

DELFT UNIVERSITY OF TECHNOLOGY

MASTER THESIS

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# Applying Fairness to Planning Practice: Operationalising Equitable Transport Planning for the City of Rotterdam

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*“The future is here, it is just not very evenly distributed.”*

William Gibson

DELFT UNIVERSITY OF TECHNOLOGY

# *Abstract*

Faculty of Civil Engineering and Geosciences

Master of Science

## **Operationalising Equitable Transport Planning for the City of Rotterdam**

by Anne Salomon VAN DER VEEN

Ethical considerations in transportation planning literature have gotten more and more attention in the previous decades. One of those considerations is about how equitable (“fair”) the good of transportation is distributed.

While there have been theoretical suggestions to incorporate equity into transportation planning methods, the proposed approaches are not yet developed enough to be used for policy decision-making by real-life agents.

This thesis aims to bridge that gap: it reflects on the suggested approaches and operationalises a novel and intriguing proposal into an applicable methodology. This is done by evaluating, expanding, formalising, implementing, and judging the proposed approaches with the City of Rotterdam as a case study.

The developed methodology is generalisable, usable, and interesting to real-life agents, as well as being sensitive to decisions made and input changes, but is not without its flaws.



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

# 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 transport. It often refers to the “just” or “fair” distribution of transport benefits over people and places.

A few authors have explored the concept of fairness in transport (e.g. Karen Lucas and Karel Martens). It can be argued that Martens’ 2015 book *Transport Justice: Designing Fair transport Networks* is the most comprehensive and theoretically underpinned proposal for incorporating fairness in transport planning. In it, Martens argues that transport 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 transport 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: *“How can an equity-based approach to transport planning be operationalised and which important considerations, benefits and issues arise when this approach is applied to a case?”* 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). “Opportunities” refers to places

that are potentially reached. 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 which 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* however describes not just (transport) equality, but also a moral judgement of that equality. In other words, are those observed inequalities in transport *fair*? Two kinds of equity are essential for transport: spatial equity and social equity, referring to equity between locations (e.g. city / rural town) and equity between socio-economic or demographic groups (e.g. higher/lower incomes) respectively.

In short, equity in transport matters when comparing groups of *people* and *places*. Policy makers are interested in creating transport 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 “sufficiencyism”. Sufficiencyism 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 transport network.

The people who experience insufficient accessibility *and* insufficient transport require transport improvements. If people experience insufficient accessibility but have sufficient transport, transport 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 transport improvements.

Merely identifying the people falling below those thresholds is already useful for policymakers, since they represent the part of the population that should be the focus of policy. However, it is also useful to quantify the *degree* of insufficiency because that allows policymakers to prioritise those people. Martens thus suggests calculating the *severity of insufficiency*: the number of people 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, and to use this indicator to compare different people in different places.

In addition to developing this indicator, Martens also proposes a new approach to transport planning that fully incorporates equity in all steps of policy making from analysing the problem to monitoring the results. It first differentiates the population into groups, if 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 transport network) and assesses how fair or unfair transport 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 step 9. Despite not covering all steps, it should be noted that the developed methodology covers more steps and more in-depth than the proof of concept by Martens, which only covered steps 1-6 with one indicator to one opportunity type.

Differentiating the population was done based on three attributes: location, time (peak/off-peak) and mode availability (car, public transport 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 travel time differences for PT and bicycling in a significant way, the total number of groups is  $4 * 1192 = 4768$  by only considering peak/offpeak for car users. 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 different accessibility indicator (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 transport. 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.

## 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 exploring steps 7,8 and 9 of the 10-step approach, transport planners at the City of Rotterdam were consulted. They suggested applying it to a relevant policy subject, namely the unfairness of bike-dependent groups.

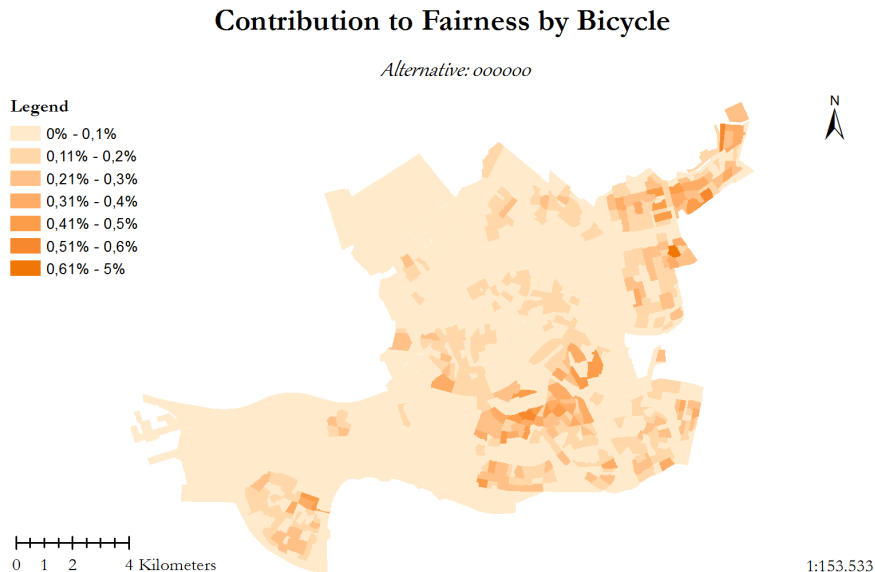


FIGURE 1: Contribution to the Total Unfairness in the Study Area (as Percentage of the Total)

Figure 1 thus maps the unfairness to opportunities by bicycle within 20 minutes for the study area. Darker colours 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.

The above results have been presented to policymakers and bureaucrats at



the City of Rotterdam in feedback sessions. They showed interest in the methodology, calling it a “useful start” and an “interesting approach” to tackle problems like accessibility poverty (*vervoersarmoede*). The openness of the developed methodology to solutions outside of transportation was considered useful, as well as its flexibility to different policy topics and activities. The term “unfairness” was considered a loaded term, and the developed methodology’s focus on making value judgements a key part of the methodology was considered interesting but potentially difficult to put into practice completely. Other concerns brought up were about the precise role of the thresholds (as a “hard norm” or more indicative) and the sensitivity of the result to changes in the inputs.

## Sensitivity

It is unclear how sensitive the end result is to (methodological) decisions made. Two key 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.

Because the Gaussian accessibility indicator 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 accessibility of groups is also more spread out for all modes. This larger spread results in more groups falling below the thresholds, and thus more unfairness measured.

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 -20% and +25%.

**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. To answer the research question *“How can an equity-based approach to transport planning be operationalised and which important considerations, benefits and issues arise when this approach is applied to a case?”*, first the methodology and its considerations are discussed, after which this summary concludes with a list of important benefits and issues identified.

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 transport. The resulting fairness indicators can be used to identify problematic areas. It can also be used to assess the impact on equity of some transport 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 to solve 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 3 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 transport 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 “sufficiencyarianism”) is already operational in other policy fields and for other public goods. Policymakers expressed interest in applying this idea to transport 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.

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 according to policymakers.

**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 generalised so that it can be applied to different cases, cultures, traffic models, or modes of transport.

*Important issues:*

**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.

**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 has been explored but still not very well understood.

## *Chapter 1*

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# Introduction and Methodology

## 1.1 Problem Statement

Transport is a key part of society: it enables us to participate in many different activities. The process of transport planning and the transport policies that follow from it can have a significant effect on transport networks. Because transport policy affects different people in different places in different ways (Martens, 2015), it is inherently political. There is thus no perfect way to do it, no “best” method to make transport policy, but there are good and bad ways to do transport planning. This means that ethical considerations might be in place.

Ethics concerns itself with what is right or wrong behaviour and the values and beliefs used to determine that. The ethical aspect of transport planning has been given more and more attention in transport literature over the last decades (Pereira, 2017). Some examples of this are research into social exclusion and the distribution effects of transport (Van Wee, 2011).

A paramount goal of transport policy is to provide accessibility (Van Wee & Geurs, 2011); in other words, the goal is to connect people with the places they want to reach. Because transport policy has a considerable impact on accessibility, it is essential to consider how transport policy benefits are distributed over those people and places.

The term “equity” is used to refer to fair (a “just”) distribution of a good. Equity in transport can refer to the fairness of the existing distribution of transport (e.g. over income levels, such as Paéz (2015)). Transport policy has an impact on the distribution of transport, so it also has an effect on this equity. These are referred to as distribution effects. Despite the political and scientific relevancy of equity in transport (Van Wee, 2011), current transport planning practice does not include equity assessments and generally ignores distribution effects (Martens, 2012; 2015; Van Wee, 2011; Pereira, 2017). Martens (2012) gives two important reasons for that:

- “(1) there is no clear definition, in practice or theory, of what constitutes a fair distribution of benefits from transportation investments; and
- (2) no standards, goals or performance measures exist, against which agencies can measure progress or success in the distribution of transportation benefit”

Recent research by Martens (2012), Golub & Martens (2014), Van Wee & Geurs (2011), and Lucas, Van Wee & Maat (2015) highlights the importance of equity to policymakers and suggests ways to incorporate equity into transport planning practices. Martens’ book *“Transport Justice: Designing Fair Transportation Networks”* is a particularly comprehensive proposal to incorporate equity into transport planning. In it, he suggests a definition of transport equity based on accessibility and proposes a novel approach to transport planning that centres around accessibility and equity indicators.

While Martens (2015) contains an exploratory case study to show that this approach has potential, there has not yet been a separate and comprehensive attempt to formalise, apply, test, and assess the usefulness of his suggested approach in a case study. In other words, this new approach to transport planning that incorporates equity is not yet operationalised. This thesis thus aims to operationalise the proposed approach with the City of Rotterdam as a case study.

## 1.2 Research Gap and Goals

Before explaining what this thesis adds to the literature, it is essential to explain briefly what ground Martens (2015) already covers. The first half of his book explores relevant philosophical concepts of justice and equity to develop the foundation underlying equity-based transport planning. He then proposes a 10-step approach that covers the planning process from identifying and prioritising problems to assessing and monitoring solutions. As a proof of concept, Martens evaluates transport equity (step 1-6 out of 10) in the metropolitan region of Amsterdam with his proposed accessibility and “fairness” indicators. This proposed approach is chosen as a point of departure for this research not just because it addresses numerous difficulties of incorporating equity (including those mentioned above), but also because his proof of concept shows that it can be implemented and can be useful for planning practice.

It is not the aim of this thesis to strengthen the philosophical foundation of this proposed approach, although this thesis will scrutinise its assumptions. Instead, it focuses on implementing and assessing the proposed approach. As Martens (2015) mentions, “not all steps of the approach have been sufficiently developed so that they can be directly applied”. This research aims to develop the proposed approach further so that it is closer to being applied and aims to reflect on its usefulness and its merits. In other words, the research gap this thesis seeks to cover is between the proposed approach and a fully-developed, useful approach for agencies that might wish to improve the distribution of transport benefits. To bridge this gap, a few goals are identified for this research:

1. Placing the proposed approach in the context of other literature
2. Formalising the approach in case-independent terms
3. Testing case-independent improvements to the method
4. Applying case-dependent changes to the method
5. Testing the sensitivity of various steps in the method
6. Reflecting on the validity and usefulness of the process and the outcomes

The scope of this research is an important side note to the above goals. Firstly, a limited amount of resources means that the research goals cannot be met for each of the ten steps in the proposed approach by Martens (2015). For example, some steps require additional quantitative or qualitative research. These steps will have to be simplified. Secondly, this is an exploratory research so while it strives for comprehensiveness, further research will be necessary.

The scientific relevance of this thesis is that it operationalises a novel approach to transport planning based on principles of justice and assesses its merits. The thesis aims to bring important considerations and potential issues to light - not just in the implementation but also in the general approach itself. Furthermore, the approach represents a new and interesting direction for transport planning research.

The societal relevance is that the approach suggests an entirely new way of thinking about planning transport, which is vital to decision makers in the transport domain. With this approach, decision makers should be able to assess accessibility in a new way that is more closely aligned with the interests of the public. It also suggests potentially essential impacts for those who are currently unjustly served by the transport networks. Operationalising this approach means that it is a step closer to being applied and being able to make transport networks more equitable.

### 1.3 Research Questions

The above research goals are translated into the following main research question:

*How can an equity-based approach to transport planning be operationalised and which important considerations, benefits and issues arise when this approach is applied to a case?*

The following sub-questions are identified as necessary to answer the main question:

1. What is the literary context surrounding equity and accessibility in transport planning?
2. How can the proposed methodology be defined, formalised, improved and implemented?
3. What are the outcomes of the approach and how sensitive are its key aspects?
4. How interesting and useful is the methodology and its outcome to policy and decisionmakers?





FIGURE 1.1: Graphic representation of the Methodology

## 1.4 Research Methodology

As Figure 1.1 shows, the research consists of two phases: a theoretical Phase 1 in which a case-independent methodology is developed and implemented, and a Phase 2 which looks at the results, the main sensitivities, reflects on these results and draws conclusions. The reflection and conclusions are not just based on the results, but also on considerations from all parts up until then, which the figure shows with additional arrows. Later chapters will cover the proposed and developed methodology extensively; this methodology only explains the structure of the thesis itself.

Phase 1 starts by providing the necessary literary context surrounding accessibility, accessibility indicators, equity and equity in transport. It also explains the chosen theoretical departure point of the thesis, which is the proposed 10-step approach by Martens (2015). After describing these theories, the thesis turns to developing and formalising a generalisable, case-independent approach. Then, it introduces the case study and implements the developed approach in this study area. Phase 2 starts by describing the results of this implemented approach: what kind of equity problems arise? Changes to some key parts of the developed approach will be explored as sensitivities. Finally, the thesis reflects and draws conclusions. This reflection is based on noteworthy considerations from earlier parts, as well as feedback received after discussing and presenting the approach to various policymakers, experts and academics.

The methods of the first phase are literature research, formalisation and implementation. Firstly, this research will start with a literature research to explore the context surrounding justice-based transport planning. Based on the literature and the proposed approach, a general mathematical definition will be defined and will be improved. Then, the theory will be combined with practice in the implementation step. For the second phase, the primary methods are the sensitivity analysis and the reflection.

## 1.5 Chapter Guide

The chapters follow the above methodology and research structure. Chapter 2 will expand on the relevant literature. Chapter 3 focuses on formalising and improving the approach, while Chapter 4 discusses the case study and implements the approach in that case study. Then, Chapter 5 discusses the results, feedback on those results and some sensitivities. Chapter 6 reflects on the approach, draws conclusions, and makes recommendations for further research and policy.

*Chapter 2*

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Literature Research

## 2.1 Introduction

This chapter is the structured result of the literature research mentioned in the methodology. The aim is to provide the necessary literary context around accessibility and equity in transport. It also aims to give insight into the difficulties of incorporating equity in transport and the current solutions proposed. The chapter first discusses accessibility in 2.2 and common accessibility indicators in literature in 2.3. Then, it discusses the theoretical and philosophical basis for a justice-based approach to transport in 2.4 and indicators suggested for such an approach in 2.5. Finally, it introduces and discusses the approach that will form the departure point for the rest of this research in 2.6.

## 2.2 Accessibility

The concept of accessibility has long played an important role in transport planning (Vickerman, 1974; Morris et al., 1979; Geurs & Ritsema-Van Eck, 2012). It has been used for analytical, evaluative and explanatory purposes in research (Vickerman, 1974; Kwan, 1998). While accessibility is often misunderstood and poorly defined (Geurs & Van Wee, 2004), a large amount of definitions originate from a seminal paper by Hansen (1959), who characterised accessibility as the “potential of opportunities for interaction”. More specifically, accessibility measures the spatial distribution of opportunities around a point, corrected for the decreasing desire of opportunities further away (Hansen, 1959). “Opportunities” in that context refers to potential destinations. The “spatial distribution of opportunities” part has become a common denominator in definitions of accessibility since then. For example, another definition of accessibility is to see it as the extent to which transport enables individuals to reach various destinations (Van Wee & Geurs, 2011).

A commonly cited explanation of what accessibility comprises is Geurs & Van Wee (2004). They distinguish four critical components of accessibility:

- the individual component, referring to what people need;
- the land use component, which is where opportunities are;
- the transport component, connecting people and opportunities;
- the temporal component, constraints that restrict access to opportunities

Lucas (2012) suggested adding a fifth component to accessibility, making the “enabling” part of accessibility more explicit:

- the cognitive component, which concerns people’s ability to transport

## 2.3 Accessibility Indicators

Various indicators have been developed to measure accessibility. Accessibility indicators need have a theoretical basis, be operationalised, be communicable and usable (Geurs & Van Wee, 2004). Indicators often fit the Hansen (1959) definition mentioned, in that they produce indices of the distribution of opportunities, taking the impedance effect distance or time into account (Kwan, 1998).

There is an essential distinction between the theory and practice of accessibility indicators. In both cases, there is no single best indicator for accessibility as the indicator depends on the specific (planning) goal and context (Handy & Niemeier, 1997). However, accessibility indicators used in research tend to favour complex and precise indicators with a strong theoretical basis, while in practice there is a clear priority given to easily understandable, communicable and useful indicators (Cheng, 2013). Bertolini et al. (2005) summarise this by saying that accessibility indicators should be “consistent with the perception of residents, workers and visitors, yet must also be understandable for participants in the plan-making process”.

Indicators of accessibility are often categorised. A simple distinction is between place-based accessibility and people-based accessibility (Lucas, 2016). Since accessibility is an attribute of a point in space, accessibility indicators can indicate how easy locations are to reach (place-based) and how easily people can reach places (individual/people-based) (Kwan, 1998). An example of a place-based accessibility indicator is the number of people living in a store’s catchment area. An example of a person-based accessibility indicators is the number of jobs a person can reach in thirty minutes. A justice-based approach to transport planning implies the focus on person-based accessibility and person-based indicators (Martens, 2015; see also 2.4).

The idea to measure accessibility on the individual scale was popularised by Hägerstrand’s seminal 1970 paper “What about people in regional science?”. Hägerstrand introduces the concept of individual space-time “prisms”, which refers to the freedom of movement individuals have over time. Lenntorp (1976) expanded on that idea by counting the opportunities within those prisms to get a spatiotemporal indicator of accessibility. These indicators, however, have “important disadvantages related to data availability and complexity, restricting applications to relatively small regions and subsets of the population” (Geurs & Van Wee, 2004).

Neutens (2010) provides a detailed comparison of multiple place and people-based indicators. A key finding is that people-based indicators are more conservative in measuring accessibility than place-based indicators since they ascribe inequalities more to the individuals than to the location itself (Neutens, 2010; Lucas, 2016). Another explanatory factor for the differences is that person-based indicators often incorporate accessibility at multiple

locations based on the activity patterns of individuals, instead of measuring accessibility solely based on work or home locations. This results in a higher amount of opportunities considered per individual.

Expanding on these two categories, Geurs & Van Wee (2004) categorise accessibility indicators in four types of indicators:

1. infrastructure-based indicators: these are based on attributes of the transport network, e.g. travel speed or congestion.
2. location-based indicators: these are based on attributes of specific locations, i.e. place-based accessibility indicators.
3. person-based indicators: these are based on attributes of specific people, i.e. people-based accessibility indicators
4. utility-based indicators: these are based on the utility of available discrete choices, e.g. the logsum (De Jong & Daly, 2005)

They conclude that infrastructure indicators are easy to interpret but are not very good at measuring accessibility since it ignores the land use component entirely and can't capture most temporal and individual factors. For example, a city centre with lots of opportunities might have a low average travel speed, thus being considered a place with low accessibility. Location and utility-based indicators overcome most of these issues, can be considered useful indicators of accessibility and can be used for social and economic evaluations. Commonly used indicators in practice are cumulative indicators (X amount of opportunities within Y amount of time) and gravity-based indicators (opportunities are weighed less the further they are away).

## 2.4 Equity in Transport

Transport policy has a direct impact on the distribution of access (the transport component) and an indirect, long-term impact on the distribution of opportunities (the land use component). Since one of the primary goals of transport policy is to provide accessibility (Martens, 2015; Van Wee & Geurs, 2011), these distributive effects of policy decisions on accessibility are essential to take into account. Despite the ability of accessibility indicators to quantify these distributive effects, accessibility indicators are not commonly used in assessing policy decisions (Van Wee & Geurs, 2011).

Unequal distribution effects are not inherently problematic: it is inevitable that transport planning benefits vary within an (urban) area (Martens, 2012; Van Wee & Geurs, 2011). However, unequally distributed benefits can be considered unfair if those benefits are systemically favour or ignore particular population groups or locations (Lucas, 2016; Martens, 2012; 2015). The values used in conventional planning practice methods like cost-benefit analysis (CBA) can create or amplify unequal distributions of access and

opportunities (Lucas, 2016; Martens, 2015; Paéz, 2010) which can be considered unfair. This unfairness is where concepts of equity and theories of justice in the domain of transport start.

Equity itself lacks a single good definition, mostly because equity can be described in many ways and many contexts (Van Wee, 2011). Equity and justice are thus used interchangeably (Pereira, 2017); here, equity is used because it is considered more neutral. According to Van Wee & Geurs (2011), equity in transport can be seen as a moral judgement over both a particular 'unfair' distribution of access, as well as the absolute level of access. Thomopoulos (2009) provides a comprehensive overview of many types of transport-related equity. Of the types described in that paper, two types of equity are particularly relevant to transport policy decisions: social equity, concerning equity between (socio-economical) population groups, and spatial equity concerning specific locations or zones (Van Wee & Geurs, 2011). Because a moral judgement is about what is right, philosophical concepts of justice/equity can be applied. Pereira (2017) boils this moral issue in transport down to three central questions: 1) Which benefits should be distributed? 2) By what moral principles? 3) What then constitutes the fairest distribution pattern?

To answer those questions, Lucas (2016), Pereira (2017) and Martens (2012; 2015) point out that it is essential to be explicit about the value system in place when making policy decisions. The mentioned method of CBA is based on utilitarian principles of maximising benefits (Lucas, 2016), which is reflected in them being limited to monetizable impacts (Thomopoulos, 2009). Both MCA and CBA are based on consequentialist principles of choosing actions based on the benefits and disadvantages of their effects (Lucas, 2016). Lucas (2016) proposes evaluating policy decisions on principles of egalitarianism and sufficientarianism instead of utilitarian principles when equity is a more important goal than maximising benefits. Egalitarianism poses that everyone should be treated equally, while sufficientarianism poses that everyone is entitled to a minimum level of service which can be considered sufficient. Injustice then occurs below this threshold value. Martens (2015) uses a similar starting point as Lucas but reflects on multiple philosophical frameworks (i.e. Rawls, 1999 [1971]; Dworkin; 1981; Walzer, 1983) to develop a thorough foundation for making policy decisions that strive for a fairer transport system. Two fundamental questions he discusses are relevant to this thesis: what constitutes an injustice in transport, and when is such an injustice large enough to consider?

To address the first question, Martens reflects on Walzer's 'Spheres of Justice' (Walzer, 1983). Walzer states that goods to which society ascribes certain social meanings should be taken out of the free exchange markets and put into what he calls a 'distributive sphere'. The goods in this sphere (also called social goods) have their distribution, which must be separated entirely from other spheres (so, from other distributions of goods). If the distribution of a

good influences the distribution of a social good, injustice occurs. For example, if the distribution of money determines the distribution of education, this is an injustice because education is a good with a significant social meaning and thus should not be influenced by the amount of an unrelated good someone has.

Martens (2015) and Van Wee & Geurs (2011) argue that transport is such a social good. Martens defines two important social meanings to support that. One meaning that Levine & Garb (2002) also share is accessibility itself, as in a person's capability to access places much like Hansen's (1959) definition. Another is potential mobility, which denotes the ease with which persons can move through space. Linking this with Van Wee & Geurs (2011)'s components mentioned earlier, the first meaning is about the distribution of opportunities (the land use component) and the second is about the distribution of access (the transport component). Martens argues that these core meanings should be "the starting point for the debate about the distribution of the transport good".

He then addresses the second question by discussing what a sufficient amount of accessibility could be and how it could be determined. Sufficiency in the transport context refers to a level below which improvements are required. Below this service level, distribution effects are severe, and injustice occurs. Lucas (2016) identifies two versions, "strong sufficientarianism" and "weak sufficientarianism". The strong version means that all attention should be focused on those below the threshold, while above this service level threshold no improvements are necessary. Weak sufficientarianism, on the other hand, implies that those below the threshold should get priority in policy, but not an absolute priority.

Determining such a threshold is not an easy question because ideas about sufficiency can vary considerably from person to person and from region to region (Van Wee, 2011), something that is also made clear by the five components of accessibility mentioned at the beginning of this chapter. Martens (2015) argues that it is more fruitful in policy to consider general levels of accessibility for groups of people instead of looking at individual accessibility. As he and Rietveld (2007) argue, the aggregation size of those groups is crucial. These groups should not be too general, since that would make them less representative of individual accessibility and less sensitive to changes. Martens (2015) also argues that they should not too fine-grained since that is likely to create data acquisition and privacy issues.

Two ranges can be relatively quickly determined, Martens (2015) argues, namely those groups with the lowest and those with the highest general level of accessibility. At those lowest and highest levels of accessibility, real-life agents can likely reach agreement on those (in)sufficient levels. Those places should also be relatively easy to find with empirical data. The difficulty is in the "domain of disagreement" in between the high and low ranges, where accessibility is not great but also not the worst. Here, Martens (2015)



suggests that democratic deliberation should occur to reach consensus as to where to put the threshold of sufficient accessibility. This democratic consensus delineates what constitutes injustice.

