosen accessibility thresholds, one threshold per opportunity type $t \in \mathbf{T}$

$z = \overline{PMI}$ chosen mobility threshold

The AFI formulation remains unchanged.