Van Wee & Geurs (2011) note a method focused on accessibility sufficiency could be useful “if distributive or equity effects are at stake (intended or not)”. In cases where these effects are absent, there is “nothing wrong with the traditional approach”. Martens (2015) on the other hand considers the sufficiency threshold as a more strict boundary, arguing that individuals with sufficient accessibility “are in no way entitled to improvements in accessibility based on considerations of justice” and that the threshold sets boundaries for where governments should operate. He does suggest using multiple thresholds to prevent difficult prioritisation issues around the threshold (e.g. a large group falling just above the threshold).

## 2.5 Fairness Indicators

Regardless of the role of government above the sufficiency threshold, a comprehensive approach for analysing and assessing distribution effects (or fairness) can be useful to policymakers. There are “no standards, goals or performance measures . . . against which agencies can measure progress or success in the distribution of transport benefits” (Martens, 2012). Having discussed the reasons for desiring to understand fairness, let us now turn to the question of measuring fairness.

There are some proposals for distribution-based indicators to use in transport planning. Lucas (2016), Van Wee (2011) and Neutens et al. (2010) have suggested using the Gini coefficient or variations thereof. This coefficient compares a perfect distribution cumulative curve with an observed Lorenz cumulative income curve. A perfect cumulative distribution means that the bottom X% of the population also has X% of the income. In the case of transport, a perfect distribution would mean that the lower 50% of the population has 50% of all available accessibility. The Gini coefficient then calculates the ratio between the perfect curve and the Lorenz curve (Neutens et al., 2010). A higher Gini coefficient means that the observed curve is further away from the perfect curve, so more substantial inequality is present.

While this kind of indicator is useful for measuring income inequality, Martens (2015) notes that it does not necessarily mean it is a good fairness measure. Fairness in the domain of income means *equality* of income. Fairness in transport refers to a *sufficiency* of transport, as argued before. Because of this difference, an inequality indicator might not be the best tool to measure insufficiencies. As an example, a population could have sufficient accessibility and a highly unequal distribution, and this could still be considered fair. An index of fairness should thus measure accessibility poverty. The suggestion made by Martens (2015) is to assess (un)fairness

with the aptly named Accessibility Fairness Index (called AFI from here on). The AFI aims to measure the fairness in a particular place or for a particular population group by combining the degree of insufficiency with the size of that part of the population. In other words, it measures how severe poverty deficiency is, where 'severe' refers to a large number of people experiencing said insufficiency. An advantage of this index is that the idea behind the AFI, which is that of accessibility poverty severity, is relatively easy to explain. However, a downside is that the number itself has no units and is somewhat abstract and thus not easy to parlay and relate to other factors.

Because the AFI measures the severity of fairness, different severities can be compared against each other. This is useful for those very "agencies that wish to create standards and goals regarding the distribution of transport benefits" mentioned at the beginning of this part. Martens (2015) also proposes two further fairness indicators that build upon this AFI. The first suggested indicator is simply a ranking of particular population groups based on the AFI score of that group. The second is the "percentage of contribution to overall accessibility deficiency". This indicator calculates for each population group how much they contribute to the total "unfairness" in the study area. It is a relative indicator that should allow policymakers to identify which groups suffer the most considerable accessibility deficiencies and should be given priority in policy.

## 2.6 Point of Departure

Martens (2015) thus effectively combines most (if not all) of the above considerations into a proposed approach for transport planning based on principles of justice. It is a comprehensive and complete approach in this relatively new direction of transport planning literature, which is why it was chosen as an interesting point of departure for this research.

The approach itself consists of ten steps. This chapter will explain the goals and ideas behind each step. The goal is to summarise chapter eight from Martens (2015). Operationalising this suggested methodology happens in the next chapters. Chapter 3 of this research will detail and formalise a methodology based on the below-suggested steps and a critical look at its assumptions. Chapter 4 will cover the case study and the case-specific changes and improvements made to this approach.

An important note to both Martens (2015) and this research is that it concerns the top-down, technical aspects of transport planning primarily. A purely technical approach is not comprehensive enough to be a substitute for the entire transport planning process and should be complemented with bottom-up, participatory methods (Martens, 2015). Another note is that the methodology described here and developed in later chapters is focused on transport-related solutions to the equity problems identified by the approach.

Transport could be a solution, but so could improvements in land use and the creation of new opportunities. Those types of solutions are outside of the scope of this research but can be considered in steps 7 through 10 of the below steps.

With that out of the way, the ten steps from Martens (2015) can be summarised as follows:

1. **Differentiate** the population into relevant groups
2. **Assess** mobility & accessibility for those groups
3. **Select** democratically deliberated thresholds
4. **Identify** groups 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

The approach starts out by defining which population groups are essential for distinguishing accessibility differences. There are many ways to define groups to capture accessibility differences: some examples are gender, age, social class, location, and mode availability. The primary goal of this first step is to differentiate groups that experience significant and structural differences in accessibility. This differentiation will then make assessments of equity between these groups (socio-economical equity) and between different locations (spatial equity) possible in the steps that follow. Thus, it means that equity assessments are possible that are in line with earlier remarks by Van Wee & Geurs (2011) on what kinds of equity matter in transport planning. A secondary goal is to choose groups in such a way that it sufficiently represents those who experience the lowest levels of accessibility; e.g. if earlier research shows that a specific part of a city experiences particularly insufficient accessibility, this part should be represented in the analysis with specific zone(s).

The second step follows the idea mentioned of what social meanings transport has (i.e. accessibility and potential mobility). It concerns measuring the levels of accessibility and potential mobility for each group chosen in step 1. Because these can be measured in many ways (as mentioned), multiple accessibility and mobility indicators are preferred, for example to different destinations and at different times. Potential mobility and accessibility are preferred over observed mobility and accessibility to include the population groups who might not travel at the moment but wish to do so.

The third step, arguably the most political step in the process, entails identifying sufficiency thresholds for potential mobility and accessibility. These sufficiency thresholds are a vital aspect of this approach and will greatly influence the outcome, so it is crucial that the decision-making process behind it is deliberative, democratic and transparent. As mentioned, it is preferable to choose a range of thresholds instead of one single threshold due to the difficulty of defining sufficiency. Another reason to have multiple thresholds is to account for variation within those general indicators of accessibility and mobility.

The fourth step is the identification of groups that experience insufficient levels of accessibility and sub-standard levels of potential mobility. Having multiple thresholds and multiple accessibility indicators will mean that more groups can be considered entitled to improvements. It should lead to a better, multi-faceted picture of the problem of accessibility deficiency and should allow for better, more specific indicators to be devised.

Where the fourth step was to identify which groups experience insufficiencies, the fifth step multiplies the size of the insufficiency with the size of the population group to measure the severity of insufficiencies. This indicator, called “Accessibility Fairness Index” (AFI) is the primary indicator of fairness.

The sixth step is about ranking the population groups. For each group and location differentiated in step 1, the AFI has been calculated. A ranking can be made by comparing each group’s AFI score to the total sum of all AFI scores in the area. With those insufficient groups identified and prioritised, the seventh step should comprise a detailed analysis of the causes of these insufficiencies. Both top-down and bottom-up methodologies could be suitable for this step. Case-specific knowledge and expert judgements are especially vital at this stage.

The eighth step is to create solutions for solving the problem outlined based on the causes identified. This is no simple matter because the causes might be complex and interdisciplinary. Solutions might lie in the domain of transport, or they might lie in other domains like social welfare or land-use planning.

The ninth step consists of an analysis of the effects and benefits of implementing those solutions. Which method to use will likely depend on the domain the solution is in. For transport, cost-effectiveness analysis could be useful. Effectiveness is about costs versus benefits. Here, the benefits are not travel time savings but are likely some of the standards from step six; e.g. the cost per percentage decrease in contribution to accessibility deficiency. Which of the proposed alternatives would result in the most substantial reductions in insufficiency for the least amount of costs?

Finally, the tenth step concerns the implementation, monitoring and assessment of the chosen measurement. Due to the range of indicators, thresholds and indicators suggested by this method, monitoring and assessing will likely also be more complicated than current methods.

*Chapter 3*

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Methodology for Equitable  
Transport Planning

### 3.1 Introduction

This chapter proposes a methodology for analysing the fairness of transport systems. As mentioned in section 2.6, the point of departure is Martens' (2015) proposed approach for an equity-based method of transport planning. The goal of this chapter is twofold:

1. to formalise, detail and improve the suggested methodology with generalisable, case-independent and consistent steps and formulas
2. to highlight the most important methodological design choices and considerations for each step in the approach

Both of these goals are valuable additions to the scientific literature. There is research about accessibility and equity in transport planning, but it is often limited to one or two modes and destination types and is rarely generalisable to different (policy) contexts, e.g. research into “food deserts” (Paez, 2008; Widener, 2015). The suggested approach in Martens (2015) is generalisable and explained, but most steps are not formalised, and not all methodological considerations are put on the table. Martens (2015) also contains an explorative case study, which focuses on the result and not the calculations that lead to that result. Golub & Martens (2014) does contain some formalisation, but only two indicators are defined.

The goal of this chapter is thus to propose a formalised methodology that is can be implemented for different policy topics, indicators and cases, and can be applied to various socio-economical and demographic groups, activity types, and cutoff values. A more abstract goal is to develop a methodology that enables the full potential of the proposed approach. Chapter 4 will attempt to implement this developed approach in a case study and will focus on the case-specific methodological considerations, e.g. the chosen level of aggregation and study area for this research.

Some steps from the proposed approach by Martens (2015) discussed in Chapter 2 require additional qualitative and quantitative result to get the best result. Due to the limited scope and resources of this research, the ten steps mentioned in 2.6 are simplified, with the focus is on developing steps 1-6. Selecting the thresholds in step 3 should be a democratic and deliberate process because of the difficulty of defining sufficiency, but here they will be based on average accessibilities similar to Martens' proof of concept. Steps 7 and 8 require additional in-depth research; here, expert judgement will be used for those steps. Two solutions are tested to explore step 9. Despite not covering all steps, this developed methodology is a significant improvement over the proof-of-concept in Martens (2015).

The steps used in this thesis are:

1. **Differentiate** the population into relevant groups
2. **Assess** accessibility and potential mobility indicators for those groups
3. **Select** thresholds for those indicators and **identify** population groups below the threshold
4. **Assess** fairness for all groups using the Accessibility Fairness Index
5. **Implement** a selected solution to reduce unfairness
6. **Assess** changes to the indicators

Each step corresponds to one section in this chapter. The next chapter discusses these six steps again but will only explain changes made to these steps to implement the methodology in the case study. For a summary of the formalised methodology from this chapter and the changes made in the next chapter, Appendix C can be consulted.

## 3.2 Differentiate Population Groups

Martens (2015) notes that accessibility indicators should take accessibility differences between people into account. Experienced differences in accessibility can have a wide variety of causes, from resource availability (mode, money, or time availability) and abilities (able to use certain modes, cognitive capabilities) to preferences (cultural, religious, gendered, or case-specific). Capturing all these differences is inherently difficult, and is complicated by the fact that these differences do not have an equally large impact on accessibility and are not consistent over time (e.g. changing preferences). This makes it practically impossible to base policy on experienced accessibility differences.

Instead of capturing all experienced differences, Martens thus suggests that *distinct and systemic* differences in accessibility between people should be captured. These are the differences that do not change much over time and contribute the most to accessibility differences. Individual or group-based indicators can capture these systemic differences. The main purpose of this first step is to differentiate groups which may experience significant and systemic differences in accessibility or mobility. The most important methodological considerations for this step are:

1. what aggregation levels to use
2. differentiating the groups themselves

Because every individual might experience accessibility differently, setting the aggregation at the individual level is by definition the most reflective of those individual differences. There are however a few important reasons why this is

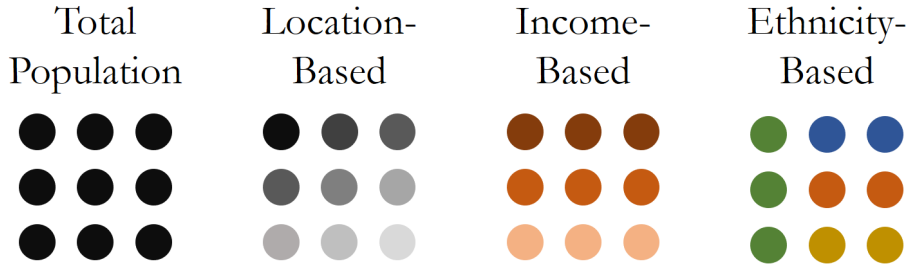


FIGURE 3.1: Example of Differentiations

not ideal. First and foremost, there are significant behavioural similarities between subsets of the population that allow them to be grouped. Secondly, it will likely impose significant data management, integrity and privacy issues. The data that is needed for such a granular distinction (individual incomes, mode availability, race, gender) is challenging to acquire and maintain. Thirdly, Neutens (2010) also showed that individual-based indicators are more conservative in measuring accessibility since they ascribe inequalities more to individual characteristics and less to systemic differences in transport. Fourthly, Rawls (1979) makes the argument that for the transparency of the government, public policy decisions should be made using only publicly available data. It also implies that some aggregation into groups is also necessary due to privacy concerns.

Considering that some aggregation is necessary, it is then important to consider which groups to differentiate. Groups can be differentiated with various *attributes* such as location, income, gender, religious background, mode availability, and ethnicity. The groups should be chosen based on attributes that correlate or influence accessibility in the given case. The attributes and groups considered can be limited by the scope of the fairness assessment (e.g. if only accessibility of the elderly is of interest, this might be a reason to consider only a few groups). A key factor in deciding attributes and groups is that for each of the groups chosen, the number of people in that group must be estimated. This group size estimation is critical for the equity assessments in later steps, which uses each group's size to prioritise equity issues.

Martens (2015) uses the term *population group* to refer to these groups, but since that is confusing for anyone with a statistical background (where a group or class is considered a subset of the population), the term *group* will be used in this thesis to refer to a number of people that have a specific and unique combination of attributes. Figure 3.1 shows an exemplary 9 zones of any chosen aggregation level.

Each colour represents a different attribute level. These 9 zones are thus divided by location, with each zone being one unique value (e.g. 'zone 1-9');



by income, with three different levels; and by ethnicity, with four colours. This means there are already  $9 * 3 * 4 = 108$  possible groups in the example. The differentiation into relevant groups thus means that the total population is 'carved up' into groups multiple times. The group differentiation enables equity assessments between those groups. Because the groups can be based on socio-economical, demographical and locational attributes, this group formulation allows equity assessments that are relevant to transport planning according to Van Wee & Geurs (2011), namely spatial equity and social(-economic) equity assessments.

The goal of this first step is to choose which attributes to base the groups on and to estimate for each group the number of people that are in it. In the above simple example, one zone was assigned one attribute level; in real-life examples, zonal distributions of attributes should be used. For example, zone 1 might consist of 20% lower income, 30% middle income and 50% higher income according to demographic data. This means that the number of people in that zone must be distributed over those groups accordingly.

Each attribute gets denoted with  $k, l, m, \dots$ . 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 for destinations and group sizes respectively). In the formulations of this chapter, only three attributes ( $i, k, m$ ) are used to differentiate the population.

Firstly, sets are defined for each of the chosen attributes. Each set contains all attribute levels of that attribute.

$\mathbf{I} = \{i_1, i_2, \dots\} :$	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

The set of groups  $\mathbf{G}$  between which equity will be assessed contains one group for each possible combination of  $i, k, m$  and is thus defined as:

$$\mathbf{G} = \{g_{ikm}, \dots\} \forall i \in \mathbf{I}, k \in \mathbf{K}, m \in \mathbf{M} \quad (3.1)$$

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

$$n_{g_{ikm}} = \text{the number of people in group } g_{ikm} \quad (3.2)$$

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

$$\sum_{i \in \mathbf{I}, k \in \mathbf{K}, m \in \mathbf{M}} (n_{g_{ikm}}) = N \quad (3.3)$$

Any indicator  $A$  can then also be calculated per group  $g$ :  $A_{gikt}$ . The methodology thus requires groups to be defined and estimated at the start, and each indicator that follows is calculated for each group whenever possible. This is a different approach than other planning practice methods. It is one of the strengths of the proposed approach and means that the accessibility, mobility, fairness, and even derived indicators like cost-effectiveness, can all be calculated for each specific group. It enables not just a large amount of equity assessments, but also allows policymakers to make very specific assessments, e.g. for a specific ethnical group in a specific location with a specific mode. Because there is no term for this yet, this thesis will coin the term *group continuity* to refer to whether an indicator is calculated for each of the differentiated groups.

### 3.3 Assessing Accessibility and Mobility

Having differentiated groups, two assessments will now be made: a potential accessibility and a potential mobility assessment. These serve as input for the equity assessment later on. The most important methodological considerations for this step are:

1. which opportunities to include
2. which accessibility indicator to use
3. which mobility indicator to use

#### 3.3.1 Accessibility

To assess accessibility, two questions must be answered: accessibility *to which* destinations, and *with which* indicators? The questions should be considered in that order since the indicator chosen depends on what kinds of destinations are important.

It is not uncommon in transport planning literature and planning practice to limit accessibility assessments to a very small number of activities.

Assessments are regularly limited to only one kind of activity (e.g. job accessibility). However, the relevance of accessibility to policymakers can extend to all sorts of activities, from work to shopping to sports to health to education. The aim of this part is thus to formalise a methodology that is suited to measure most, if not all of these different activities.

There are many indicators to choose from when assessing accessibility. Each has their nuances and influences on the result, as Neutens (2010) demonstrates. Martens (2015) argues that one, single accessibility indicator is likely not enough to capture the “multi-dimensional character” of accessibility. The benefit of the “group continuity” mentioned in 3.2 is that it addresses this

multifaceted character of accessibility by making assessments for every single group. As an example, the complex issue of accessibility to jobs could be looked at for different ethnicities, income levels, and neighbourhoods, capturing one subject from multiple angles with multiple indicators.

Place-based accessibility indicators have an advantage over people-based indicators because they are more easily calculated and explained than people-based indicators. Accessibility indicators based on individual persons face the data, privacy, transparency, and sensitivity issues mentioned earlier. Martens (2015) notes that an indicator that estimates general, potential accessibility is preferred over an indicator that estimates specific, experienced accessibility. Experienced accessibility is dependent on the many different resources available to a person (e.g. time, money, capability) and can change quickly over time. This means that an indicator of experienced accessibility is not suited to capture the earlier mentioned distinct, systemic differences between individuals. A place-based accessibility indicator that is calculated based on groups is, in a way, a “personalised” place-based indicator and can thus capture a lot of the differences in experienced accessibility. That, however, does not mean people-based indicators cannot be useful; if the data requirement issues are solved, the privacy issue can be mitigated by aggregating the data.

Neutens (2010) also notes an important difference in the ability of place-based and people-based indicators to assess issues with equity: people-based indicators result in significantly lower Gini scores across the board. In other words, the level of inequality people-based indicators report is significantly higher. This is because the people-based indicators in that particular study take the available time for activities into account. The additional constraint almost inevitably results in lower accessibility scores. In some cases, the constraints that activities pose on accessibility might be important for assessing fairness. If, for example, the focus is on day-to-day accessibility to supermarkets, opting for an accessibility indicator that takes activities into account might make a large difference in the assessment of equity. Thus, when choosing a suitable accessibility measure, the kind of fairness that is assessed and the sensitivity of different indicators to that fairness should be taken into account.

Neutens (2010) and Taken & Anselin (1998) mention four commonly used place-based indicators:

1. Minimum Distance (*DMIN*): the minimum travel (i.e. network) distance to an opportunity type.
2. Minimum Time (*TMIN*): the minimum travel time to an opportunity type
3. Cumulative (*CUM*): the number of opportunities within a predefined amount of time/distance/generalised cost (*GC*) for a particular opportunity type.
4. Gravity-based (*GRAV*): the attractiveness of locations multiplied by the travel time/distance and corrected with a distance-decay parameter

The *DMIN* indicator is the simplest of the four. It measures the network distance to the closest opportunity, so it cannot measure any accessibility differences between groups (beyond location-based groups, that is). The *TMIN* indicator is capable of expressing some of those population differences, i.e. different groups preferring different modes and thus having different (average) travel times. Both *TMIN* and *DMIN* only consider the closest opportunity, whereas *CUM* and *GRAV* consider all opportunities.

Neutens (2010) shows that the first two and the last two are correlated, but that the correlation between these two groups of indicators is low. *TMIN* and *DMIN* should only be used for measuring accessibility to destinations when the number or quality of the destinations does not matter. This limitation does not preclude them from being used in fairness assessments. Since it measures proximity to an activity, it could be used if proximity is the most important goal. An example of this indicator in practice is the Flemish policy of “basis mobility” (Vlaamse Parlement, 2016) which dictated that everyone should be able to reach a bus stop within 750 meters. The more advanced *CUM* and *GRAV* indicators can capture more dimensions of accessibility because they consider all destinations. This makes them much more appropriate for a general assessment of fairness in transport systems.

These place-based accessibility indicators can be expanded and improved. Research by Martinez (2011) for example suggests that a survey-based distance decay function that takes people’s perception of what is near and far into account can improve gravity-based indicators. Derivatives of these indicators should also be considered. For example, the accessibility to one activity type could be directly compared to the accessibility of another activity type. Perhaps a substantial difference in accessibility to elementary schools when compared to high schools could be considered unfair. The difference in these two values could then be used as a new measure. It might also be interesting to average accessibility over multiple population groups and opportunities.

This thesis will use the cumulative indicator and will test a gravity-based indicator as a sensitivity. The cumulative indicator is used in this research for two reasons. Firstly, it has inherent advantages: it is an indicator of capturing potential accessibility that has low data requirements and is easily calculated and explained. Secondly, it is also used to allow direct comparisons to Martens' (2015) exploratory case study and its results. Specifically, he uses the amount of jobs reachable with cutoff values of 20, 30 and 45 minutes and differentiates the population based on public transport and car accessibility. A notable downside of the cumulative indicator is that the cutoff value used can have a tremendous impact on the results: a small change in travel time can sometimes result in unreasonably large changes in accessibility. This can happen when lots of destinations are out of reach with one cutoff value, but become within reach when that cutoff value is increased only slightly. The slight improvement makes it look like it adds a lot of accessibility, where in reality the experienced accessibility hasn't changed much. It should be noted that this problem is larger when zones are more aggregated.

In line with earlier accessibility research, this thesis uses the term "opportunity" to refer to destinations that are considered. The term opportunities is used to reflect that it is a *potential* destination, as opposed to a *chosen* destination. Opportunities are specific to certain activities. The term "opportunity type" will refer to the potential destinations of a specific activity: for example, one school is an opportunity, but "schools" is an opportunity type.

The accessibility indicators  $A$  are calculated for each group specifically. 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  $P(op_t)$ . First, sets (which are in addition to earlier defined sets) and decision values are defined:

$\mathbf{T} = \{t_1, t_2, \dots\}$  : set of all opportunity types chosen (e.g.  $\mathbf{T} = \{\text{Schools, Jobs, } \dots\}$ )

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

$v$ : 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:

$$A_{g_{ikm}}^{tv} = \sum_{op_t \in \mathbf{O}_t} (P(op_t)) \quad \forall g \in \mathbf{G} \quad (3.4)$$

$$P(op_t) = \begin{cases} 1 & \text{if } tt_{ikm}^{op_t} \leq v, \\ 0 & \text{otherwise} \end{cases} \quad (3.5)$$

$$\text{where } tt_{ikm}^{op_t} = \text{group-specific travel time to } op_t \quad (3.6)$$

Gravity-based accessibility indicators compare the attractiveness of opportunities discounted by the distance or travel time to those opportunities. The commonly used exponential gravity-based approach follows from the works of Kwan (1998) and others and is chosen based on the Neutens (2010) and Geurs & Van Wee (2011) discussions of accessibility indicator approaches. Based on Ingram (1971) and Bhat et al. (2002), the specific Gaussian formulation of the gravity-based approach is used. This means that it uses a Gaussian curve (also called “Bell curve” or “Normal curve” in statistics literature, all referring to the same distributions) to decrease the weight opportunities that are further away. The inflection point of this curve (where its second derivative becomes positive) is the average travel time to an activity. In statistics, this location is one standard deviation from the peak (the mean). Figure 3.2 shows the curve for every given average travel time  $x$ . Figure 3.3 shows is the same graph, but for scalar multiples of  $x = 10$ .

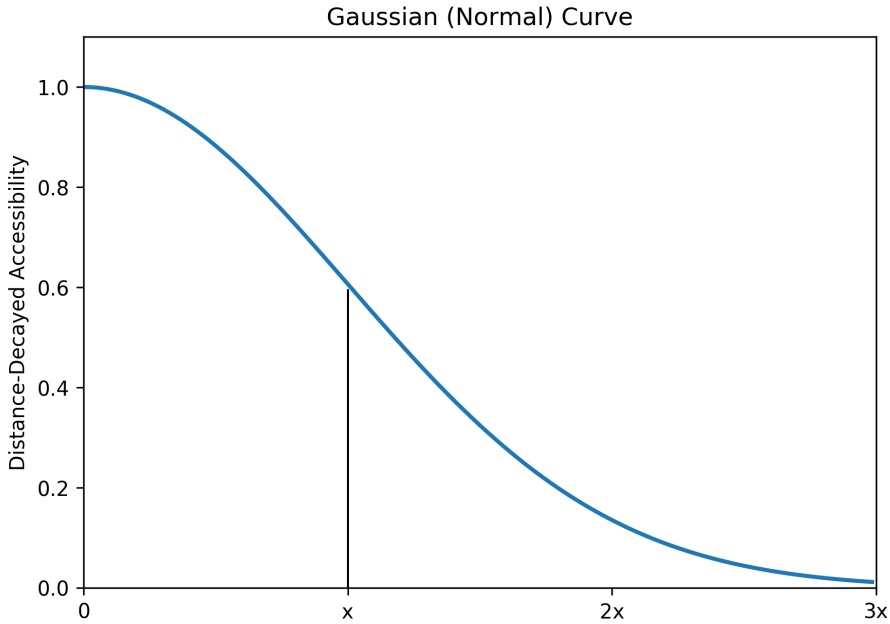


FIGURE 3.2: The Gaussian Curve

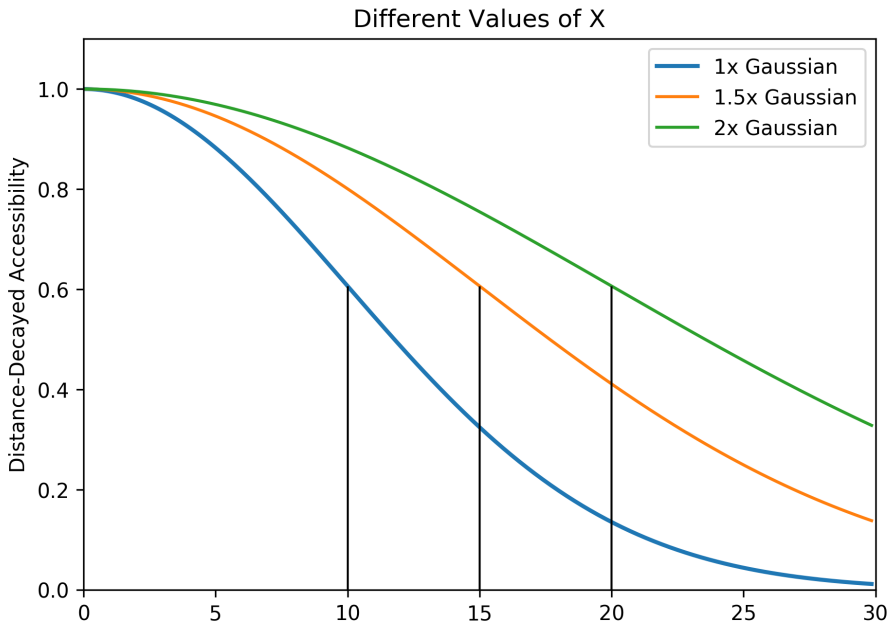


FIGURE 3.3: Three Gaussian Curves

The Gaussian gravity indicator has numerous advantages over regular negative exponent functions. Its primary advantage is that its accessibility doesn't immediately decay like regular exponent functions, which is closer to what empirical research shows (Bhat et al., 2002). Secondly, by explicitly incorporating the inflection point  $x$  in the formula, accessibility per type of opportunity can be based on average travel times. This makes the indicator more sensitive to the distribution of different opportunity types. Thirdly, it can be explained relatively easily as a comparison between the actual travel time to an opportunity and the observed average travel time for that activity. Fourthly, because the curve describes a normally distributed phenomenon, 95% of the surface area of the curve is between 0 and  $2x$ . Figure 3.4 below graphs the Gaussian curve is plotted together with a comparable Cumulative cutoff function that “decays” to zero after a cutoff of  $2x$ . In other words, when travel times are more than twice the average, opportunities rapidly stop contributing to the overall accessibility for both functions. This decay after  $2x$  is also much faster with the Gaussian curve than with regular exponents. Note how the Gaussian curve decays slower for values  $< x$ , and higher for values  $> x$ , especially after  $2x$ .

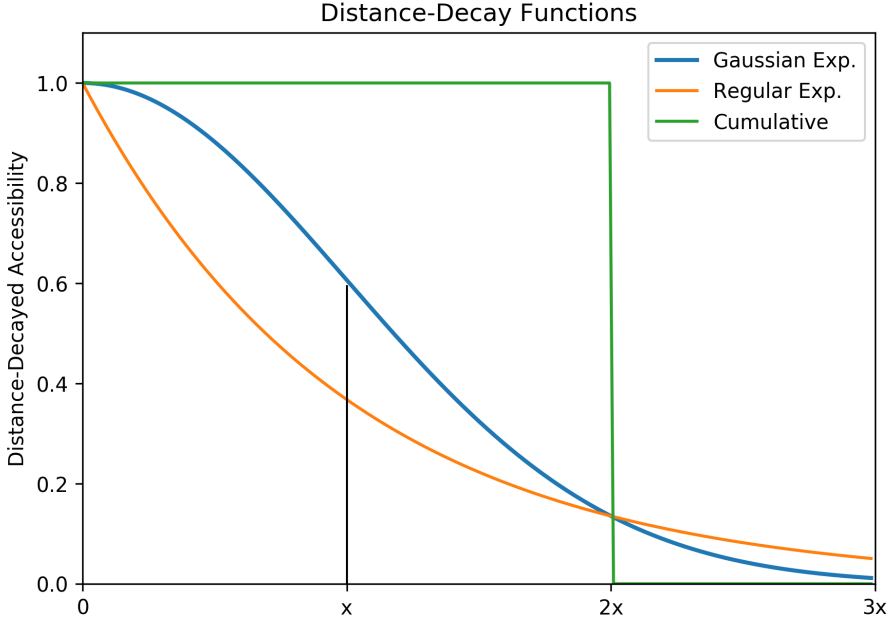


FIGURE 3.4: Three Decay Functions.

The Gaussian formulation that the literature (Ingram, 1971; Bhat et al, 2002) suggests has been adapted to the notation here as well. As mentioned, it uses a so-called  $t^*$  value, representing the average travel time, which determines the inflection point of the Gaussian curve. The  $t^*$  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  $|\mathbf{O}_t| = n$ , 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 thus:

$$A_{g_{ikm}}^{tv} = \sum_{op_t \in \mathbf{O}_t} \left( W(op_t) * \exp \left( - \left( \frac{tt_{ikm}^{op_t}}{t^*} \right)^2 / 2 \right) \right) \quad \forall g \in \mathbf{G} \quad (3.7)$$

$$W(op_t) = \frac{1}{|\mathbf{O}_t|} \quad (3.8)$$

$$t^* = \frac{1}{2}v \quad (3.9)$$

In words, a Gaussian curve is drawn with the inflection point around the average travel time. This curve is then used to reduce the importance of opportunities the farther away they are (the distance-decay function). This



distance-decayed value is multiplied by the weight (the attractiveness) of the opportunity itself. Because the gravity-based indicator considers all opportunities, this *weight \* distance decayed time* part is summed over all opportunities to get the accessibility for a group to an opportunity type.

### 3.3.2 Mobility

Martens (2015) argues that equity assessments in transport should be based not only on accessibility, but also on the quality of the transport network. As mentioned, the goal of these assessments is to delineate transport planning. The assumption made is that the quality of the transport network can indicate whether transport solutions are needed. Only those people who experience insufficient accessibility *and* insufficient quality of transport require improvements. If people experience insufficient accessibility but have sufficient transport, transport policy is likely not the solution to the accessibility problem (land use use is). The quality of the transport system is assessed using a mobility indicator. In this section, the indicator for the quality of the transport network is explained. In section 3.4, a threshold for this indicator will determine what level of quality is sufficient.

The aptly named “Potential Mobility Index” proposed by Martens (2015) will be used as the indicator of potential mobility. It sums, for each group, 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 thus also has group continuity. A low score indicates high travel times compared to the ideal shortest line of travel.

First, the set containing “all other zones” is defined:

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

This results in the following PMI definition:

$$PMI_{g_{ikm}} = \sum_{j \in \mathbf{J}_i} (d_i^j) / \sum_{j \in \mathbf{J}_i} (tt_{ikm}^j) \quad \forall g \in \mathbf{G} \quad (3.10)$$

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

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

In addition to the above Euclidean-distance-based PMI, a PMI based on the network distance is tested as a sensitivity. Martens (2015) argues that the above PMI “has significant advantages over the widely used level of service criterion” because it captures both inefficient network structures as well as low network speeds, which “jointly determines a person’s potential mobility”. However, inefficiencies in network structure are not at all easy to remedy in dense urban areas, because it mostly reflects geographical barriers. Thus the

PMI will also be calculated based on the network distance instead of Euclidian distance in the sensitivity analysis. This network-based PMI should only reflect low speeds and not network structures. It is identical to the above formulation, except for the  $d$ , which becomes group-specific:

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

(Sidenote: Martens (2015) uses a different notation, summing each  $d$  over each  $t$  and dividing over the number of zones. The above notation sums all distances and times, which means the number of zones is implicit but not disregarded. This more elegant, simpler formulation is thus preferred.)

### 3.4 Identifying Thresholds and Groups Below the Threshold

The third step entails setting sufficiency thresholds for accessibility and mobility. Together, these two thresholds delineate the domain of transport planning: transport planning should focus on areas with insufficient accessibility *and* insufficient mobility. Each group falls above or below these thresholds, and only groups that fall below both thresholds are considered experiencing “unfairness”.

The most crucial methodological consideration in this step is the process of devising the threshold values. Ideally, identifying accessibility and mobility thresholds is a democratic and deliberative process. What is “sufficient” is a normative judgement, thus requiring the input of relevant stakeholders (Martens, 2015). When time and resources are limited, thresholds can be initially set using average accessibility and mobility levels. Another reason to consider setting the thresholds with averages is that some indicator values might not mean much to stakeholders. The PMI is an example of that: its unit is kilometers/hour, but the “speed” it measures is not the actual average travel speed as one might expect. At the very least, these determined thresholds should be communicated or discussed with relevant stakeholders.

The accessibility thresholds should be opportunity-specific, but not group-specific. Thresholds for accessibility can differ wildly between opportunities, and this can be considered fair (for example, a threshold of 5 accessible high schools and 20 accessible elementary schools are very different thresholds but can both be considered fair). Unless there are clear reasons for doing so, these thresholds should be the same across groups. For example, groups could be distinguished based on modes of transport. Significant accessibility differences between modes can be considered unfair, so having thresholds per mode means that that unfairness is ignored.

For the formalisation, a set of thresholds per opportunity type is defined. Because the mobility threshold represents the quality of the network, an aspect which is opportunity-independent, only one threshold is sufficient.

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

$z$  : chosen mobility threshold

Identifying the number of people below the threshold means that the estimations for the group sizes as mentioned in step 1 (see 3.2) is combined with the accessibility and mobility calculations from step 2 (see 3.3) and the thresholds from this third step. For each of the chosen thresholds, the number of people in all groups falling below the threshold can be determined, as well as how far those people are below the threshold. Because the thresholds are opportunity-type-specific, the number of people falling below the threshold is also specific to an opportunity type. For example, a particular group might have 10 people with insufficient accessibility to hospitals, but 20 people with insufficient accessibility to schools.

The result of these first three steps is that fairness of transport can be assessed in varying dimensions. A suggested visualisation by Martens (2015) of these indicators is to put the mobility on the x-axis and accessibility on the y-axis as pictured in figure 3.5. Each zone thus has a “position” in this coordinate system defined by its accessibility and mobility score. Higher values on both mean that a group is in the upper right corner, while low values will put it in the lower left of the graph.

The thick horizontal and vertical black line represent the sufficiency thresholds for accessibility and mobility. For accessibility, a range of thresholds can be defined, leading to multiple horizontal lines. The graph is centred around the point where these values cross. The lowest-scoring areas get a position in the bottom left (Quadrant 1). Improvements to transport will likely push areas upwards and to the right, towards Quadrant 3, where they are above the thresholds that the next step defines.

$$(x, y) = (PMI_{imk}, A_{imk}) \quad \forall i \text{ in } \mathbf{I}, k \text{ in } \mathbf{K}, m \in \mathbf{M}$$

*Accessibility Threshold* :  $z \in \mathbf{Z}$

*Mobility Threshold* :  $average(PMI_{car})$

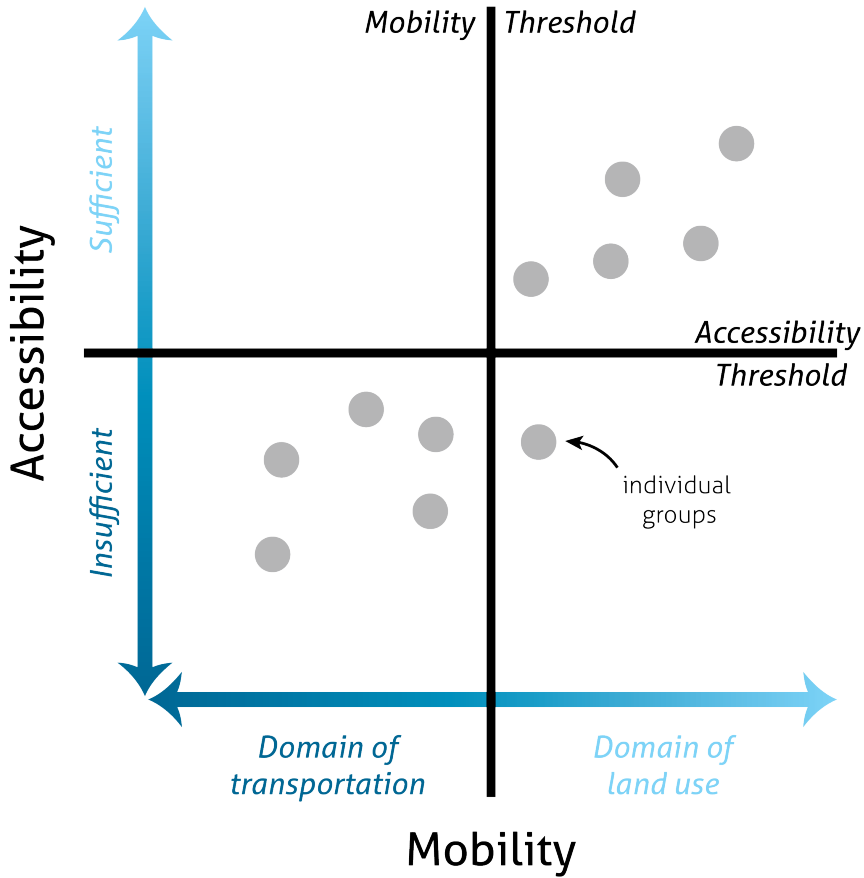


FIGURE 3.5: Suggested Visualization of Accessibility, Mobility Assessment and Thresholds

## 3.5 Assessing Fairness and Ranking Population Groups

While groups experiencing sub-standard accessibility and mobility can already be considered an indicator of fairness, Martens (2015) proposes the “Accessibility Fairness Indicator” (*AFI*) as a better indicator of fairness. For groups whose accessibility and mobility scores (from 3.3.1 and 3.3.2) 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 3.2. Large values of the *AFI* indicate that a lot of people experience a lot of insufficiency. The *AFI*, contrary to what its name suggests, thus indicates how large *unfairness* is for a particular group. It is a value without a unit.

The result is that for each zone, the degree to which that zone lacks accessibility to a type of opportunity is quantified. Fairness is thus defined as the *severity of accessibility insufficiency*, with severity defined as how many people are how far below a threshold. A methodological consideration could be whether this severity of accessibility deficiency is the best indicator to quantify equity. Because this step entails nothing besides calculating the indicator for each group, there are no further considerations.

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  $t = \text{hospitals}$ ). It calculates the difference between accessibility  $A_{g_{ikm}}$  from earlier steps and the accessibility 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  $z$ . This function thus makes explicit that only groups with insufficient accessibility and mobility are given an *AFI* score.

$$AFI_{g_{ikm}} = ((y_t - A_{g_{ikm}}^t)/y_t)^2 * n_{g_{ikm}} * Q(g_{ikm}) \quad \forall g \in G \quad (3.11)$$

$$Q(g_{ikm}) = \begin{cases} 1 & \text{if } A_{g_{ikm}}^t < y_t \wedge PMI_{g_{ikm}} < z, \\ 0 & \text{otherwise} \end{cases} \quad (3.12)$$

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

The percentage of the total “unfairness” each zone contributes can be calculated per zone. This “contribution percentage” also has group continuity and can thus be considered for specific  $m, k, l$  combinations, but can also be averaged over groups.

### 3.6 Implementing change(s) in the model

Having assessed and ranked the groups with the *AFI* equity indicator, the methodology now turns towards investigating and creating solutions to the assessed equity problems. Conventional methods for finding solutions to transport problems could be applied, although the nature of the problem and its relation to the solution should be investigated further. Martens (2015) recommends doing additional qualitative and quantitative research on the areas that previous steps have found to find the causes of the accessibility insufficiencies. An example of qualitative research into accessibility insufficiencies is the research of Bastiaansen (2012), who did research into experienced job accessibility in Rotterdam-South.

The most important methodological considerations are the decisions on how to interpret the results from earlier steps, how to investigate its causes and how to create solutions. Because this approach features multiple indicators derived from other indicators, the resulting values might obscure assumptions and issues with earlier steps. One example is to consider the role of the study area in determining the outcome. Because the Cumulative and Gaussian indicators for accessibility take all opportunities in the study area to some degree into account, it is important to consider the influence of the extent of the study area.

The spatial distribution of the resulting indicators should also be considered in the results. Transport solutions often impact a large selection of zones. It is thus important to consider clusters of zones as well as individual zones in this step. Instead of only focusing on areas with the most severe accessibility deficiencies (those with the lowest ranking), a cluster analysis could be very useful to find problematic areas on less granular levels of zoning. For example, if an entire neighbourhood is experiencing some sub-standard accessibility, each individual zone might not rank very poorly but the zones together might experience a lot of accessibility deficiency.

For this thesis, no additional research into the causes of insufficiencies can be done which is why this step is not fully developed or formalised. Expert judgement will stand in place of additional research, with the *AFI* from the previous step as the foundation on which the experts can suggest improvements or measures. This is largely done to explore if the indicators are sensitive to such improvements. Changes in the model will be made based on the largest insufficiency of a specific group in line with policy goals in the cases study.

## 3.7 Assessing changes

After changes to the model in the model have been made, the analysis steps are performed again. Changes to the AFI and ranking will then be assessed. It is expected that improvements to the model decrease the insufficiencies, but it is unclear to what degree this will happen and how these improvements will be distributed over space.

While it is outside of the scope of this research, appraisal and monitoring methods could be introduced in this step (ex-post) or in the previous step (ex-ante). A simple method could be to estimate the relation between the scale of improvements, the cost of improvements and the size of the decrease in deficiencies. Another interesting consideration is the role of network effects and the value of deficiency decreases. Because network effects are at play, it is unclear if a few big, but costly, improvements are to be preferred over a large amount of cheaper improvements.





*Chapter 4*

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Case Study Implementation

## 4.1 Introduction

The previous chapter outlined the approach in generalised (case-independent) steps. This chapter will consist of implementing the approach to the chosen case study, which is the City of Rotterdam. The City of Rotterdam was chosen in part for its interest in equity in policy. Currently, “vervoersarmoede” (literally: accessibility poverty, but very similar to transport related social exclusion) is an important policy topic (Gemeente Rotterdam, 2017) and policymakers at the City have expressed interest in using policy to make their transport networks more equitable. Another reason is that they facilitated this research by providing access to their traffic model and expertise.

The first goal of this chapter is to describe relevant characteristics of the transport networks in the case study together with some relevant socio-economical factors. The second goal of this chapter is to explain which methodological changes were made to the general approach from Chapter 3 and why they were made. Chapter 5 will discuss the results of this implementation.

## 4.2 The City of Rotterdam

Rotterdam is one of the largest cities in the Netherlands with 639,587 inhabitants as of April 2017 (CBS Statline, 2017). It is located in the province of South-Holland, in close proximity to the cities of Delft and The Hague. The agglomeration of Rotterdam (“Stadsregio Rotterdam”) includes the cities and places like Schiedam, Vlaardingen, Capelle aan de IJssel, Nieuwekerk aan de IJssel, Krimpen aan de IJssel, Spijkenisse, Berkel en Rodenrijs, and Barendrecht. Including these areas, the agglomeration has 1.2 million inhabitants (CBS Statline, 2017) with the majority living in Rotterdam. In the maps below, the municipality is outlined in black. This administrative zone (Dutch: *Beheersgebied*) excludes a significant part of the agglomeration.

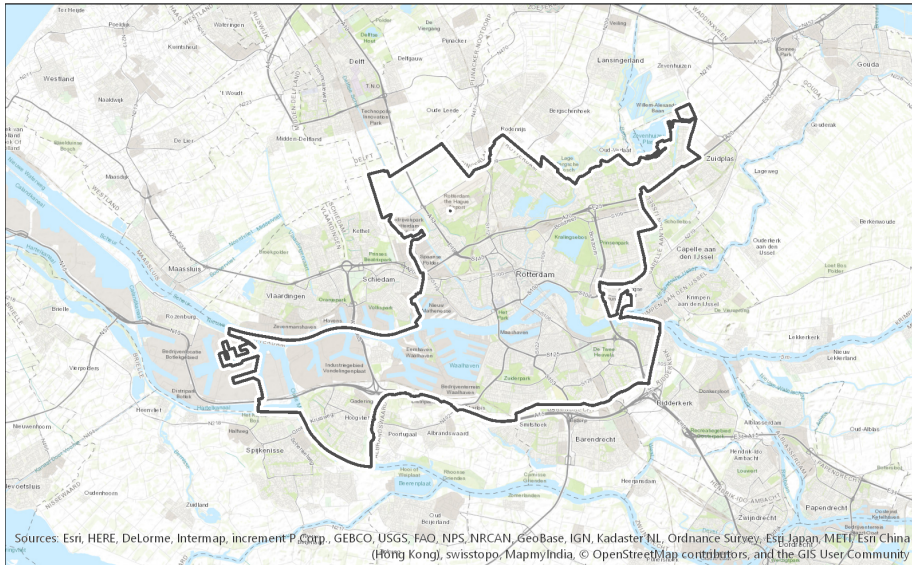


FIGURE 4.1: Topographical Map of Rotterdam.

### 4.2.1 Residents and Jobs

Figure 4.2 maps the distribution of inhabitants in the agglomeration of Rotterdam. It depicts the residential density for each zone of the Rotterdam traffic model, the RVMK. The dense urban cores of Rotterdam are visible. There are three residential clusters near the center of the map. These are colloquially and conveniently known as Rotterdam Noord (North), Rotterdam Zuid (South), and Rotterdam West.

Figure 4.3 shows that jobs are clustered in the previously mentioned residential cores. The largest peak can be seen in the city centre, which lies between those three residential cores. The source for these job numbers is from the LISA database (“*Landelijk Informatiesysteem van Arbeidsplaatsen*”; National Information System of Workplaces), a national register containing the location and amount of workers for all 1.2 million workplaces registered in the Netherlands. This dataset has been linked to the same traffic zones as the previous map.

## Residential Density Map

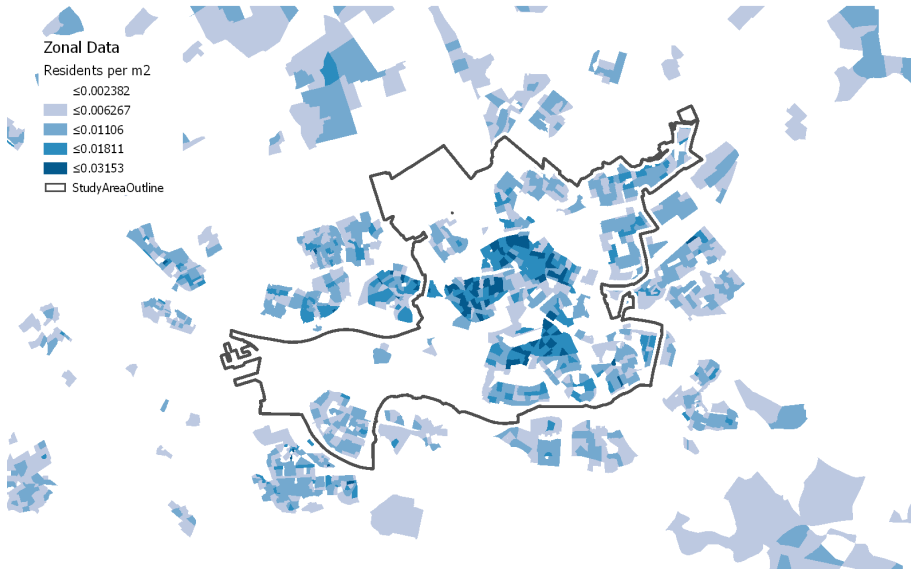


FIGURE 4.2: Residential Density Map of Rotterdam. Data source: RVMK.

### 4.2.2 Networks

The public transport network is very dense and of high quality. It is characterised by a widespread 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.

The subway forms the backbone of the transport network in the densest urban parts of the city, where subway line A,B and C connect Schiedam in the west to Blaak and Alexander in the east. This important line crosses the other two subway lines D and E which runs in a north/south direction, as can be seen in figure 4.5. These east/west and north/south lines cross each other in the city center.

Compared to other Dutch cities, Rotterdam has a more extensive road network throughout the entire city with higher capacities. The 'Rotterdamse Ruit' (*Rotterdam Diamond*) are the four highways (A20, A16, A4 and A15) that form a rectangle and are important backbones to the road network. Many parts of the city are accessible by car, even in the urban cores. The Maas river that runs from east to west through the city center poses a large physical barrier, with only a handful of river crossings in the city.

## Job Density Map

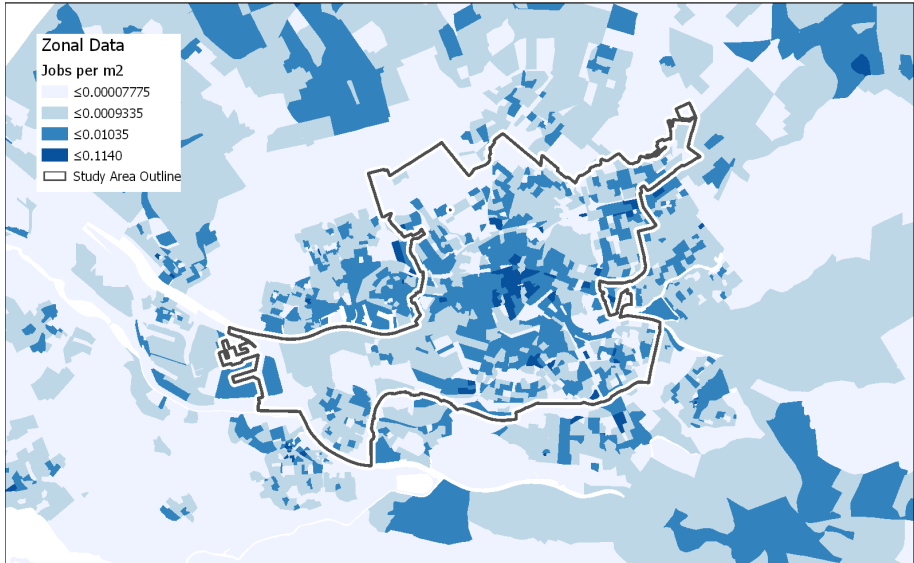


FIGURE 4.3: Job Density Map of Rotterdam. Data source: LISA.

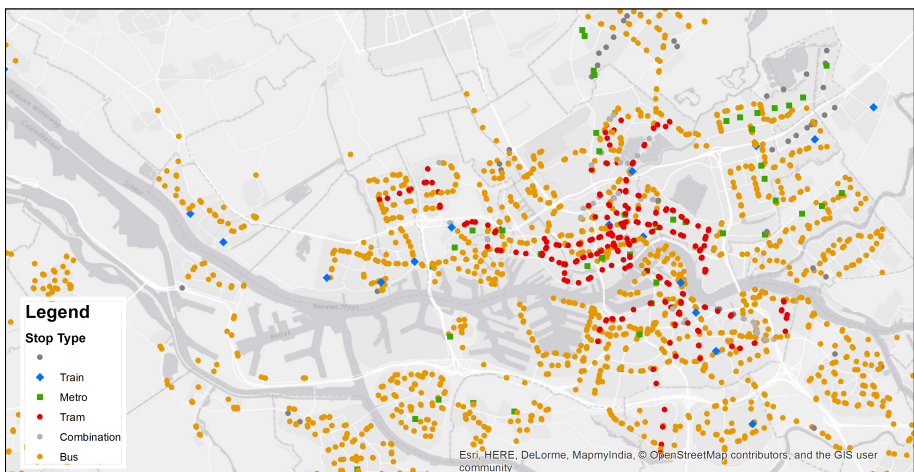


FIGURE 4.4: Public Transit Network Stops in Rotterdam



FIGURE 4.5: Subway Lines (Blue) and Train Lines (Yellow) In Rotterdam

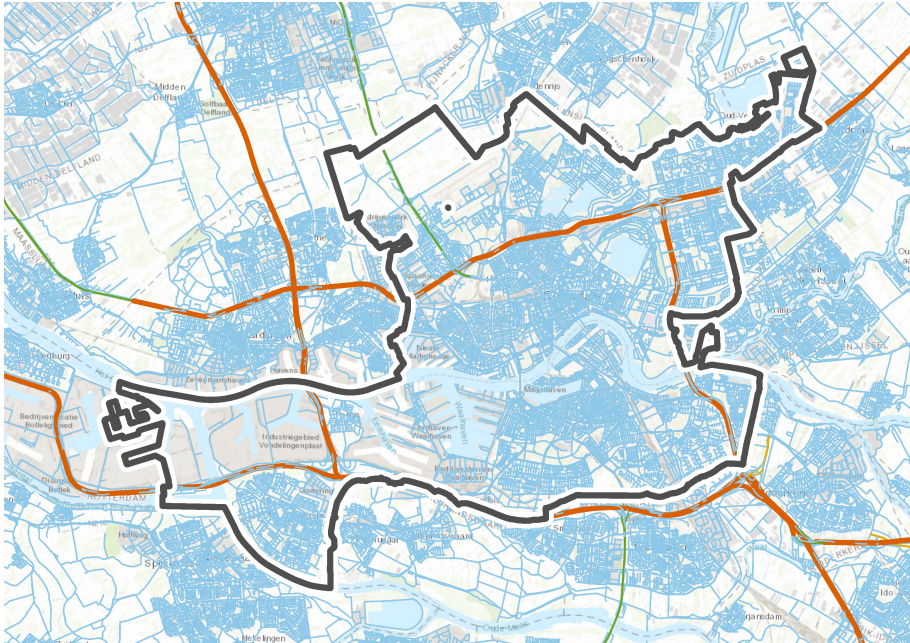


FIGURE 4.6: Road Network of Rotterdam (Red = Highways)

Finally, car ownership as depicted in figure 4.7 is an important factor for a later step. The map shows the average amount of cars owned by households per neighbourhood. A correlation with the earlier map depicting families can be seen, with suburbs (which are also closer to the highways) showing higher car ownership numbers.

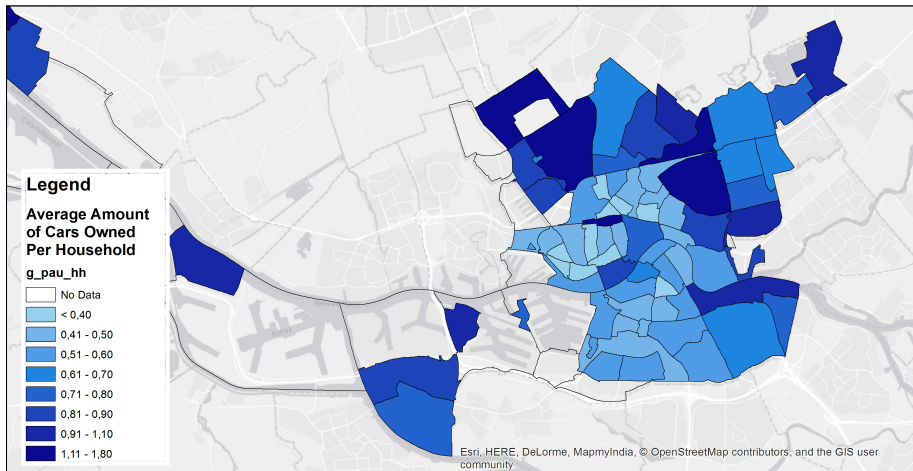


FIGURE 4.7: Average number of cars owned by households.  
Data source: Statline.

## 4.3 Full Approach

This second half of the chapter will discuss how the methodology from the previous chapter has been implemented. Case-specific changes are explained, as well as specific calculations. The goal of this section is to make this research reproducible and to show what changes have been made for the implementation. The below list of steps is a more detailed version of the steps from the start of Chapter 3. A data preparation step is added and the other steps are given substeps which will be discussed in 4.3.1 - 4.3.6. The data preparation step concerns calculations and decisions on input values (e.g.

selecting the study area and zones to use)

1. Data Preparation (4.3.1)
  1. Traffic Model Assignment & Extraction
  2. Study Area
  3. Skim Matrix Reduction
  4. Opportunity Selection
  5. Zonal Data
  6. Euclidean Distance Calculation
2. Identifying the relevant population groups (4.3.2)
  1. Define Groups
  2. Calculate Group Sizes
3. Measuring the accessibility and potential mobility indicators of those groups (4.3.3)
  1. Accessibility calculation
  2. Mobility calculation
4. Identifying thresholds for those measures and identifying population groups with insufficient levels (4.3.4)
  1. Calculating average accessibilities
  2. Calculate average mobility
5. Assessing the severity of those insufficiencies using the Accessibility Fairness Index and ranking population groups (4.3.5)
  1. Calculate AFI
  2. Calculating contributions and rankings
6. Implementing a change in the area(s) and assessing changes (4.3.6)
  1. Map the AFI
  2. Implement changes in the traffic model
  3. Assess changes to the indicators



### 4.3.1 Data Preparation

#### Traffic Assignment & Extraction

Arguably the most important input value to the rest of the approach are the travel times derived from the traffic model. This research uses the Rotterdam Traffic Model (“RVMK”), which is modelled in the software package OmniTRANS 6.0.26. The model is a static model with simultaneous mode choice and trip assignment. To calculate travel times, a traffic assignment is done on the 2015 model. This assignment will calculate mode and trip choices for freight transport, car transport (both peak and off-peak), public transport and bike transport, in that order. The PT and bicycle assignments do not take network loads into account and are thus an all-or-nothing assignment based on the amount of people that don’t choose car as their mode of transport. Car assignment iterates with a convergence criterion  $\epsilon$  of  $1 e^{-9}$  or 20 iterations (whichever one occurs first). The car assignment is thus done twice, once for peak hours and one for off-peak hours.

Travel times in traffic models are stored in a so-called “skim matrix”. This is a large table where each row in the table is an origin zone and each column a destination zone. The values in the table correspond to “OD” travel time, between origin and destination. So, for example, the travel time from zone 2 to zone 4 is found by looking up the second row, fourth column value.

Two Ruby scripts were used; one to run the assignment and create the skim matrices, and another to export the travel times from OmniTRANS to comma-separated value files (.CSV’s). The two Ruby scripts can be found in appendix D. CSV’s are plain text documents, which have the advantage of being very simple to create and read with varying programming languages. The output of this substep is one CSV for each of the four modes.

#### Study Area Choice

As mentioned in earlier chapters, an important choice to make when applying the method to a case study is selecting the study area and aggregation level. Once the study area is chosen, the skim matrix CSVs can be trimmed down to only include those OD values that matter for calculating accessibility and mobility, which will improve performance in the steps that follow.

The study area serves two purposes: it defines the areas for which accessibility and mobility indicators are calculated, but it also defines the destinations that are considered in those calculations. In this research, destinations outside the study area but within reach of a zone will thus not contribute to a zone’s accessibility. In other words, the assumption is that only destinations within the study area are important. The reason for this assumption is for consistency and to allow direct comparisons between

## Study Area

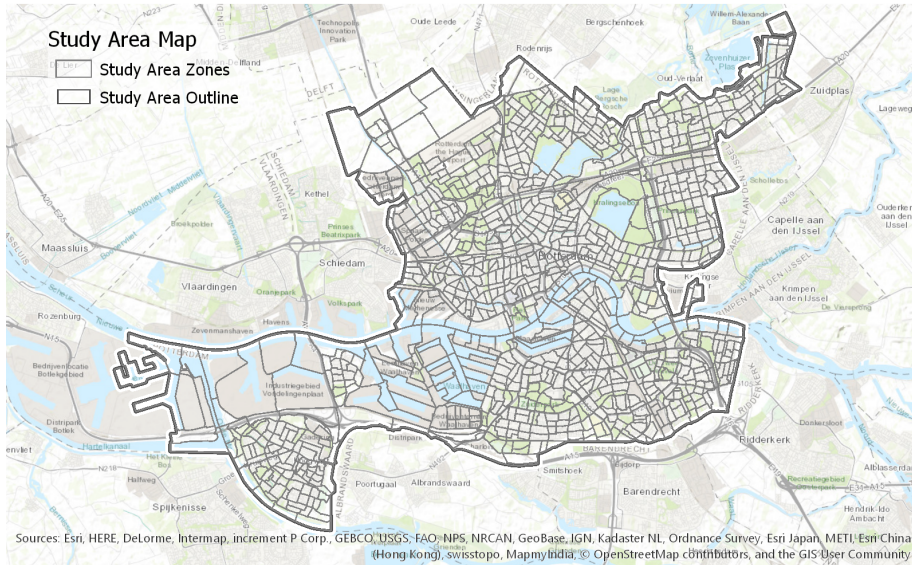


FIGURE 4.8: Study Area. Data source: RVMK.

different opportunities. While this may sound like a minor or unimportant assumption, it will likely have a noticeable impact on the results. This is especially the case at the edge of the study area. If, for example, important destinations are just outside of the study area, they will not be taken into account and the reported accessibility is lower than it might be in reality.

The study area chosen should not be larger than the area of control of the policy makers, since it would then likely point to measures that the policy makers wouldn't be able to amend. It should also be entirely covered by the services datasets to ensure correct accessibility measurements. This means that the study area can be no larger than the area where all input datasets overlap.

In this case, most of the destinations in the data source are available for all of the municipality, but some are only available for the core of the municipality (which excludes Hoek van Holland and Rozenburg). Because of this, the study area chosen spans the municipality from Spijkensisse in the south-west to Nesselande in the north-east. It does contain nearly all residential zones in the municipality itself - the only residents not included are those in the town of Rozenburg and in Hoek van Holland.

The traffic model zones are chosen as the aggregation level. The Rotterdam traffic model ("RVMK") consists of 5791 traffic model zones in total. In the vicinity of Rotterdam the traffic zones are based on zip codes, while further

away administrative and regional zones are used. Within the City of Rotterdam the zones are based on “Postcode-5-zones” (zip codes with 5 characters, i.e. 4 digits and 1 letter). This zoning is smaller than neighbourhoods and larger than housing blocks.

There are numerous advantages to using the traffic model as the aggregation level. Because the zoning is taken from the traffic model, there is no need to convert, aggregate or disaggregate the values in the skim matrices. An advantage of this model in particular is that the zones also contain a very accurate amount of jobs and inhabitants per area. The zones are also very small, which means that when opportunities are aggregated per zone, the travel times to those opportunities are not significantly larger or smaller than the actual travel time. Another advantage is that socio-economical data aggregation is also largely based on zip codes, which makes disaggregation rather straightforward.

For further steps, a simple CSV table is created that contains all zone numbers that are included.

### **Skim Reduction**

Because the number of zones selected is much smaller than the total number of zones in the model and in the skim matrices, and because this approach only considers OD travel times and distances within the study area, the skim matrix can be reduced in size significantly. The original CSVs extracted from the traffic model are around 350MB large. A script runs through each row in the skim matrix CSV and checks if both O and D are in the study area CSV. If that is the case, that row is saved and written to a new file. With the study area containing 1192 out of 5791 areas, this reduces each 14-million record long skim matrix to only 1.4 million records and only 25MB.

The output of this step is 4 reduced OD skim matrices and a CSV with a list of all zone numbers.

### **Opportunity Selection**

As mentioned in 3.3.1, the methodology is suited to consider a large number of destinations. Instead of only looking at one or two, a comprehensive set of destination types is proposed. It has two aims: one, to allow a weighing for “the” unfairness of a group, and two, to reflect the most important activity types in daily life. For example, accessibility and equity assessments can be made for hospitals or for jobs. However, policymakers might also want to make assessments for a specific area without specifying or choosing opportunities (e.g. “how accessible is this neighbourhood”). Thus, some weighing and prioritisation of opportunities must be made. A simple hierarchy is proposed that reflects the most important activities: work, services and

leisure. Seven opportunity categories are considered: Jobs, Health, Educational, Commercial, Cultural, Recreational & Sport. Each category consists of multiple actual opportunity types (e.g. Commercial consists of supermarkets and clothes stores). Below is thus the proposed hierarchy based on a Dutch context. This hierarchy should be seen as a suggestion; it can and should be adapted to different cultural contexts and policy goals.

### *Service*

- Health (e.g. hospitals)
- Educational (e.g. elementary schools, high schools)
- Commercial (e.g. supermarkets)

### *Leisure*

- Cultural (e.g. theatres, museums)
- Recreational (e.g. playgrounds)
- Sports (e.g. swimming pools)

### *Work*

- Jobs

As also mentioned briefly in Chapter 3, *opportunity types* will refer to opportunities associated with a particular activity and form the lowest level in the hierarchy (e.g. hospitals or schools), *opportunity categories* will be capitalised and will refer to the seven overarching categories of opportunity types (e.g. Health, Educational, Commercial). For this research, each opportunity type in an opportunity category is considered equally important: hospitals, pharmacies and nursing homes all contribute equally to accessibility in the Health category. However, the relative importance of opportunity types and categories could be linked to the groups (e.g., weighing health services more for the elderly). The specific opportunities chosen in this case study are detailed in the next chapter.

The selection of opportunities was in part influenced by the available data. As mentioned in the previous chapter, the goal is to create a comprehensive set of opportunities that reflects the most important activities in day-to-day life, and to do so mostly based on open data sources. For each of the seven opportunity categories mentioned in the previous step, the most important opportunity types are considered. Instead of aiming for comprehensiveness within such a set of opportunity types the goal here was to have a handful of opportunity types that are roughly equivalent in importance.

The primary source for these locations is the “*Voorzieningen*” dataset provided by the municipality and freely available to the public (<http://www.gis.rotterdam.nl/gisweb2/default.aspx>). This dataset contains many different opportunities, from crematories, childcare, police stations and

gyms to language centers and park&ride facilities. All opportunities are from this dataset except three. Jobs data originates from the LISA dataset embedded in the traffic model zones, and Commercial opportunities (Supermarkets and Clothes Stores) are from Openstreetmaps datasets. This means that the Jobs data is the only dataset which is not entirely open to the public.

Below is an overview of all chosen opportunities per opportunity category. For convenience, each opportunity type has been given a two-digit code in the scripts. The first digit denotes the category it is in, the second digit denotes which opportunity type it is (e.g. Elementary Schools are the first opportunity type in category 2, so the opportunity type is shortened to “21”).

#### **Category 1: Health Opportunities (n = 102)**

- Type 11: Pharmacies (n = 75)
- Type 12: Hospitals (n = 7)
- Type 13: Nursing homes (n = 20)

The Spijkensse Medisch Centrum is an important hospital that fell just outside of the main study area. To prevent very skewed results for Hoogvliet, this hospital has been manually added. It can be seen in the bottom left of the map below.

#### **Category 2: Educational Opportunities (n = 289)**

- Type 21: Elementary Schools (n = 206)
- Type 22: High Schools (n = 66)
- Type 23: Higher Education (MBO, ROC) (n = 7)
- Type 24: Higher Education (HBO, Universities) (n = 10)

#### **Category 3: Commercial Opportunities (n = 410)**

- Type 31: Supermarkets (n = 143)
- Type 32: Clothes & Fashion (n = 267)

Commercial opportunities could have been expanded with services like hardware stores and electronics stores, but for this research they were not considered important enough to all population groups to be considered.

#### **Category 4: Cultural Opportunities (n = 103)**

- Type 41: Theatres (n = 31)
- Type 42: Libraries (n = 25)
- Type 43: Museums (n = 43)
- Type 44: Cinemas (n = 4)

### Category 5: Recreational Opportunities (n = 93)

- Type 51: Recreational Areas (n = 30)
- Type 52: Playgrounds (n = 63)

It was the intention to also find a good dataset for parks, but this was not found.

### Category 6: Sport Opportunities (n = 48)

- Type 61: Swimming Pools (n = 16)
- Type 62: Tennis and squash (n = 24)
- Type 63: Multi-sport centers (n = 8)

### Category 7: Work Opportunities

- Type 71: Jobs (n = 265483 in 1192 areas;  $\mu = 222,7$ )

## Health Opportunities

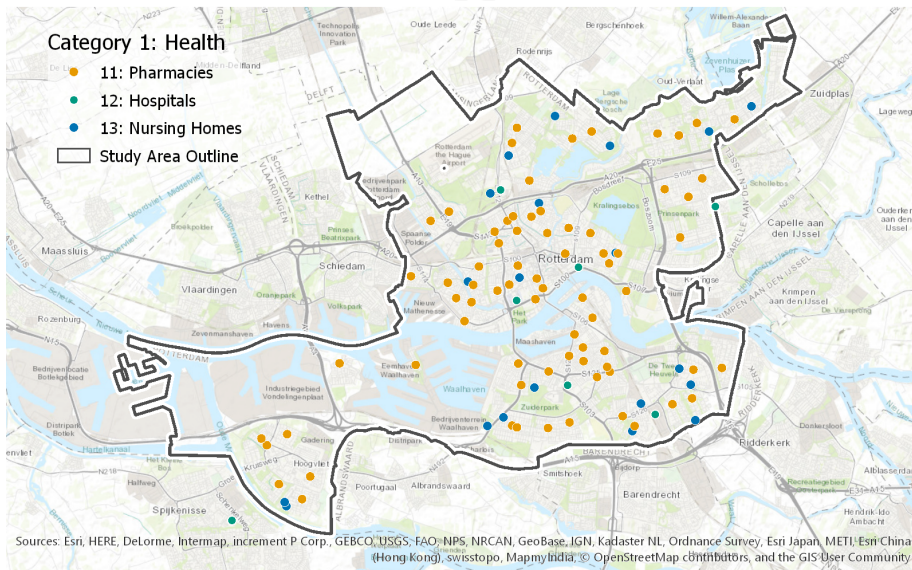


FIGURE 4.9: Health Opportunities. Data: City of Rotterdam

## Educational Opportunities

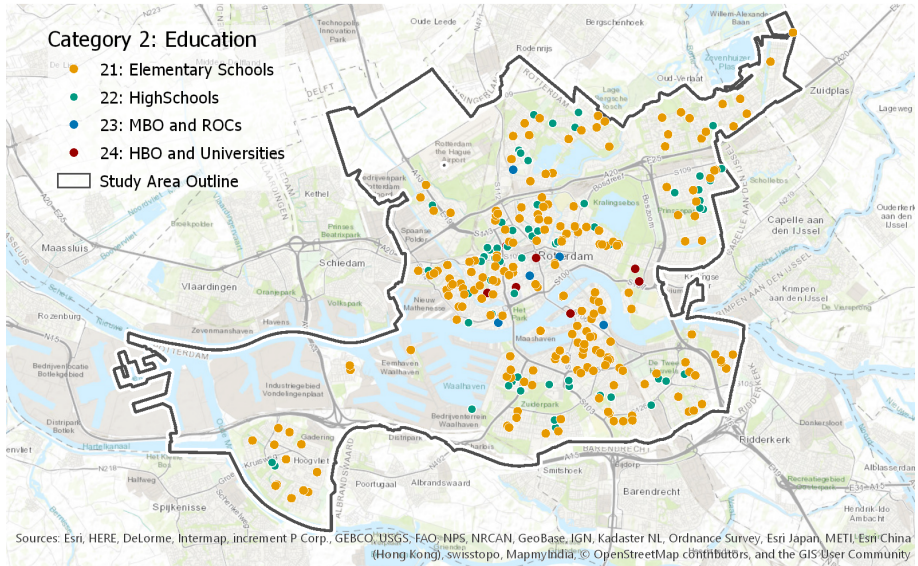


FIGURE 4.10: Educational Opportunities. Data: City of Rotterdam.

## Commercial Opportunities

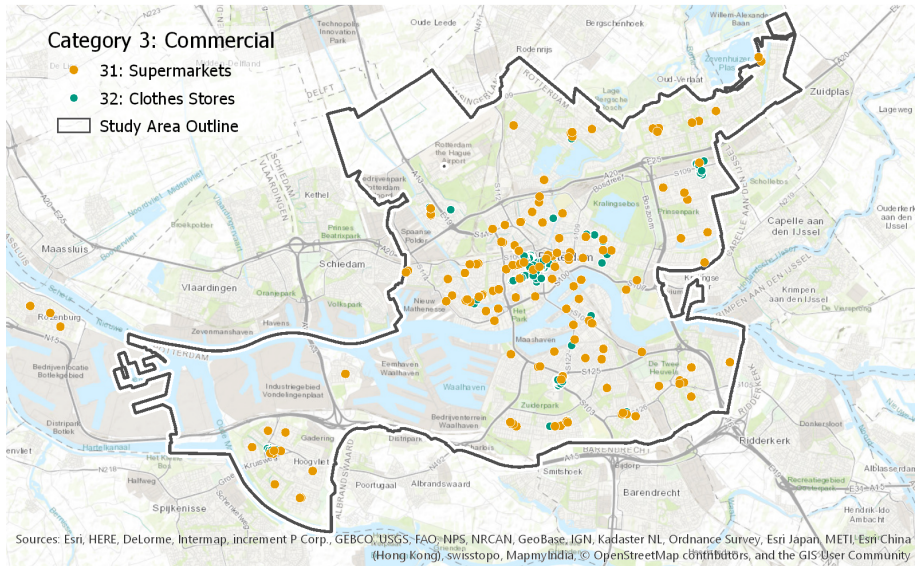


FIGURE 4.11: Commercial Opportunities. Data: City of Rotterdam.

# Cultural Opportunities

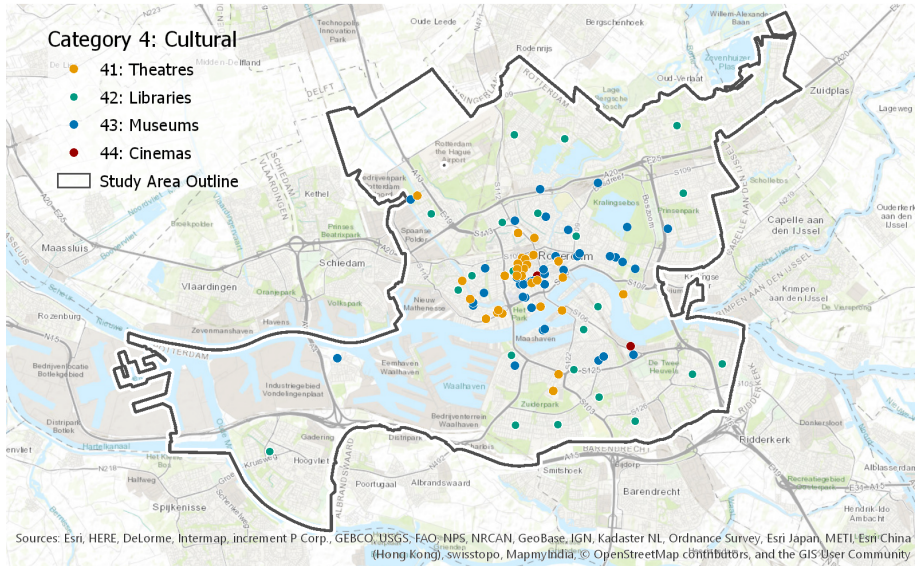


FIGURE 4.12: Cultural Opportunities. Data: City of Rotterdam.

# Recreational Opportunities

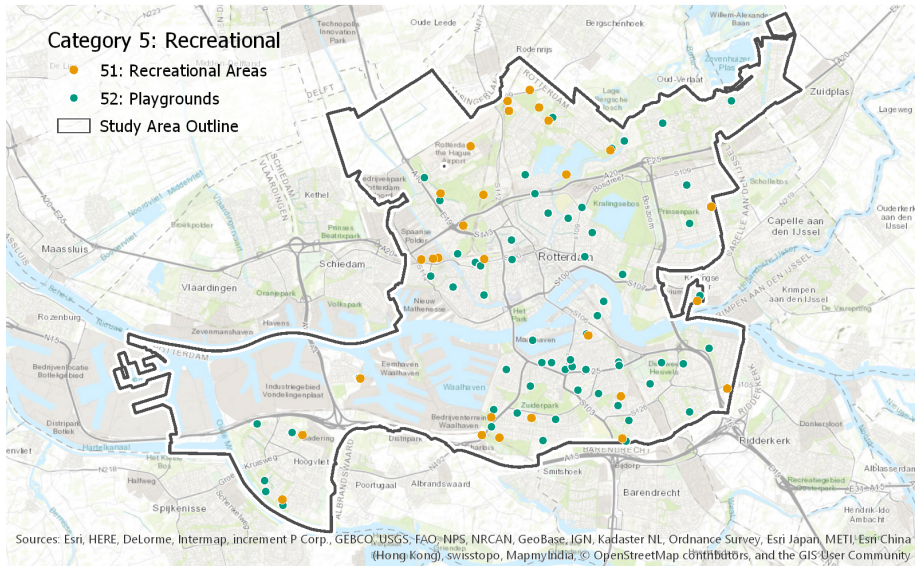


FIGURE 4.13: Recreational Opportunities. Data: City of Rotterdam.



## Sport Opportunities

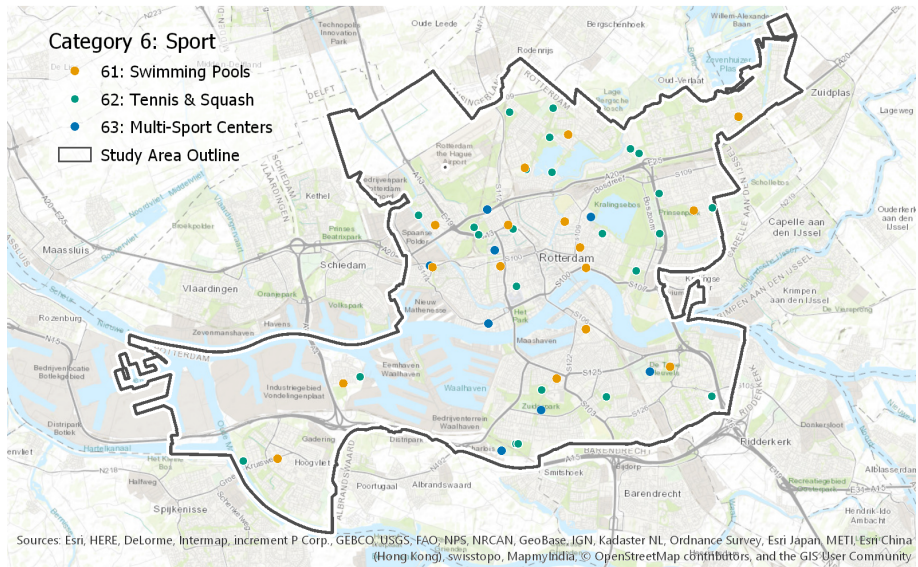


FIGURE 4.14: Sport Opportunities. Data: City of Rotterdam.

## Zonal Data

The first step in the approach involves estimating various population sizes. This research uses a dataset from the Central Bureau of Statistics (CBS) with the average amount of cars per household, and residential data from the traffic model. The residential data comes directly from population counts and this needs no adjustments. However, the CBS dataset is at the neighbourhood level, which is larger than the traffic zones in the traffic model. This necessitates a spatial disaggregation. It is thus assumed that the average amount of cars in a neighbourhood holds true for the zones that are within that neighbourhood.

The output of this step is a CSV with, for each of the zones in the study area, the total amount of people living in that area and the cars per household value for that zone. Part 4.3.2 will explain how the population estimations are calculated.

## Euclidean Distances

Euclidean (“as the crow flies”) distances are calculated in this data preparation step so that all travel times and distances are calculated before the rest of the approach starts. For this calculation, the centroids first exported from OmniTRANS to an ArcGIS shapefile. Then, an OD Euclidean distance matrix is created in a Python script that calculates the distance from each centroid to each centroid. The matrix thus contains all Euclidean distances between all origin and destination pairs. The distance between two points is the hypotenuse of the right-sided triangle whose edges are defined by the difference in longitude and latitude between the two points:

$$D_{ij} = \sqrt{(|lat_i - lat_j|^2 + |lon_i - lon_j|^2)} \quad (4.1)$$

$D_{ij}$  : Euclidean distance from origin i to destination j

The output of this step is a CSV with, for each of the OD pairs in the study area, the Euclidean distance in kilometres.

With the data preparation out of the way, the steps of the methodology can now be considered.

### 4.3.2 Identifying Population Groups

The goal for this research was to differentiate the population based on location, mode choice/availability, and income levels, as these were suggested the most important factors by Martens (2015). Income was also considered as an important group distinction due to earlier research in the study area

(Bastiaansen, 2012) but there was no data available at the municipality or from open sources that allowed a good enough estimation of income levels on the chosen aggregation level. Instead, this is only partly reflected in the mode choice as that correlates with income.

Fairness is thus assessed for each zone in the traffic model (location), for people who choose to use car/PT/bicycle at different times (peak/off-peak). The groups  $G$  thus should be:

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

Due to the traffic model used, the six combinations of  $k$  and  $m$  has been reduced to four in the implemented code. The PT model makes a distinction between frequencies at night versus during the day, but only has minor frequency changes between peak and off-peak. The bicycling network model is based on the (lower-level) road network with additional bike paths, all set to a maximum speed of 15 km/h. Thus, there is no distinction between peak and off-peak assignment. It was thus decided to only consider  $k$  for cars. This means that instead of the intended 6 groups (3 modes at 2 times), only 4 are considered (car-peak, car-offpeak, PT and bicycling) in this research. Martens (2015) assessed 3 groups (car in peak, car off-peak and PT) so including bike as a mode is an improvement over that.

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  $k \in \mathbf{K}$ .

The number of people will be based on the actual amount of residents per zone provided by the municipality, on car ownership, and on the known modal split. Car ownership data has been taken from the Bureau of Statistics; specifically, the average number of cars per household. Within the study area, this value ranged from 0.3 to 1.8, a delta of 1.5. Based on expert judgement from transit planners at the municipality, it is assumed that the modal split for cars can vary approximately 25 percentage points from the mean. The modal split for trips in the study area 2015 was 53% by car, 30% by PT and the remaining 17% by bike or walking. It is thus assumed that a cars per household value of 0.3 corresponds to a car population of 30% and a cars per household value of 1.8 corresponds to a car population of 80%, with other cars per household values linearly in between. The simple linear function  $C(i)$  thus estimates the share of people using cars based on the cars per household value.

$$n_{g_{i,k,car}} = n_i * C(i) \quad \forall i \in \mathbf{I} \quad (4.2)$$

$$n_i = \text{total number of people in zone } i \quad (4.3)$$

$$C(i) = \left( \frac{(\text{cars per household})_i}{3} \right) + 0, 2 \quad (4.4)$$

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.

$$n_{g_{i,k,PT}} = (n_i - n_{g_{i,k,car}}) * 0, 65 \quad \forall i \in \mathbf{I} \quad (4.5)$$

$$n_{g_{i,k,bike}} = (n_i - n_{g_{i,k,car}}) * 0, 35 \quad \forall i \in \mathbf{I} \quad (4.6)$$

The output of this step is, for each of the three modes and 1192 zones, the amount of people estimated to use each mode of transport has been estimated.

### 4.3.3 Measuring Accessibility and Mobility

Unchanged from the previous chapter, two indicators for accessibility (Cumulative and Gaussian indicators) and two for mobility (PMI based on Euclidean distance and PMI based on network distance) are used. The mobility and accessibility assessments can be done in parallel as their calculations do not influence or depend on each other.

#### Calculating Accessibility and Mobility

Calculating accessibility is done according to formula 3.4 and 3.7. It requires that sets of opportunity types and their opportunities are defined. As mentioned in 4.3.1, 18 types are chosen. Set  $\mathbf{O}$  then contains the actual opportunities for each type (e.g. all the hospitals in the study area).

**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 $t \in \mathbf{T}$

No changes are made in the formulation for calculating mobility, besides applying the above defined groups and opportunities. The output of this step is that for each group, accessibility and mobility has each been calculated twice per mode and per opportunity type.

#### 4.3.4 Identifying thresholds and identifying population groups with insufficient levels

Due to limited time and resources, this research will not base the sufficiency thresholds for accessibility and mobility on values that have been discussed with relevant stakeholders. Instead, this research will make the same pragmatic decision as the explorative case study in Martens (2015) and will base the thresholds on the average accessibility and mobility of people travelling by car off-peak. This average is considered a good starting point because it usually represents a sufficient level of transport relative to all modes: travelling by car is usually a direct and fast method of transport.

There are three additional case-specific reasons for using an average as the basis for a threshold. One is the ability to compare these results with Martens (2015). The second reason is that this implementation looks at a wide variety of opportunity types. It is impossible to define one threshold for all of those: a threshold for elementary schools (n=206) has to be a different value than that of high schools (n=66). Setting a threshold that is based on the average accessibility of a mode means that the threshold has a different absolute value between opportunity types but a similar relative value.

The third reason is related to the fact that changes in the model will improve the average accessibility and will increase the thresholds. In one sense, this is a problem: when a network change leads to a thresholds increase, the reduction in unfairness will appear smaller than it actually is. An area might be sufficient under the old threshold values but insufficient under the increased values. But this increase in thresholds can also be seen as a feature: accessibility issues are almost always relative, so having the thresholds slowly

increase due to network improvements means that this approach will always be able to find insufficiencies.

The output of this step is one list of accessibility thresholds and one mobility threshold:

$\mathbf{Y} = \{y_{t_1}, y_{t_2}, \dots\}$  : set of accessibility thresholds, one threshold per opportunity type  $t \in \mathbf{T}$ ,  $y_t = \text{avg}(A_{g_i, \text{car, offpeak}}^t)$

$z = \text{avg}(PMI_{\text{car}})$ : mobility threshold

### 4.3.5 Assessing the severity of those insufficiencies using the Accessibility Fairness Index

As mentioned in the previous chapter, calculating the AFI is not much more than multiplying how far below the threshold each group is by the size of each group. Only those groups that fall below the thresholds have their AFI calculated.

Due to the multiple opportunity types and two accessibility indicators in this research, the average weighed accessibility over all opportunity types will also be calculated. This should indicate overall “unfairness“ to all considered of opportunities. Because the Cumulative indicator can vary greatly in value over different opportunity types (e.g. 5 hospitals versus 40 schools), a weighed average does not say a lot. Therefore, the Cumulative accessibility is normalised over the total amount of opportunities in the study area per type so that all Cumulative accessibility values are also between 0 and 1. This is also essential to allow comparisons between Cumulative and Gaussian indicators in the sensitivity analysis of Chapter 5. The normalisation does not influence the result, it only influences the scale of the values.

The output of this step is to have, for each zone, the AFI score for each opportunity type or category, as well as the contribution percentages and rankings for the areas.

### 4.3.6 Implementing a change in the model and assessing the changes

The choice to make a change in the model is directly based on the previous fairness assessments. For this research, two changes will be made based on the preliminary results of this approach. Because this case study has looked at a long list of opportunity types, the changes in the model will be aimed at alleviating one kind of unfairness instead of all of them. This makes choosing a particular solution easier and more akin to actual measures that might be implemented. Another interesting aspect is to see what the change will be to all other opportunity types when only one is changed. Transport experts at

the municipality of Rotterdam have been consulted. They selected the importance of bike accessibility to elementary schools within 20 minutes as something that would be interesting to assess and improve. Given a map of the AFI as percentage of the total for bicycle groups to elementary schools (so  $AFI_{i,off-peak,bicycle}^{t=21}$ ), they were asked which small and which large change they would made to alleviate the mapped equity issues. These have subsequently been implemented in the OmniTRANS traffic model, with the entire methodology being done twice more to see the changes in indicator values. These results are also presented in the next chapter.





## *Chapter 5*

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# Results & Sensitivity

## 5.1 Introduction

The result of the developed methodology is that assessments have been made regarding accessibility, mobility, and equity. These assessments have then been combined with expert judgement to make improvements aimed at reducing a specific kind of unfairness. This chapter will first discuss these results in 5.2, as well as a summary of feedback received from planners and policy experts in 5.3.

Then, the chapter will discuss the sensitivities and choices tested in 5.4. The sensitivity of the results to the chosen accessibility and mobility indicators has been tested by using fundamentally different indicators. Besides those two sensitivities, four “choices” have also been tested. These are four important choices that the methodology allows decision makers to choose: the group differentiations, the opportunities, the cutoff values and the thresholds. For each of these choices, it is explored whether the results of the developed methodology are responsive to these changes and in what way.

## 5.2 Results

Due to “group continuity”, the accessibility, mobility and equity assessments are known for each of the 4768 differentiated groups (1192 zones and 4 mode-time combinations) and, in the case of accessibility and equity, are also known to specific opportunity types. Thus for each of the groups the following information is known:

- 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)

Because it is impossible to show all results, only a few highlights will be shown. The goal is to map and graph the results that led to the changes made in the network.

The first result is thus the determination of population sizes for each zone and for each mode. Below, the absolute group sizes for each of the 1192 zones and 3 modes of transport are mapped. These numbers are the direct result of formula 4.2, 4.5 and 4.6 in 4.3.2. Because the difference between the number

of car users and PT users is not very easy to see in this map, the number of zones per category has been added to the legend. It should also be noted that these numbers are based on modal splits, so they represent mode usage and not mode availability.

As expected, the spatial distribution of these three populations is related to the overall population density in the city (see also figure 4.2). Overall, the car-using population is spread more throughout the city than the PT-using population, which seems slightly more clustered around the city center. Neighbourhoods near the highways like Nesselande, IJsselmonde and Hoogvliet can be seen to have a relatively large car-dependent population. Bicycle-using people are clustered in the three neighbourhoods surrounding the city center.

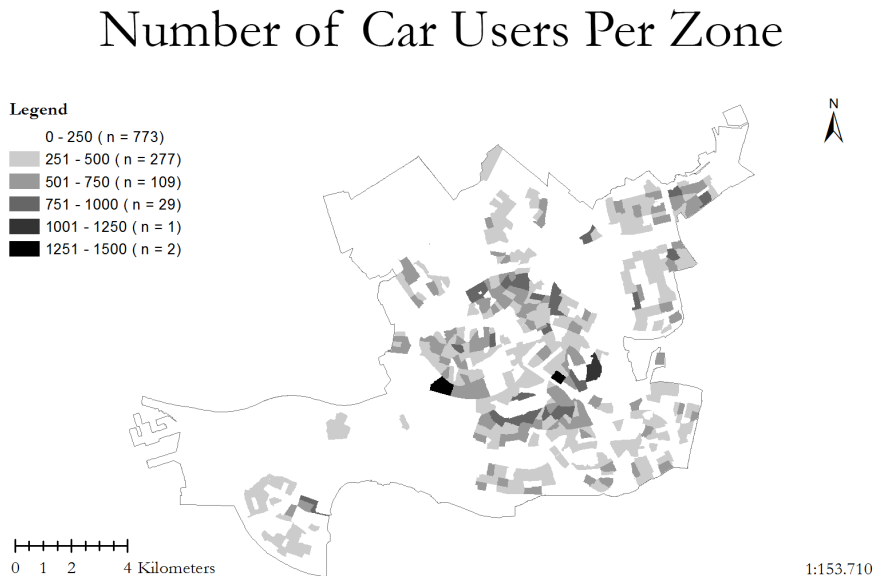


FIGURE 5.1: Estimated No. of Car Users.

## Number of PT Users Per Zone

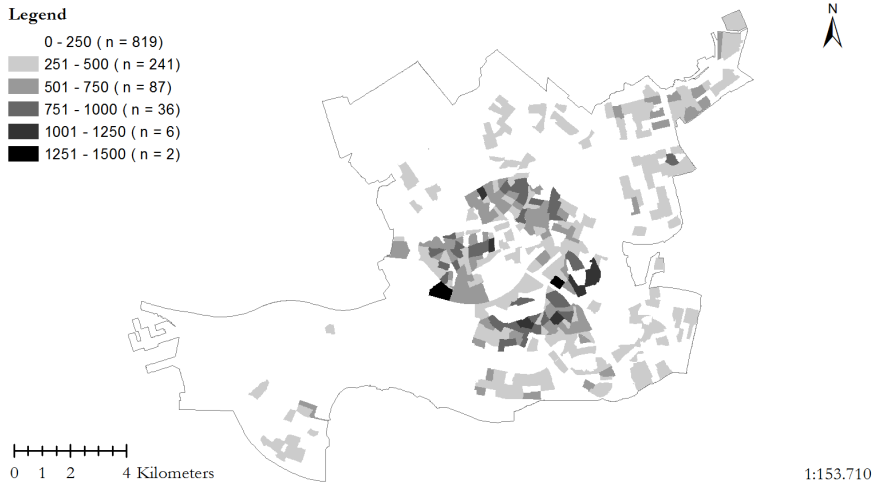


FIGURE 5.2: Estimated No. of Public Transport Users.

## Number of Bicycle Users Per Zone

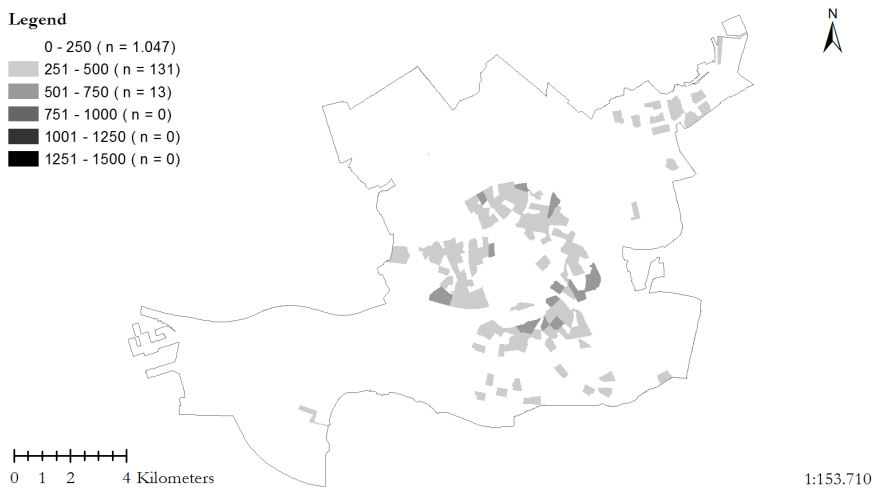


FIGURE 5.3: Estimated No. of Bicycle Users.

The accessibility assessment has been made for all modes to all opportunity types. Using the hierarchy of opportunity types as suggested in 4.3.1 to average accessibility scores, figure 5.4 shows the accessibility to all opportunities of all types considered. Each group is one (largely transparent) dot. It shows the 1192 zones four times, one for each of the mode-time combinations (i.e. car-peak, car-offpeak, PT and bicycling). The position on the y-axis shows the accessibility score, which is the percentage of all opportunities that can be reached within 20 minutes with that specific mode at that time.

As (somewhat) expected, Car-dependent groups experience a much better accessibility across the board than public transport and bicycling. Perhaps counter to intuition, accessibility is noticeably better by bicycle than by public transport. This is very likely due to the public transport access, egress and wait times that are modelled, which has a significant effect on journeys less than 20 minutes compared to the slower (but frictionless) bicycling mode of transport.

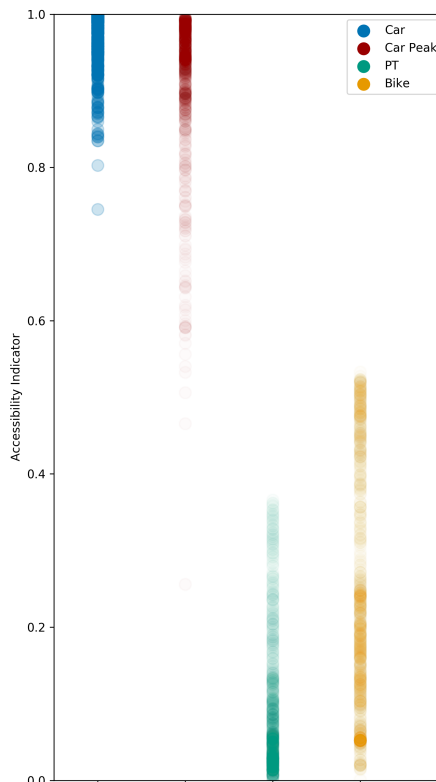


FIGURE 5.4: Accessibility per Mode-Time Combination.

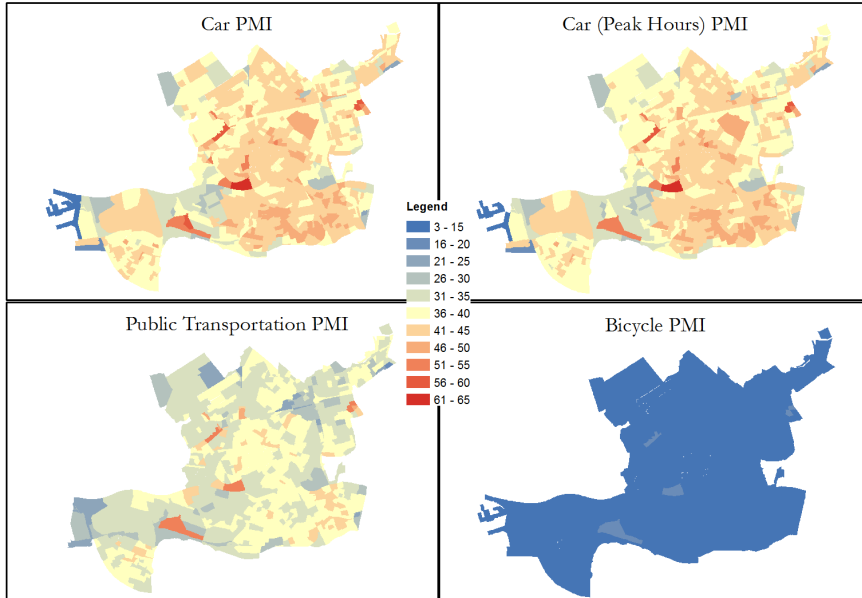


FIGURE 5.5: Potential Mobility Index in km/h for each group in each zone.

Figure 5.5 shows the values for the “PMI” mobility indicator per mode. A first observation is that the PMI does not differ much for cars between peak and off-peak hours. In general, the PMI scores are high for cars across the city, which can be explained by the multiple highways and many major artery roads that the city is covered with. Public transport does not fare much worse, and its PMI spatial pattern is also fairly constant throughout the city, which reflects the high quality transport services. The bicycling PMI is very low compared to the other three. This can be explained entirely by the modelled maximum speed of 15 km/h over the network - the PMI divides distances over travel times, and the travel times are higher when bicycling. Some outliers are noticeable (i.e. the red areas in public transport map). These are consistent across various modes, which indicates that the connectivity in the underlying traffic network model is the likely culprit. A cursory investigation revealed that the connectors for these zones were not perfectly modelled due to rezoning, which artificially reduced travel times.

Combining the above results, figure 5.6 graph shows the suggested accessibility versus mobility graph by Martens (2015). The y-values are the same as in 5.4, but the PMI is used as the x-values. Furthermore, the average accessibility and mobility for car drivers off-peak is shown with a black line.

The patterns and differences mentioned earlier between modes are still visible

here: the accessibility for public transport fairing significantly worse than bicycling in this alternative, and both fairing way worse than car accessibility. The aforementioned PMI outliers are also identifiable, as they are much farther to the right in the graph than the bulk of the other groups. As an example, consider the bicycle groups at coordinates (15, 0.4) and the PT groups at (50, 0.1).

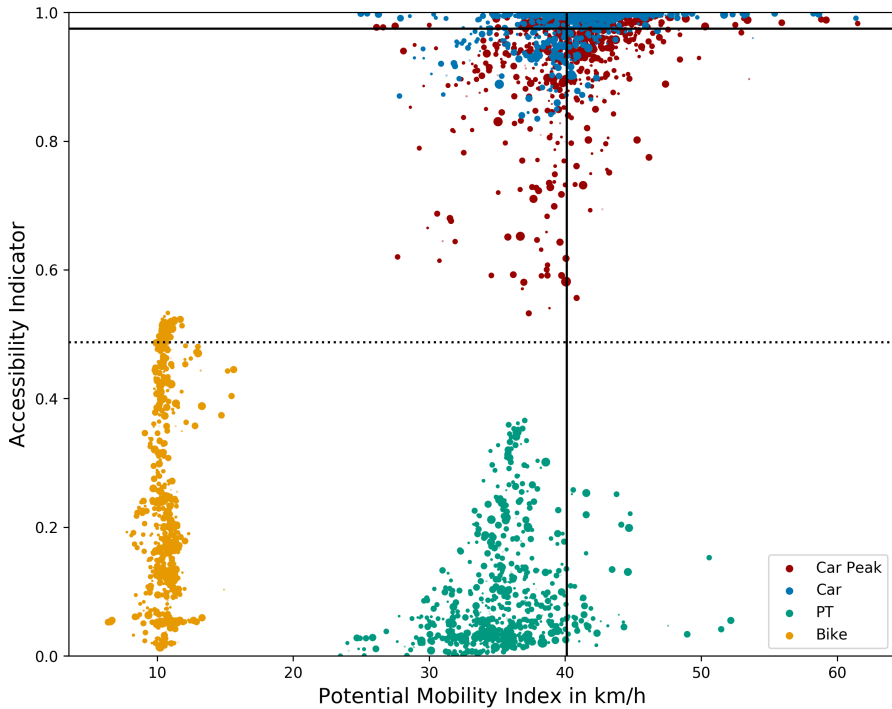


FIGURE 5.6: Accessibility versus PMI.

With the accessibility and mobility assessments made, the equity assessment can also be made. As explained, the thresholds used are based on the average mobility and accessibility for car groups off-peak, which in both cases are rather high compared to PT and bicycle groups in this case with the 20 minute cutoff value. Figure 5.7 shows the same graph as 5.6, but with each group (each circle) sized according to the AFI calculated for that group.

As expected, there are no values above the mobility and accessibility thresholds and the circle sizes increase as the accessibility indicator decreases. This effect is especially noticeable with the red Car Peak circles. The legend circle sizes represent the average circle size. It is visible that the distance from the threshold as well as the population size determine the AFI, with the former explaining most of the circle sizes and the latter explaining the

variations in circle sizes. It also shows that public transport groups are experiencing the most unfairness overall in this case, which makes sense given their poor accessibility scores and large population sizes (compared to bicycling) mentioned. Bicycle unfairness is also quite large.

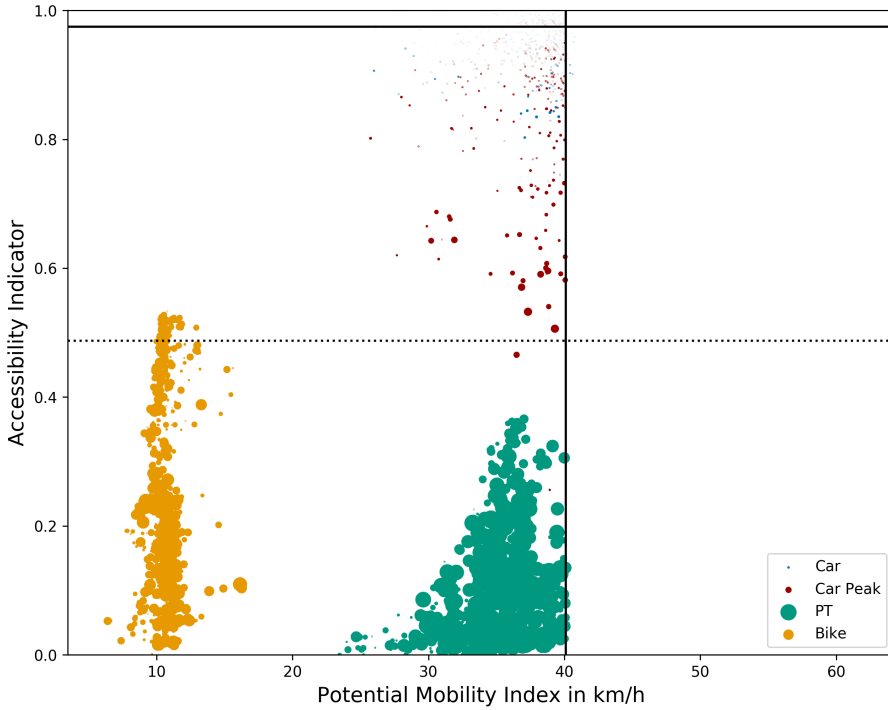


FIGURE 5.7: Accessibility versus PMI, sized to AFI.

Transport planners suggested looking at equity by bicycle, because bicycling infrastructure is an important policy subject in the City of Rotterdam. Figure 5.8 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, 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 considered problematic.



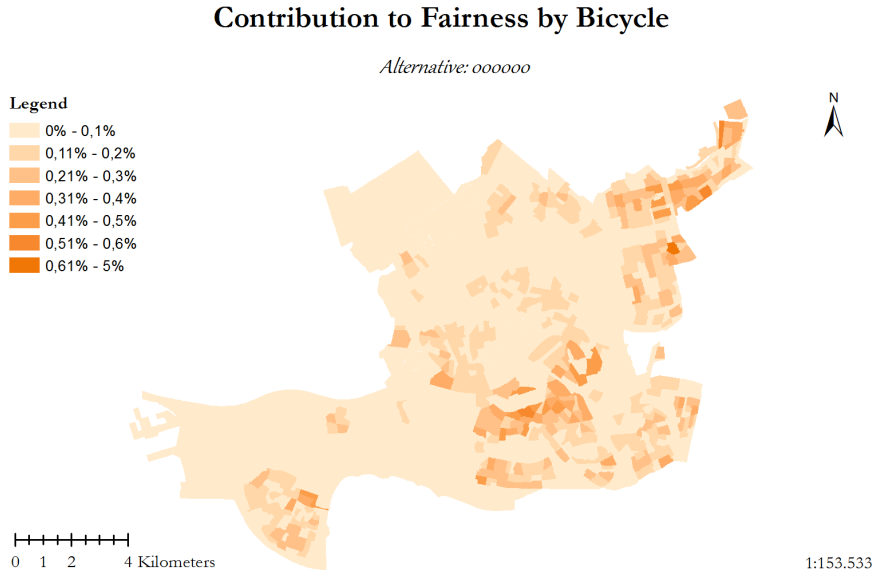


FIGURE 5.8: Contribution to the Total Unfairness in the Study Area (as Percentage of the Total)

Two improvements to the bicycling network were implemented in an attempt to reduce this unfairness. These two suggestions were the result of a brief discussion based on the question *“What small change and what large change would you make to the bicycling network when the goal is to improve equity issues experienced by this “unfair” cluster of neighbourhoods?”*

The model experts noted that the bridges over the Maas river have been modeled at a speed of 5 km/h instead of the default 15 km/h. This reduced speed is their implementation of modelling the observed effect that such a bridge has on choice behaviour. It could be argued however that this reduction in speed is too large and therefore unrealistic. For example, because of that speed change the travel time over the largest bridge (the Erasmus bridge) is increased from 3 minutes to 9.5 minutes. Thus, the first small change is to increase the speed on these bridges to 10 km/h, which does not negate the effect the bridge has on choice modelling but is a more realistic travel time. The following links (coloured red) in the network were changed in the OmniTrans RVMK traffic model. Figure 5.9 shows this.

The second change implemented is to improve two important bicycling corridors between this problematic area and the large amount of opportunities on the north side of the river. The links in these corridors were

increased to 17.5 km/h to represent a “bicycle highway” type of measure. Figure 5.10 shows the links selected for making the second change.

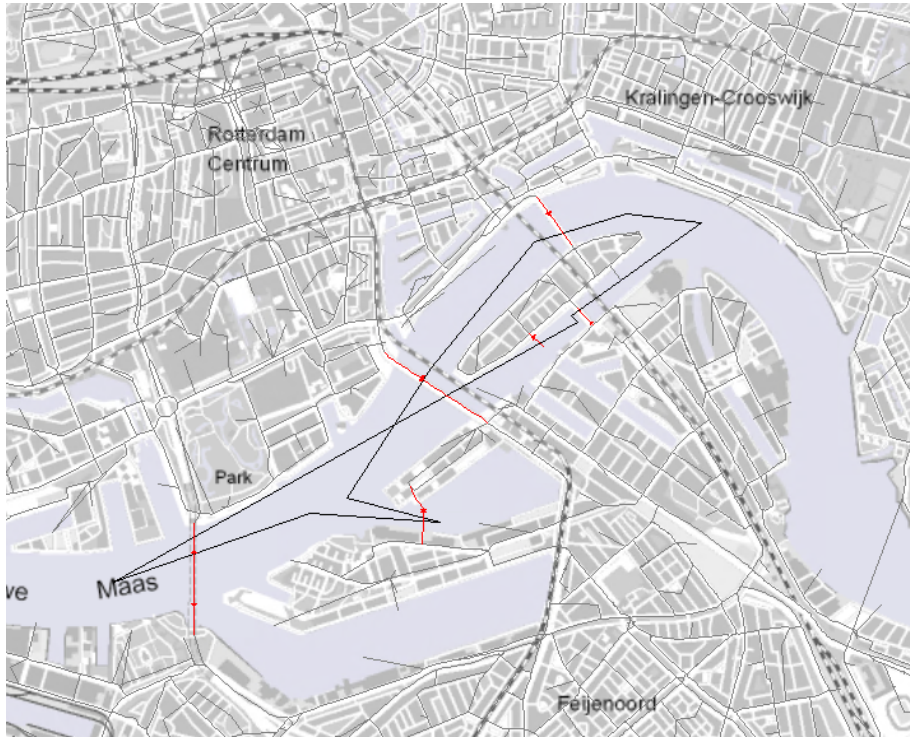


FIGURE 5.9: Change 2 Made to the Model



FIGURE 5.10: Change 2 Made to the Model

As a result, the bicycle groups are improved in the accessibility graphs. The graphs below are only for the Cumulative indicator. Previously no bicycle group had an accessibility above 0.55, while in the second graph below a new cluster emerges of groups above 0.4. These use an accessibility threshold of 100% of the average car accessibility. If 50% is chosen instead, which is depicted by the dotted line in figure 5.11, the changes to the network would push quite a lot of groups above the threshold.

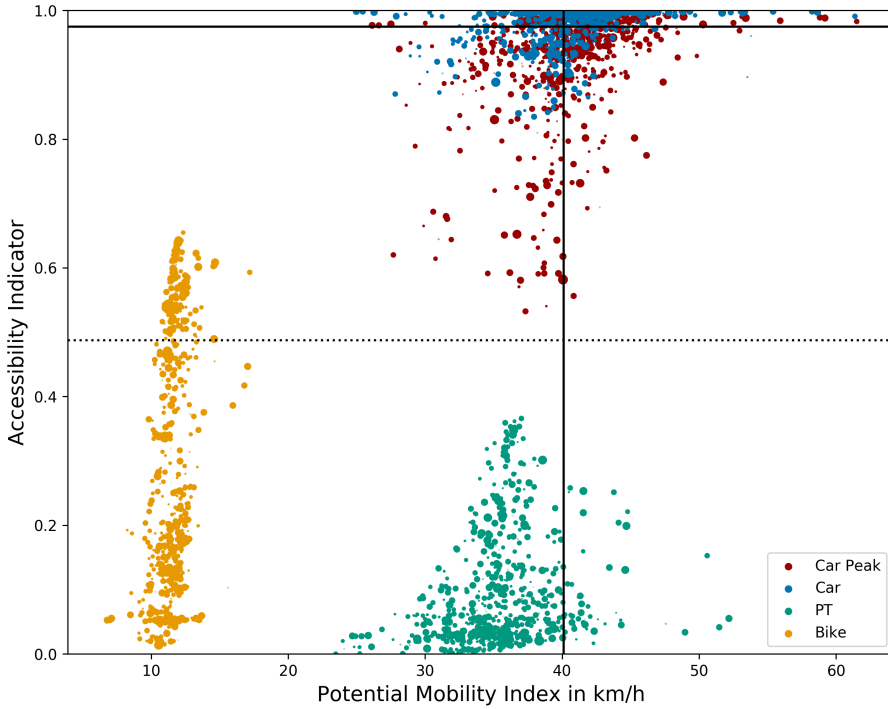


FIGURE 5.11: Accessibility versus PMI for Change 2.

When figure 5.11 is directly compared to figure 5.6, the mentioned improvements to bicycle groups is visible by a shift upwards for a lot of groups. To quantify this shift, the following table shows the decrease in the total amount of unfairness for all bicycle groups:

Change	Bike Unfairness	%
Unchanged	1,184,656	0%
Change 1	1,130,575	-4.6%
Change 2	991,266	-16.3%

TABLE 5.1: Decrease in Sum Unfairness after Improving the Network.

As a result of the improvements made, the total unfairness experienced in the study area (summed over all groups, including those not in Rotterdam-South) decreased by 4.6% in the first scenario and by 16.3% in the second scenario. While it is not explored in this thesis, the decreases in unfairness could also be used in appraisal methods. Interestingly, the unfairness is reduced quite significantly, especially when a large change is made to the network. The map

below shows the spatial distribution of this change. Figure 5.12, when compared to figure 5.8, shows that the change results in reduced equity problems largely in those areas that it was aimed at. It also works the other way around, with some areas in the city center improving in accessibility. The reach of the change is not much farther than Rotterdam-South itself, which makes sense given the cutoff value of 20 minutes in these alternatives. With a larger cutoff value, a larger part of the city should benefit from the improvement.

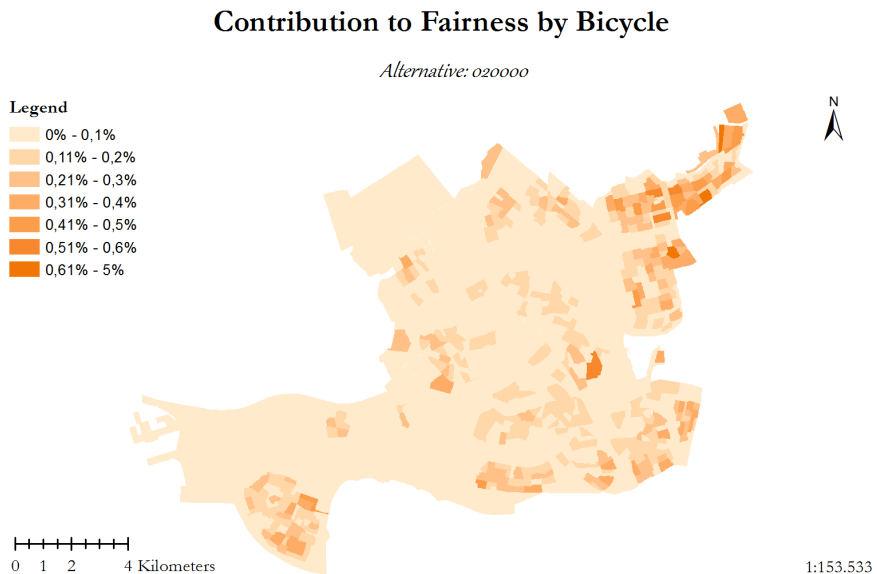


FIGURE 5.12: Contribution to Fairness for Bicycle Groups with Change 2.

## 5.3 Feedback

The above results have been shown and presented to a handful of policymakers at the City of Rotterdam in an informal setting for feedback, as well as being presented to a larger group of approximately 30 bureaucrats. This part summarises their responses and feedback briefly.

Numerous policymakers showed interest in the results in the approach itself. They considered the methodology a “useful start” and an “interesting approach” to tackle problems like accessibility poverty (*vervoersarmoede*). This is partly because the methodology allows solutions to be found both in transport or in land-use. Currently, the transport department works largely

in isolation from the other municipal departments. The methodology could bring those together, e.g. when accessibility to health is a problem for a certain group, the problem identified by transport planners could be solved with a collaboration between the transport and municipal health departments.

The above example is also made possible by the flexibility that the methodology allows for: accessibility is measured to specific destinations, so much more specific problems can be identified. Policymakers liked this aspect and would thus want to use the methodology to focus on specific problems and to allow for more granular and focused solutions (*maatwerk*). The “group continuity” was considered a major advantage that enables policymakers to be more transparent (since for any group, each calculation step can be shown) and allows them to be specific. They also noted that the approach and its indicators are much closer to the subjective experience of transport and accessibility, when compared to current practice. The Cumulative indicator in particular was considered easy to communicate and to base policy around.

The term “unfairness” was considered a loaded and subjective term. It requires explanation because it lacks a good definition and can change over time and between people. Other terms like “inequality” and “equity” are considered more neutral and thus less likely to be (politically) problematic. Another related piece of feedback was that policymakers wondered how the developed methodology would fare politically. The methodology’s focus on making value judgements (on accessibility) was considered “bold and enticing”, but this might also be a weakness in some people’s eyes. Usually, assessments are made first, with value judgements made on the results. Such a methodology can then be considered objective and impartial. The developed methodology, however, requires subjective value judgements halfway through. For those who disagree with a sufficientarian approach to transport planning, the methodology’s fairness/equity assessments can be considered problematic or even useless.

One person noted that enforcing the thresholds as a norm (i.e. as hard sufficientarianism) would probably mean “the people would grab their pitchforks”. The sentiment, that a threshold value should not be given the utmost importance in the process of transport policy creation, was echoed by a few other policymakers. On the other hand, the thresholds could form the link between the developed methodology and policy goals. For example, when the threshold is considered a minimum level to prevent the most dire accessibility problems, it could be given a lot of importance in policy creation. The metropolitan transport agency, “MRDH”, has experimented with setting “societal performance” levels for transport. The threshold values could be fill that role. All in all, there were multiple opinions on the precise role of the threshold values and what they represent.

Methodologically, the precision and transparency of the developed methodology were considered strong aspects by policymakers. There were some worries about garbage-in, garbage-out, which refers to the idea that the

quality of the input values and data can determine the output and results. For example, if a school is missing from the dataset, how large is the impact on the results? Another potential issue is whether to consider the thresholds as static or as moving goalposts. For policy, it might make more sense to set the threshold values for a longer time period and to focus policy on solving all or most issues that arise. On the other hand, if the thresholds are based on averages and updated regularly, this would allow measures or improvements to always be based on the largest issues at hand, which is closer to what the public expects from policymakers.

## 5.4 Sensitivities & Choices

### 5.4.1 Sensitivity of the Accessibility Indicator

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.

The first sensitivity test replaces the Cumulative accessibility indicator with a gravity-based Gaussian accessibility indicator as formulated in formula 3.7.

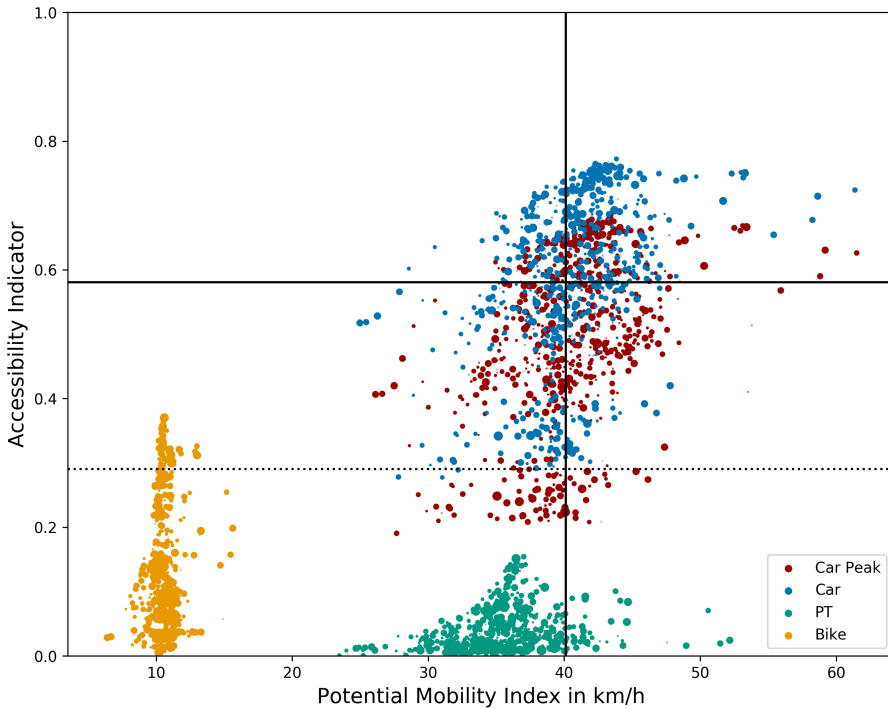


FIGURE 5.13: Accessibility versus PMI with Gaussian indicator.

The PMI versus Accessibility graph sees large shifts. No group achieves an indicator value of 0.8, and the spread of car accessibility is much larger than with the Cumulative indicator. Both changes are directly related to the use of the distance decay function. Despite considering all opportunities, its distance-decay function places an additional constraint on opportunities, which lowers overall accessibility scores. Because the average accessibility is lower for all modes, it also lowers the accessibility threshold and the size of the accessibility unfairness.

The large reduction in accessibility thresholds means that the sum of unfairness that these groups experience ends up lower than the previous alternative. Perhaps counter-intuitively, the increased spread in car accessibility leads to *more* unfairness for car-dependent groups, as more groups are falling below the accessibility and mobility threshold. This can be seen in the spatial distribution map as well, with more areas lighting up. The difference is quite large for areas that are red in figure 5.15 but aren't in 5.14. This is probably because of the distance decay function: since the driving distance from this part to a lot of opportunities is near the cutoff value of 20



minutes, there are opportunities that are entirely considered with a Cumulative indicator but get reduced significantly with the Gaussian.

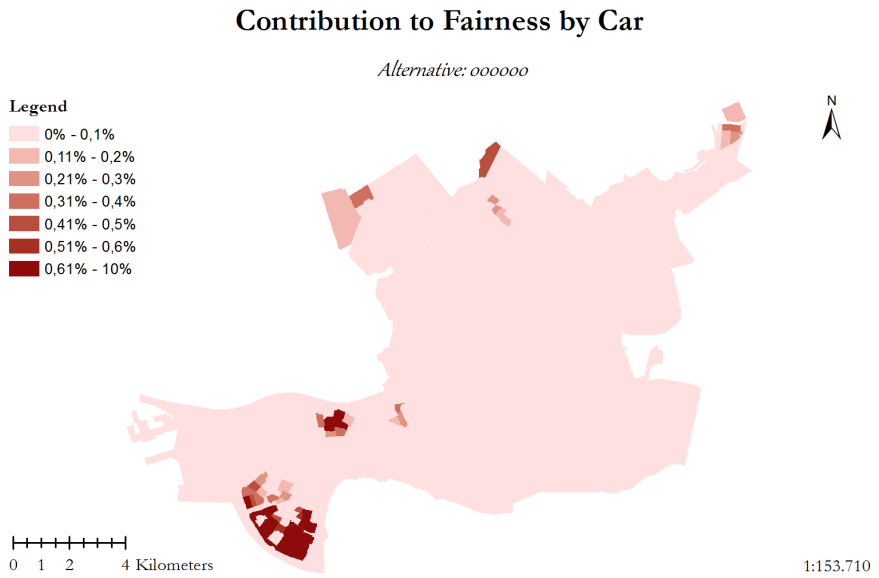


FIGURE 5.14: Unfairness with a Cumulative indicator

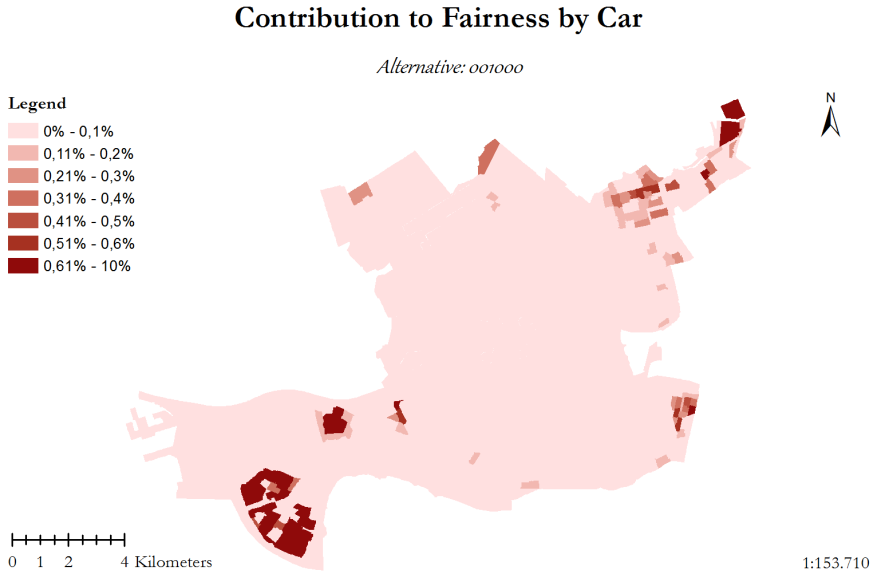


FIGURE 5.15: Unfairness with a Gaussian indicator

## 5.4.2 Sensitivity of the Mobility Indicator

The second sensitivity test involves 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. When summing all unfairness for each of the modes of transport considered, it turns out that unfairness for car users and bicycle users remains the same but that more PT users fall below the average accessibility line in this scenario, causing a 6% increase in unfairness there.

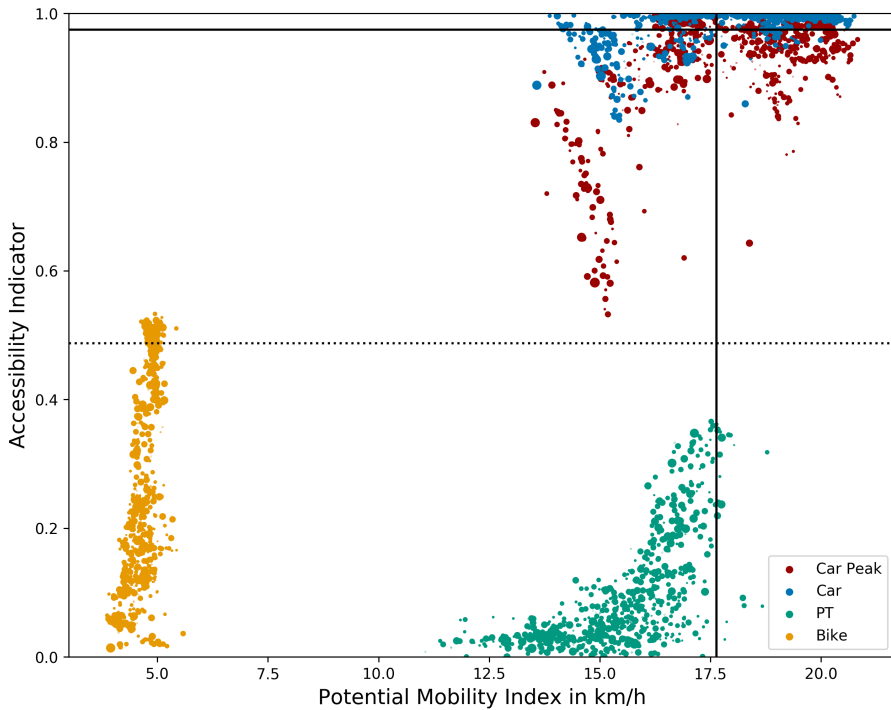


FIGURE 5.16: Accessibility versus PMI with Gaussian indicator.

### 5.4.3 Influence of Choices Made on Results

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 5.6 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. This is in no small part because all attributes chosen directly influence the travel time. If attributes were chosen that do not directly impact travel time (e.g. income or ethnicity), this would still be visible in the result because of the differing group sizes and would thus result in differing equity assessments for those groups.

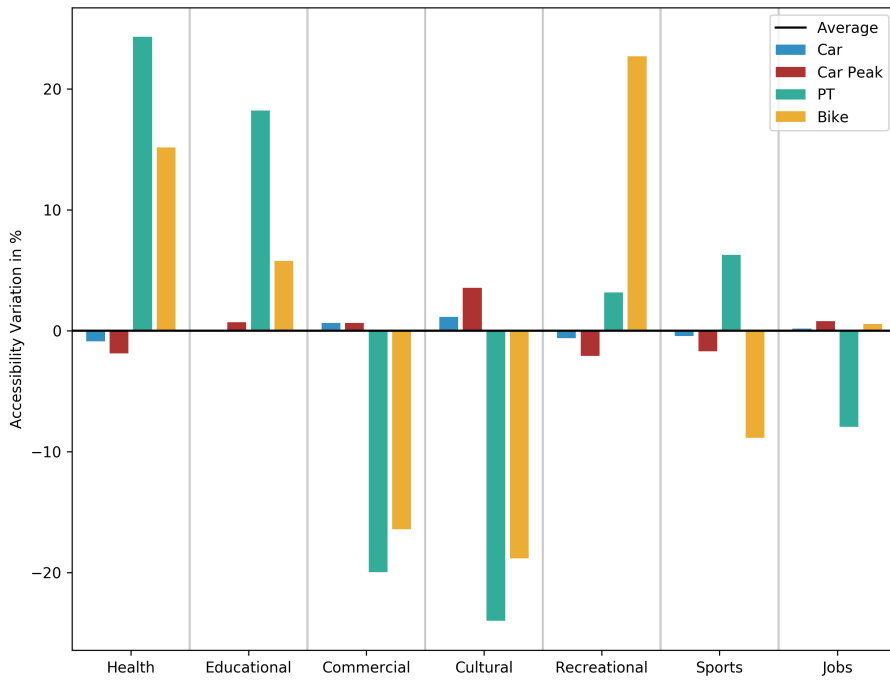


FIGURE 5.17: Variation in Accessibility per Opportunity Category

## Opportunities

The results show a large variability in accessibility between opportunity types. Figure 5.17 depicts each of the seven opportunity categories, and graphs the difference in percentage points between the average accessibility in that category (with a particular mode) compared to the average accessibility of all categories combined (with a particular mode). Health opportunities, for example, are 25% more accessible than the average opportunity when travelling by public transport, whereas Commercial opportunities are 20% less accessible. These numbers represent how differences in spatial distribution can influence the accessibility assessment.

The results also scale “correctly” to reducing the total number of opportunities, as figure 5.18 shows. The graph below depicts the same as Figure 5.6, but with half of the opportunities removed. As expected, the accessibility scores also half, because the cumulative counts are still normalised according to the original total number of opportunities. It should also be noted that the unfairness indicators do not change. This is because the thresholds are based on the average, which is also halved, so the relative change to the thresholds remains unchanged.

## Thresholds

The threshold values chosen impacts the result directly, since the accessibility deficiency is based on the threshold values. Using 100% of the average car accessibility for the thresholds means that all bicycle and PT groups are below the threshold when cutoff values are 20 or 30 minutes, which highlights the large difference in accessibility that car owners have, but it might not be useful in planning practice or when developing policy. Using threshold values of 50% of the average car accessibility seems to be well-suited to assess PT and bicycling groups, since a significant percentage of the groups fall above such a threshold.

## Cutoff Value

The results depend a lot on the chosen cutoff value for the accessibility indicators. The 20, 30 and 45 minutes cutoff values for travel time show very different accessibilities. At 20 minutes cutoff, all PT and bicycling groups experience unfairness. Car user groups also experience unfairness. At 45 minutes cutoff value however, only a small amount of bicycle and PT groups near the edge of the study area experience some unfairness. Bicycle unfairness, for example, drops by 80% when the cutoff value is increased from 20 to 45 minutes. Figure 5.19 shows these bicycle groups. It depicts the same map as figure 5.8, but with a cutoff value of 45 instead of 20 minutes. Because it shows the percentage of the total unfairness in the study area for each zone, it does not show this 80% reduction but does show the changes in distribution: unfairness is mostly visible around the edges and is largely invisible near the center.

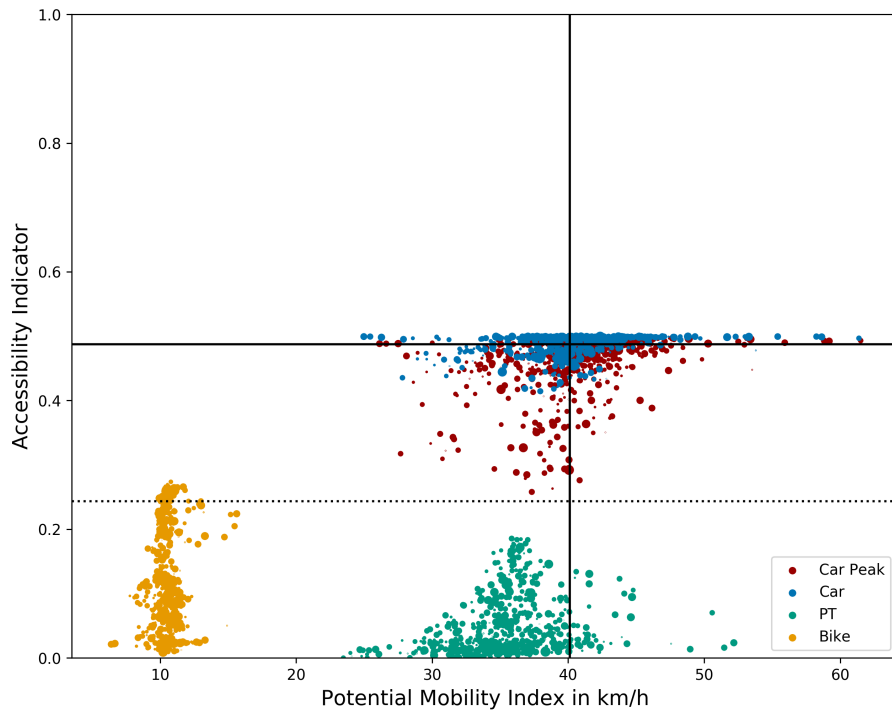


FIGURE 5.18: Accessibility versus PMI with Half of the Opportunities Removed

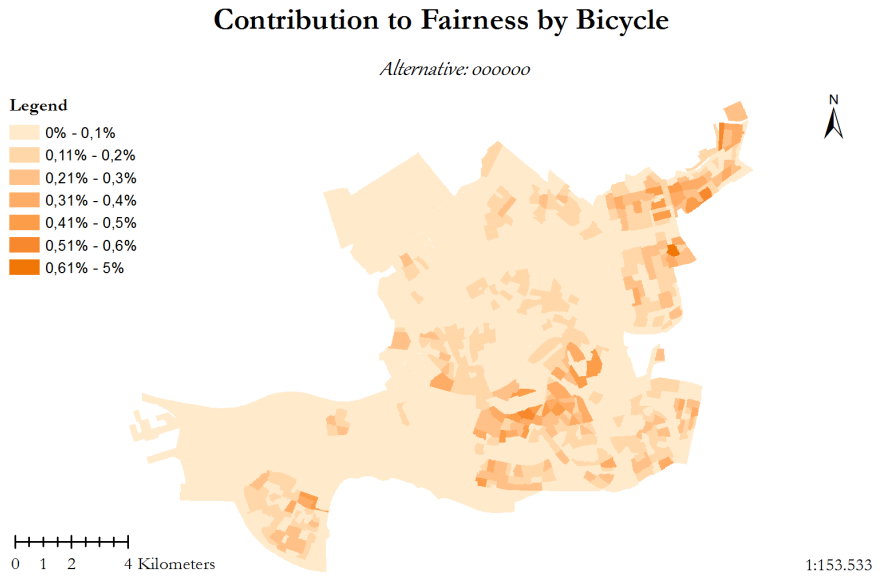


FIGURE 5.19: Contribution to the Total Unfairness in the Study Area (as Percentage of the Total) with Cutoff Value of 45 Minutes





## *Chapter 6*

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# Conclusions

## 6.1 Discussion

This concluding chapter will first reflect and discuss on the thesis and the results from the previous chapter. Then, it will draw conclusions that aim to answer the research question. Finally, it gives recommendations for further research and for policymakers.

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 formalised methodology (see appendix C) is consistent with the proposed approach by Martens 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. Even within the case study presented, there were numerous options and choices that could have been left to decision makers, like the considered activities and opportunities, the cutoff values and the groups chosen. While this thesis has not made an attempt at doing so, it is not impossible or unreasonable to link the impacts on equity measured to current or adapted appraisal methods.

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. The methodology's flexibility was also appreciated, especially the degree to which the assessments can be specified to a particular demographic or socio-economical group. This enables more refined and specific solutions (*maatwerk*).

It is however unclear how much of the aforementioned research gap has been closed. This is in part because it is unclear what a fully developed, useful and applicable methodology would look like. But it is also because it is not entirely clear if various methodological decisions made in Chapter 3 and 4, such as the chosen aggregation size, indicators, and study area, were chosen correctly. 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. Considering the role that income can play in equity issues, this could be considered a very important aspect of the methodology, especially when combined with generalised cost-based indicators instead of travel time-based indicators.

Developing and implementing the methodology was also not as easy as it might look on the surface. The mentioned uncertainty around methodological decisions was not just an issue with the steps of the methodology itself, but also with the specific implementation. While the theoretical foundation under the proposed approach by Martens appears solid, it does not provide any answers to the difficult questions that the operationalising process posed. It 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. There is thus still room to improve fundamental parts of the developed methodology from this thesis, 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 transport 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. While policymakers expressed interest in applying this idea to transport planning, they were also worried about a few aspects. One aspect is the political implications of this methodology, especially of using the somewhat loaded term “unfairness” to describe what is in fact a population-weighted accessibility deficiency. While that could definitely be considered an indicator of unfairness, there can be indicators of fairness based on other value systems.

Another issue brought up by them is the difficulty of setting those sufficiency thresholds and considering their importance. 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.

Furthermore, policymakers wondered how to best interpret and consider the role of these thresholds in the developed approach. Should it be considered a norm, directly dictating policy, or more as something indicative? Should it be set relatively high, so that equity issues for a large group of people can be

addressed, or should it be set low to focus on the most dire equity issues, or both? These are interesting normative questions that this thesis leaves unanswered.

## 6.2 Conclusions

This part will draw conclusions by answering the research question, “*How can an equity-based approach to transport planning be operationalised and which important considerations, benefits and issues arise when this approach is applied to a case?*”. The answer to the research question consists of three parts: one, the developed methodology; two, the discussion covering various (methodological) considerations; and three, an overview of the major benefits and issues identified.

This thesis has formalised and operationalised most of the steps proposed by Martens. The developed methodology can be used to assess accessibility, mobility, and both social and spatial equity in transport. It can do this for various or for specific socio-demographic subsets of the population in zones of arbitrary sizes. The resulting fairness indicators can be used to identify problematic areas, if a threshold for “sufficient accessibility” can be determined. It can also be used to assess the impact on equity of some transport and land-use policies, namely those that have an impact on travel times. The developed methodology can be based primarily or partly on public datasets and can be found in appendix C.

The most important methodological considerations are:

1. the chosen aggregation level
2. the chosen attributes on which to differentiate groups
3. the chosen opportunities
4. the accessibility and mobility indicators chosen
5. the thresholds and the process behind setting those thresholds
6. the interpretation of the result
7. the relation between the results and solutions

The major benefits and issues of the developed methodology have been identified: *Important benefits*:

**Useful** — The developed methodology already provides useful insights into accessibility and equity according to policymakers.

**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 generalised so that it can be applied to different cases, cultures, traffic models, or modes of transport.

*Important issues:*

**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.

**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 has been explored but still not very well understood.

## 6.3 Recommendations

This recommendations part will first give recommendations for interesting research topics that could build on the current thesis. Then, it will give some recommendations to policymakers.

First and foremost, further research can be done to improve the developed methodology in various aspects. This can be based on the issues identified in the previous part, for example by performing a full sensitivity analysis of the methodology, or by investigating the normative and subjective issues that are not fully fleshed out yet. It could also focus on an improved implementation of the methodology into transport planning, for example by developing more if not all of the steps in the proposed methodology by Martens (2015). Research could also explore various group-dependent destinations, for example coupling income levels with jobs that are specific to those income levels.

An assumption made in this research is that potential accessibility and mobility can be used to indicate equity problems. This assumption could be further investigated with “ground truth checks”, e.g. comparing the results of the methodology with actual experienced accessibility deficiencies or equity issues. This could be additional quantitative research (comparing this method to other equity measures) or qualitative research (comparing this method to equity issues experienced by residents, for example).

Another direction might be to use the methodology for an interesting range of equity comparisons, for example comparing vastly different cities/regions with

the same methodology. It could also be interesting to do “ex post” equity assessments of various public investments, from new roads and rail lines to smaller-scale frequency and travel time changes. This is especially interesting when combined with a further developed link between the developed methodology and appraisal methods.

The currently developed methodology is already considered developed enough to inform policy by some policymakers at the City of Rotterdam. Whether it can also shape policy is a harder question to answer, especially given some of the notable uncertainties mentioned in the previous part. However, the group-based accessibility and mobility assessments can be useful to policymakers regardless of whether the equity assessments are made, especially since they can be specified to assess accessibility and mobility for particular socio-economical and demographical groups. The equity assessments are usable and can be implemented, but it is difficult to say whether their outcomes are robust enough to shape or steer transport policy; more research is needed to flesh out the details and to improve the robustness of the developed methodology from this thesis.

The concept of setting/determining thresholds, however, was well-received among policymakers despite some of the difficulties associated with creating them. Thus, a recommendation is to experiment with incorporating thresholds into policy. This could start by adding relatively low thresholds for accessibility, for example by setting an accessibility standard that covers the bottom 10% of people in a given study area. Solutions could then be explored that significantly reduce these accessibility deficiencies, with monitoring and additional qualitative research to explore to what degree this has alleviated the problems found by the methodology. If these experiments turn out to align with the interests of the affected groups, the thresholds could be raised and larger solutions could be explored that address larger equity issues. Such an approach seems a good balance between exploring equity in transport planning and enabling further constructive development of the methodology in planning practice.

## *Appendix A*

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## *Appendix B*

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# Samenvatting

## Introductie

Transport planning is het proces waarmee beleid en maatregelen tot stand komen voor verkeer en vervoer. In de afgelopen decennia zijn *ethische* overwegingen steeds meer een rol gaan spelen in dat proces. Ethiek is een tak van de filosofie die zich bezig houdt met (morele) waardeoordelen: als er verschillende manieren zijn om iets te doen, wat is dan de "juiste" aanpak? Een ethische overweging die de laatste tijd meer aandacht heeft gekregen, is de rol van *rechtvaardigheid* of *eerlijkheid* (Engels: *equity*) in verkeer en vervoer. Wie plukt er de vruchten van beleid en maatregelen, en is dat wel zo "eerlijk"?

Een aantal auteurs hebben onderzocht of die afwegingen over rechtvaardigheid in transport planning toegepast kunnen worden. Een van de meest uitgebreide en theoretisch onderbouwde voorstellen is Karel Martens' boek *Transport Justice: Designing Fair Transportation Networks* (2015). Hierin stelt Martens een dat transport planning eerlijkheid kan meenemen door veel meer aandacht te geven aan bereikbaarheid. Hij stelt een "rechtvaardigheidsindicator" voor, gebaseerd is op bereikbaarheids- en mobiliteitsindicatoren, om het probleem concreet te maken.

Zijn voorgestelde benadering is echter nauwelijks geoperationaliseerd (toegepast). Gezien de mogelijk grote implicaties voor transport planning en beleid vormt het operationaliseren en beoordelen van zijn voorgestelde aanpak in een echte casus een wetenschappelijke en maatschappelijk relevante uitdaging. Het is het doel van dit onderzoek om de voorgestelde aanpak te detailleren, de aannames kritisch te bekijken, de aanpak met formules en methodes tot een beleidsinstrument te maken en te reflecteren op het nut van de toegepaste aanpak. De Gemeente Rotterdam zal als casus dienen.

De bijbehorende onderzoeksvraag luidt: "*Hoe kan een op rechtvaardigheid gebaseerde benadering van transport planning worden geoperationaliseerd en welke belangrijke overwegingen, voordelen en problemen ontstaan wanneer deze aanpak wordt toegepast op een casus?*" Om de onderzoeksvraag te beantwoorden, zal eerst de literatuur en de (verbeterde) aanpak worden uitgelegd. Daarna worden de resultaten gepresenteerd, evenals een korte gevoeligheidsanalyse. Ten slotte wordt de onderzoeksvraag beantwoord en zullen enkele aanbevelingen gedaan worden.

## Literatuur

Hansen (1959) definieerde bereikbaarheid als "de ruimtelijke verdeling van bestemmingen rond een punt, gecorrigeerd voor de afnemende wens van bestemmingen die verder weg zijn" (Hansen, 1959). Aangezien bereikbaarheid rond een punt is, kan dit verwijzen naar individuen maar ook naar plekken

(bijvoorbeeld: een goed/slecht bereikbare stad). Ook bereikbaarheidsindicatoren kunnen verdeeld worden in die twee categorieën. Omdat rechtvaardigheid in de praktijk vooral om individuen of groepen gaat, zijn alleen bereikbaarheidsindicatoren voor individuen belangrijk voor dit onderzoek. Een voorbeeld van zo'n indicator is het aantal banen dat iemand kan bereiken in een half uur.

Er zijn de afgelopen decennia veel bereikbaarheidsindicatoren bedacht, van eenvoudige tot erg geavanceerde indicatoren. Een voorbeeld van zo'n eenvoudige indicator is de minimale reistijd of afstand tot de dichtstbijzijnde bestemming (bijvoorbeeld, de dichtstbijzijnde supermarkt). Een vaak gebruikte indicator telt alle bestemmingen die binnen een bepaalde tijd (de "afkapwaarde") bereikt kunnen worden. Dit wordt een "cumulatieve bereikbaarheidsindicatoren" genoemd. Geavanceerdere indicatoren nemen de afstand tot bestemmingen ook mee: hoe verder weg een bestemming is, hoe minder het meetelt. De meest geavanceerde bereikbaarheidsindicatoren proberen in te schatten welke kansen bereikbaar zijn voor ieder individu, rekening houdend met wat ze op een dag doen (zoals waar ze werken en boodschappen doen).

Alle bereikbaarheidsindicatoren zeggen iets over de ruimtelijke spreiding van bestemmingen. Wanneer gekeken wordt naar de *gelijkheid* van verkeer en vervoer, dan zijn bereikbaarheidsverschillen belangrijk. Een stad en een dorp zullen dus ongelijk zijn. *Rechtvaardigheid* gaat niet alleen over die gelijkheid, maar ook over het (waarde)oordeel dat wij daar over vellen. Met andere woorden, zijn die ongelijkheden in vervoer wel *eerlijk*? Voor transport planning zijn twee soorten rechtvaardigheid belangrijk: *ruimtelijke rechtvaardigheid*, waarmee ongelijkheid en oneerlijkheid op verschillende plekken bedoeld wordt, en *sociale rechtvaardigheid*, waarmee ongelijkheid en oneerlijkheid tussen verschillende socio-economische en demografische groepen bedoeld wordt. In veel steden hangt inkomen en bereikbaarheid sterk samen; is die ongelijkheid wel eerlijk?

Samengevat is rechtvaardigheid tussen *mensen* en tussen *plekken* van belang voor beleidsmakers. Beleidsmakers willen graag dit soort overwegingen meenemen, maar worden belemmerd door het gebrek aan goede methoden, instrumenten en indicatoren. Het is belangrijk dat zo'n rechtvaardigheidsindicator geavanceerd genoeg is om rechtvaardigheid goed te meten. Voor transport planning is het ook belangrijk dat zo'n indicator goed gecommuniceerd, begrepen en meegenomen kan worden in beleid.

Om rechtvaardigheid mee te nemen, is het belangrijk om duidelijk te zijn over welke waarden de basis vormen van zo'n waardeoordeel. In de huidige gang van zaken liggen "utilitaire" waarden ten grondslag aan transport planning. Dit houdt in dat beleid en maatregelen zo veel mogelijk voordeel moeten bieden aan zo veel mogelijk mensen met zo min mogelijk kosten. Verscheidene academici stellen dat in het geval van rechtvaardigheid dit schrijnende situaties kan opleveren, doordat er mensen en plekken die keer op keer buiten

de boot vallen. “Zo veel mogelijk mensen” is namelijk iets anders dan “*alle* mensen”. Om schrijnende situaties te voorkomen, moet het utilitaire gedachtegoed gedeeltelijk worden vervangen door een “basisniveau”. Het idee hierachter is dat iedereen recht heeft op een minimum basisniveau, goed genoeg om mee vooruit te kunnen. Dit niveau kan dan als een norm gezien worden: wanneer het minimum niet gehaald wordt, is dat een reden om beleid of maatregelen te vormen die dat probleem oplossen. Mensen die keer op keer buiten de boot vallen kunnen dan “opgevangen” worden door zo’n basisniveau.

Martens stelt voor een rechtvaardigheidsindicator te gebruiken die zulke basisniveaus gebruikt. Hij stelt twee basisniveaus voor: één voor bereikbaarheid en één voor de kwaliteit van het transportnetwerk. Zijn stelling is dat transportplanning zich dan moet richten op de mensen die onvoldoende bereikbaarheid hebben *en* onvoldoende transportmogelijkheden hebben. Immers, als mensen onvoldoende bereikbaarheid ervaren maar over veel goede vervoersopties beschikken, dan kan dat bereikbaarheidsprobleem waarschijnlijk niet opgelost worden door *nóg* meer vervoer aan te bieden. Wanneer deze twee basisniveaus bepaald zijn, kan in kaart gebracht worden wie onder de niveaus valt en wat er moet gebeuren om dat te verhelpen.

Voor beleid is het niet alleen belangrijk wie er onder zulke basisniveaus vallen, maar ook hoe erg dat is. Martens stelt daarom voor om te kijken naar het *aantal* mensen en *hoe ver* die onder dat basisniveau vallen. Immers, een grote groep mensen onder zo’n basisniveau is voor beleid belangrijker dan een kleine groep; wanneer een groep heel erg ver onder zo’n basisniveau valt, is dat ook belangrijker dan een groep die net buiten de boot valt. Martens stelt dus de “rechtvaardige bereikbaarheidsindex” voor. Dit vermenigvuldigt het aantal mensen met hoe ver ze onder het basisniveau van bereikbaarheid vallen. Een voorbeeld: de bereikbaarheid naar scholen zou op 5 scholen binnen een half uur gesteld kunnen worden. Wanneer duizend mensen maar twee scholen kunnen bereiken, is dat belangrijker dan tien mensen die maar vier scholen kunnen bereiken.

Martens stelt ook een nieuwe aanpak voor transportplanning voor, waarin deze index volledig is meegenomen in alle stappen, van het analyseren van het probleem tot het monitoren van de resultaten aan toe. Omdat rechtvaardigheid belangrijk is tussen groepen mensen, onderscheidt hij eerst de populatie in groepen die ook vaak verschillen in bereikbaarheid (bijvoorbeeld inkomen, geslacht, of migratieachtergrond). Vervolgens wordt voor elke groep de bereikbaarheid en mobiliteit berekend. Daarna worden de basisniveau’s vastgesteld en wordt voor elke groep in elke buurt de rechtvaardigheidsindex berekend. Dit resulteert in een prioriteitstelling, die de basis vormen voor onderzoek naar de oorzaken en voor het implementeren van oplossingen. Zijn voorgestelde aanpak kan worden samengevat met de volgende tien stappen:

- 1 ) *Onderscheid* inwoners in groepen



- 2 ) *Bereken* bereikbaarheid & mobiliteit voor die groepen
- 3 ) *Stel* basisniveau's vast
- 4 ) *Identificeer* groepen die daar onder vallen
- 5 ) *Bereken* de mate van onrechtvaardigheid voor die groepen
- 6 ) *Prioriteer* de groepen aan de hand van bereikbaarheid
- 7 ) *Identificeer* de oorzaken van de bereikbaarheidsproblemen
- 8 ) *Identificeer* mogelijke oplossingen
- 9 ) *Beoordeel* de voor- en nadelen van die mogelijke oplossingen
- 10 ) *Implementeer* en monitor de oplossingen

## Ontwikkelde Aanpak

In dit onderzoek is de aanpak van Martens ontwikkeld tot beleidsinstrument en verbeterd. Deze samenvatting probeert de ontwikkelde en toegepaste aanpak uit te leggen zonder formules. Bijlage C kan worden geraadpleegd voor een overzicht van de geformaliseerde aanpak. De tien stappen zijn enigszins vereenvoudigd vanwege beperkte tijd en middelen voor dit onderzoek. Zo is het vaststellen van de basisniveau's in stap 3, iets wat eigenlijk onderbouwd zou moeten met een democratisch en doelbewust proces, op basis van gemiddelde bereikbaarheid gedaan. De focus van dit onderzoek ligt op het ontwikkelen van stappen 1-6. Stap 7 en 8 vereist aanvullend diepgaand onderzoek; in plaats daarvan zal het oordeel van experts van de Gemeente Rotterdam worden gebruikt. Twee maatregelen zullen worden getest om stap 9 te verkennen. De ontwikkelde aanpak is een grote stap vooruit ten opzichte van de verkennende casus die Martens zelf heeft gedaan.

Het onderscheiden van de inwoners gebeurde op basis van drie kenmerken: locatie, tijd (spits / dal) en gekozen transportmiddel (auto, openbaar vervoer en fietsen). Er wordt gekeken naar 1192 zones in de stad Rotterdam, 3 transportmiddelen op 2 momenten van de dag. Omdat het "RVMK" verkeersmodel nauwelijks onderscheid binnen en buiten de spits voor OV en voor fietsverplaatsingen, is het onderscheid in tijd voor die middelen niet gemaakt en is het totale aantal groepen  $4 * 1192 = 4768$ . De omvang van elke groep is bepaald aan de hand van demografische gegevens van het Centraal Bureau voor de Statistiek. Met deze groeps groottes kan de rechtvaardige bereikbaarheidsindex, die het aantal mensen meeneemt, berekend worden. Ook de bereikbaarheidsindicatoren zullen voor elke groep apart berekend worden.

Om bereikbaarheid te berekenen zijn twee vragen essentieel: bereikbaarheid naar wat, en met welke indicator? Voor dit onderzoek is een selectie van

bestemmingen gekozen die de belangrijkste activiteiten in het dagelijks leven weerspiegelt. De 18 gekozen bestemmingstypes vallen in zeven belangrijke categorieën: gezondheid, onderwijs en commercie; culturele, recreatieve en sportfaciliteiten; en banen. Een cumulatieve bereikbaarheidsindicator telt dan het totale aantal bestemmingen van elk type binnen een bepaalde reistijd (binnen 20, 30 en 45 minuten). Voor de gevoeligheidsanalyse wordt ook een zogeheten Gaussiaanse indicator gebruikt, die bestemmingen verder weg minder zwaar mee laat tellen.

Het meten van de kwaliteit van het transportnetwerk gebeurt met een door Martens voorgestelde indicator die hij de "Potentiële Mobiliteitsindex" (PMI) noemt. Deze berekent voor elke zone de gemiddelde reistijd en de gemiddelde hemelsbrede afstand naar alle andere zones. Deze index, gemeten in km / uur, geeft aan hoe goed je vanuit een zone naar alle andere zones kan reizen. De "PMI" verschilt voor elke zone, vervoersmiddel en tijdstip. Een andere variant van deze indicator (die niet de hemelsbrede maar de daadwerkelijk gereisde afstand meeneemt) wordt getest als gevoeligheid.

Voor de basisniveau's zijn in deze scriptie de gemiddelde bereikbaarheid en mobiliteit voor automobilisten gebruikt. Na die berekening zijn de groepen geïdentificeerd die onder dat niveau voor bereikbaarheid en mobiliteit vallen. Vervolgens wordt de rechtvaardige bereikbaarheidsindicator berekend door het aantal mensen onder deze norm te vermenigvuldigen met de mate waarin ze onder de norm vallen. Deze is daarna in kaart gebracht om een idee te krijgen van de ruimtelijke verdeling van onrechtvaardigheid (zie figuur B.1).

Deskundigen van de gemeente Rotterdam zijn geraadpleegd om gebieden te identificeren die aanzienlijke oneerlijkheid ervaren en om verbeteringen aan te bevelen die die oneerlijkheid kunnen verlichten. Deze verbeteringen zijn in het "RVMK" verkeersmodel geïmplementeerd. Daarna zijn alle genoemde stappen opnieuw doorlopen om de verschillen te beoordelen; met andere

woorden, om te kijken of in de resultaten inderdaad verbeteringen te zien zijn.

## Resultaten

De resultaten van stap 1 t/m 6 van de aanpak is de volgende informatie voor elk van de 4768 groepen (1192 zones en 4 transportmiddel-tijdcombinaties):

- 1 ) het aantal mensen in elke groep
- 2 ) de bereikbaarheid naar elk van de 18 bestemmingstypes
- 3 ) de mobiliteit van elke groep in de casus
- 4 ) het verschil tussen de bereikbaarheid en het vastgestelde basisniveau
- 5 ) de onrechtvaardigheid van elke groep
- 6 ) het percentage onrechtvaardigheid dat elke groep bijdraagt aan het geheel
- 7 ) de rangorde van elke groep, van meeste tot minste onrechtvaardigheid

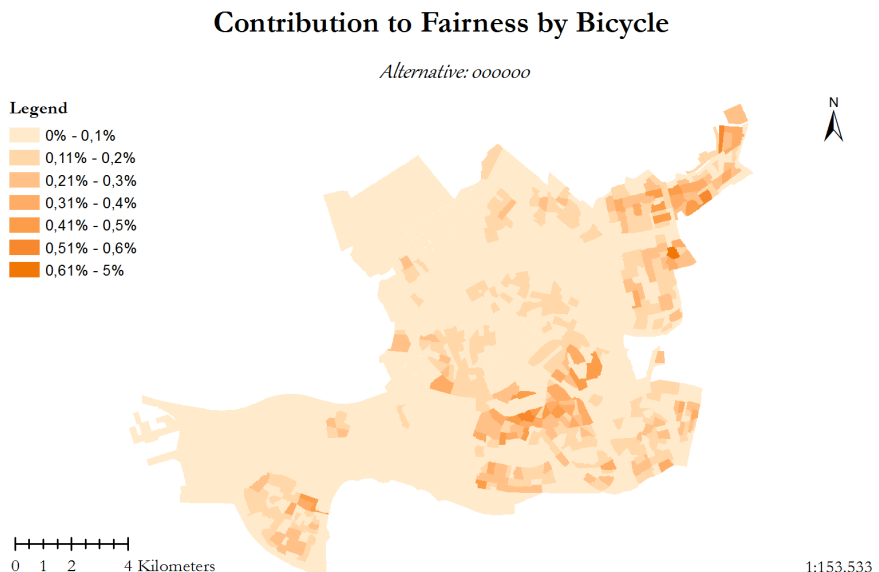


FIGURE B.1: Onrechtvaardigheid Per Zone met de Fiets

Voor stappen 7,8 en 9 van de aanpak zijn transportplanners bij de gemeente Rotterdam geraadpleegd. Zij stelden voor om de aanpak toe te passen op een relevant beleidsthema, namelijk onrechtvaardige bereikbaarheid naar scholen

toe met de fiets. Figuur B.1 heeft die onrechtvaardigheid in kaart gebracht, voor bereikbaarheid per fiets naar scholen binnen 20 minuten reistijd. Donkere kleuren duiden op *meer* onrechtvaardigheid. Omdat scholen buiten het studiegebied niet konden worden meegenomen zijn de donkere vlekken bij bijvoorbeeld Nesselande niet onverwacht. oneerlijkheid verwacht in de buurt van enkele randen van het studiegebied, zoals Nesselande in de rechterbovenhoek. Het cluster van donkerdere zones ten zuiden van het midden van de kaart (Rotterdam-Zuid) was niet te verklaren en werd daarom als problematisch gezien.

Twee verbeteringen aan het fietsnetwerk zijn geïmplementeerd in het verkeersmodel om deze onrechtvaardigheid te verminderen. In scenario 1 werden de bruggen over de Maas, die voor fietsers gemodelleerd waren op 5 km/h om hun geografische barrière te representeren, gemodelleerd op 10 km/u. (De standaard fietssnelheid in het model is 15 km/u.) In scenario 2 zijn twee belangrijke fietscorridors tussen Rotterdam-Zuid en het centrum verhoogd tot 17,5 km/u om een "fietssnelweg" te modelleren. Door deze scenarios daalde de totale onrechtvaardigheid in het studiegebied verlaagd met 4,6% in het eerste scenario en met 16,3% in het tweede scenario. De meeste verbeteringen vonden plaats in het bovengenoemde cluster van zones in Rotterdam-Zuid, maar de gebieden er omheen hadden er ook profijt van. Deze afname van onrechtvaardigheid zou eventueel gebruikt kunnen om kosten-effectieve berekeningen te maken en verschillende verbeteringen op rechtvaardigheid te toetsen en vergelijken.

## Gevoeligheidsanalyse

Omdat deze aanpak nog erg nieuw is, is het onbekend hoe gevoelig de resultaten zijn voor keuzes die gemaakt zijn in het ontwikkelen van de aanpak. Twee keuzes, namelijk de gekozen bereikbaarheidsindicator en de mobiliteitsindicator, zijn aangepast om de gevoeligheid van het resultaat te testen. Een voordeel van de aanpak is dat beleidsmakers ook keuzevrijheid hebben: de beleidsmaker staat vrij om de basisniveaus, bestemmingen, bevolkingsgroepen en de maximale reistijd te kiezen. Er zijn ook een aantal tests gedaan om te zien of de resultaten gevoelig zijn voor deze vier keuzes.

De Gaussiaanse bereikbaarheidsindicator is een stuk gevoeliger voor het ruimtelijke patroon van bestemmingen dan de Cumulatieve bereikbaarheidsindicator. Omdat de Gaussiaanse indicator veel bestemmingen verdisconteert, zijn alle bereikbaarheidswaarden lager dan bij de Cumulatieve indicator. De groepen zijn ook meer verspreid, met meer variatie in bereikbaarheids- en mobiliteitswaarden voor elk vervoersmiddel. Deze grotere spreiding resulteert in meer groepen die onder de basisniveau's vallen.

Door de mobiliteitsindicator te veranderen van hemelsbrede afstanden naar netwerkafstanden, wordt de waarde ervan aanzienlijk verlaagd voor alle modi.

Interessant is dat de totale hoeveelheid oneerlijkheid in het studiegebied toeneemt wanneer deze verschillende PMI wordt gebruikt. Aangezien de gemeten bereikbaarheid niet verandert, moet dit betekenen dat de verdeling van mobiliteit verandert en er meer gebieden onder de PMI-drempelwaarde komen.

Zoals gezegd laat de ontwikkelde aanpak een paar belangrijke beslissingen open voor beleidsmakers. Wanneer die keuzes worden genomen, zouden de resultaten ook moeten veranderen. Om te testen of het resultaat inderdaad gevoelig is voor die keuzes, is de impact van die vier keuzes onderzocht:

**Groepskeuze** De resultaten zijn afhankelijk van de gekozen transportmiddelen, tijden en locaties.

**Bestemmingskeuze** De gekozen bestemmingstypes (scholen, ziekenhuizen etc) laten een grote variatie zien in bereikbaarheid en dus in onrechtvaardigheid. Vergeleken met gemiddelde bereikbaarheid kunnen bestemmingstypes -40% and +30% afwijken.

**Reistijdkeuze** De resultaten zijn sterk afhankelijk van de gekozen maximale reisduur voor de bereikbaarheidsindicatoren. 20, 30 en 45 minuten reistijd laten zeer verschillende bereikbaarheidsscores zien. Met bestemmingen binnen 20 minuten reizen, ervaren bijna alle OV- en fietsgroepen een mate van onrechtvaardigheid vergeleken met automobilisten. Met een waarde van 45 minuten ondervinden slechts een klein aantal groepen aan de rand van het studiegebied onrechtvaardigheid.

**Basisniveaukeuze** Er is een direct verband tussen de resultaten en de gekozen drempelwaarde.

## Conclusies

De conclusies zijn niet alleen gevormd door de bovenstaande resultaten, maar ook door feedback van verschillende beleidsmakers, ambtenaren en academici waarmee het onderzoek besproken en bediscussieerd. Nadat de belangrijkste conclusies zijn besproken, eindigt deze samenvatting met een lijst van belangrijke voordelen en problemen van de aanpak naargelang de onderzoeksvraag.

Deze scriptie is er in geslaagd om de meeste stappen van de door Martens voorgestelde aanpak te formaliseren en operationaliseren. De ontwikkelde aanpak beoordeelt in de eerste plaats potentiële bereikbaarheid en mobiliteit. Wanneer deze beoordeling wordt gecombineerd met gekozen basisniveau's, kan de "rechtvaardige bereikbaarheidsindex" zoals voorgesteld door Martens (2015) worden gebruikt om zowel sociale rechtvaardigheid (tussen mensen) alsmede ruimtelijke rechtvaardigheid (tussen plekken) in transport te

beoordelen. De resulterende rechtvaardigheidsindicator kan worden gebruikt om problematische gebieden te identificeren. Het kan ook worden gebruikt om de impact op rechtvaardigheid van sommige maatregelen te toetsen. De ontwikkelde methodologie kan grotendeels of volledig gebaseerd zijn op openbare datasets.

Door de voorgestelde tien stappen te operationaliseren en te implementeren in een case voor de gemeente Rotterdam, is de kloof tussen het verkennende voorbeeld van Martens (2015) en een bruikbaar beleidsinstrument aanzienlijk verkleind. De ontwikkelde aanpak is geformaliseerd (zie bijlage C) en kan dienen als een goed startpunt voor verder onderzoek, bijvoorbeeld onderzoek naar meer geavanceerde indicatoren met eenzelfde doel. De ontwikkelde aanpak is casus-onafhankelijk geformuleerd en flexibel genoeg om op verschillende beleidscontexten en -doelen te worden toegepast. De combinatie van bereikbaarheid, mobiliteit en rechtvaardigheidsbeoordelingen van de ontwikkelde aanpak werd door planners en beleidsmakers bij de gemeente Rotterdam als interessant en waardevol beschouwd. Het biedt een goed startpunt voor het oplossen van moeilijke vervoersgerelateerde sociale problemen waarvoor politici oplossingen zoeken, bijvoorbeeld sociale uitsluiting. De ontwikkelde aanpak wordt door planners en beleidsmakers nu al als een nuttig instrument beschouwd om rechtvaardigheid en maatregelen te beoordelen.

Het is echter onduidelijk in hoeverre de genoemde kloof is gesloten. Verschillende methodologische beslissingen gemaakt in hoofdstuk 3 en 4, zoals de gekozen aggregatiegrootte en het studiegebied, hadden anders gekozen kunnen worden. Oorspronkelijk was het de bedoeling om inkomen toe te voegen aan de groepen, en om zelfs te experimenteren met inkomensafhankelijke bestemmingen, maar dit werd niet bereikt vanwege onvoldoende gegevens. Het kostte ook meer tijd en moeite dan verwacht om de geïmplementeerde methodologie zowel flexibel en robuust te maken om tegemoet te komen aan de vier keuzes en twee gevoeligheden die in het vorige deel werden genoemd. Hoewel de theoretische onderbouwing onder de voorgestelde benadering door Martens goed lijkt, biedt deze geen antwoord op allerlei lastige keuzes die gemaakt moeten worden tijdens het operationaliseringsproces. Er is dus nog ruimte om de fundamentele onderdelen van de hier ontwikkelde aanpak te verbeteren, bijvoorbeeld door factoren op te nemen die gebruikelijk zijn in bereikbaarheidsonderzoek, zoals competitie en ruimtelijke zelfselectie, of door meer geavanceerde (op activiteiten gebaseerde) indicatoren en modellen te gebruiken.

De rol van het gebruikte waardesysteem is ook belangrijk voor het contextualiseren van de resultaten. In tegenstelling tot andere methodologieën die worden gebruikt in de transportplanning, plaatst het een waardeoordeel centraal in de methodologie door basisniveau's te stellen voor bereikbaarheid en mobiliteit. Dit idee is al operationeel in andere beleidsterreinen en voor andere publieke goederen, maar is niet de enige

manier waarop rechtvaardigheid in transportplanning meegenomen zou kunnen worden. Beleidsmakers toonden interesse om dit idee toe te passen op vervoersplanning, maar maakten zich ook zorgen over de politieke implicaties en de uitdaging om die basisniveau's vast te stellen. Het voorgestelde proces om de niveau's vast te stellen omvat een democratisch en transparant proces dat leidt tot een consensus onder de belanghebbenden. Er zijn echter drie problemen die de implementatie van dit proces in de weg kunnen staan. Ten eerste is het moeilijk om een dergelijk proces te creëren en te onderhouden. Het is bijvoorbeeld niet duidelijk welke belanghebbenden in dit proces moeten worden betrokken. Ten tweede, de precieze rol van de basisniveau's zelf is nog niet duidelijk. Is het een harde of een zachte grens? Martens (2015) stelt voor om meerdere basisniveau's te gebruiken om het belang van een enkele drempel te verminderen, maar dit maakt het proces zeker niet eenvoudiger. Ten derde: omdat de drempels kunnen worden gebaseerd op gemiddelden (of eenvoudigweg kunnen worden bepaald door beleidsmakers), is het heel goed mogelijk dat het beoogde om pragmatische redenen worden overgeslagen.

De resultaten zijn erg gevoelig voor de gekozen bereikbaarheidsindicator, zijn niet erg gevoelig voor de gekozen mobiliteitsindicator en zijn gevoelig voor variatie in maximale reistijd, kansen, basisniveau en gekozen groepen. Bij het interpreteren van de resultaten van de ontwikkelde aanpak moet wel goed rekening gehouden worden met de gemaakte keuzes in de aanpak. De volledige gevolgen van alle methodologische keuzes is echter nog niet bekend. De geteste beslissingen en gevoeligheden hebben gepoogd de grootste onbekendheden aan te pakken, maar het is verre van volledig genoeg om alle ongewenste effecten in kaart te brengen. Zoals eerder vermeld, is door de gemaakte keuzes bij het kiezen van het studiegebied en de beschikbare gegevens een sterk "randeffect" zichtbaar in de resultaten. Dit effect kan echter gemakkelijk worden verward met daadwerkelijke onrechtvaardigheid: omdat het centrum van het studiegebied ook het centrum van de stad Rotterdam is, zullen de gebieden aan de randen gevoelig zijn voor onrechtvaardigheid vanwege hun grote afstand tot het centrum.

Om de onderzoeksvraag te beantwoorden zijn de belangrijkste voordelen en problemen opgesomd.

*Belangrijkste voordelen:*

**Bruikbaar** — De ontwikkelde aanpak wordt al als bruikbaar gezien door beleidsmakers

**Interessant voor beleidsmakers** — Beleidsmakers willen rechtvaardigheid graag meenemen in het proces, maar dat was tot nu toe door een gebrek aan goede methoden niet goed te doen. Ze geven aan dat de ontwikkelde aanpak veel interessante inzichten kan bieden voor bereikbaarheidsproblemen en kan helpen met het vinden van oplossingen voor bereikbaarheids- en rechtvaardigheidsproblemen.

**Flexibel** — De aanpak kan gebruikt worden voor vele bestemmingen, groepen, ruimtelijke schaalniveau's, beleidscontexten en -onderwerpen.

**Algemeen** — De aanpak is algemeen genoeg dat het kan worden toegepast op allerlei steden, culturen en vervoersmiddelen.

*Belangrijkste nadelen:*

**Aannames & Keuzes** — Methodologische keuzes en aannames, zoals het gekozen studiegebied of de gekozen bestemmingen, hebben een direct effect op de resultaten. Het is niet duidelijk of de keuzes gemaakt in dit onderzoek de de "juiste" zijn.

**Gevoeligheid** — Hoewel dit onderzoek de gevoeligheid van de resultaten verkende, is het nog niet duidelijk hoe veel invloed elk stukje van de aanpak precies heeft.

**Waardeoordelen** — Het instellen van basisniveau's is een waardeoordeel en het wordt halverwege de aanpak gedaan. Dit is in tegenstelling tot andere analyses in transportplanning, en het invullen van die stap wordt als een grote uitdaging gezien door beleidsmakers.

## Aanbevelingen

Allereerst zullen aanbevelingen voor wetenschappelijk onderzoek gedaan worden. Daarna zullen enkele aanbevelingen voor beleidsmakers gemaakt worden.

Vervolgonderzoek kan worden gedaan om de ontwikkelde aanpak in verschillende opzichten te verbeteren. De verbeteringen kunnen gebaseerd zijn op de nadelen uit de conclusies, bijvoorbeeld door een vollediger gevoeligheidsanalyse van de aanpak uit te voeren, of door de normatieve en subjectieve kwesties te onderzoeken die nog niet volledig zijn uitgewerkt. Vervolgonderzoek zou zich ook op een verbeterde implementatie van de aanpak in de praktijk kunnen richten, bijvoorbeeld door alle stappen in de door Martens (2015) voorgestelde aanpak te ontwikkelen.

Een aanname in dit onderzoek is dat bereikbaarheid en mobiliteit kunnen worden gebruikt om rechtvaardigheidsproblemen in kaart te brengen. Deze aanname zou verder kunnen worden onderzocht met validatieonderzoek, bijvoorbeeld door de resultaten van de aanpak met daadwerkelijk ervaren bereikbaarheids- of rechtvaardigheidsproblemen te vergelijken. Dit kan aanvullend kwantitatief of kwalitatief onderzoek zijn.

Een andere interessante onderzoeksrichting is het toepassen van deze aanpak in allerlei situaties en vergelijkingen, bijvoorbeeld door heel verschillende steden of regio's met dezelfde aanpak te vergelijken op basis van rechtvaardigheid. Het zou ook interessant kunnen zijn om 'ex



post'-beoordelingen te maken van verschillende infrastructuurinvesteringen. Dit is vooral interessant in combinatie met een verder ontwikkelde aanpak die ook goed kosteneffectiviteit kan meenemen.

Volgens sommige beleidsmakers is de hier ontwikkelde methode al goed genoeg om beleid te informeren. Of het ook het beleid vorm kan geven is een andere vraag. Gezien enkele onzekerheden die in het vorige deel worden genoemd lijkt dat nog niet helemaal mogelijk. Desalniettemin zijn de op groepen gebaseerde bereikbaarheids- en mobiliteitsscores al erg interessant en nuttig voor beleidsmakers, ongeacht of de rechtvaardigheidsberekeningen ook gedaan worden. Hun nut ligt vooral in de mogelijkheid om maatwerk te bieden als het gaat om bereikbaarheidsproblemen: men kan zeer specifieke socio-economische en demografische groepen vergelijken met de ontwikkelde aanpak. Het is moeilijk te zeggen of de uitkomsten voldoende robuust zijn om beleid vorm te geven of te sturen; meer onderzoek is nodig om de details uit te werken en om de robuustheid van de ontwikkelde aanpak uit deze scriptie te verbeteren.

Een belangrijke aanbeveling voor beleid is dat er meer geëxperimenteerd zou moeten worden met het bepalen van normen of basisniveau's in verkeer en vervoer. Experimenten zouden kunnen beginnen met een norm die de onderste 10% van de mensen in een bepaald studiegebied dekt. Oplossingen zouden dan kunnen worden onderzocht om bereikbaarheid voor deze inwoners aanzienlijk te verminderen, met aanvullend onderzoek om na te gaan in hoeverre deze oplossingen de door de methodologie gevonden problemen ook echt heeft verholpen. Wanneer dit een duidelijk en positief effect heeft op de grootste rechtvaardigheidsproblemen in verkeer en vervoer, kunnen hogere en belangrijkere normen/basisniveau's uitgeprobeerd worden. Een dergelijke aanpak waarbij de niveau's langzaam opbouwen als de maatregelen effectief zijn, met ruimte voor methodologische verbeteringen, lijkt een goede manier om dit onderzoek een vervolg te geven.



## *Appendix C*

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# Formal Definition of the Methodology

## C.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 C.1 - C.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:

$$\mathbf{G} = \{g_{ikm}, \dots\} \forall i \in \mathbf{I}, k \in \mathbf{K}, m \in \mathbf{M} \quad (\text{C.1})$$

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

$$n_{g_{ikm}} = \text{the number of people in group } g_{ikm} \quad (\text{C.2})$$

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

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

**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
$\mathbf{G} = \{g_{ikm}, \dots\}$	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.

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

$$n_i = \text{total number of people in zone } i \quad (\text{C.5})$$

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

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.

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

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

## C.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. $\mathbf{T} = \{\text{Schools, Jobs, } \dots\}$ )
$\mathbf{O}_t = \{op_1^t, op_1^t, \dots\} :$	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:

$$A_{g_{ikm}}^{tv} = \sum_{op_t \in \mathbf{O}_t} \left( P(op_t) \right) \quad \forall g \in \mathbf{G} \quad (\text{C.9})$$

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

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  $|\mathbf{O}_t| = n$ , 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:

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

$$W(op_t) = \frac{1}{|\mathbf{O}_t|} \quad (\text{C.12})$$

$$t^* = \frac{1}{2}v \quad (\text{C.13})$$

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.

### C.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  $j \in \mathbf{J}$

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

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  $j$ ,  $i \in \mathbf{I}$ ,  $j \in \mathbf{J}$

### C.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 C.2 and C.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 C.1. Large values of the AFI indicate that a lot of people experience a lot of insufficiency. The AFI values thus indicate how large *unfairness* 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  $t = \text{hospitals}$ ). 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

$$AFI_{g_{ikm}} = ((y_t - A_{g_{ikm}}^t)/y_t)^2 * n_{g_{ikm}} * Q(g_{ikm}) \quad \forall g \in G \quad (\text{C.15})$$

$$Q(g_{ikm}) = \begin{cases} 1 & \text{if } A_{g_{ikm}}^t < y_t \wedge PMI_{g_{ikm}} < z, \\ 0 & \text{otherwise} \end{cases} \quad (\text{C.16})$$

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.



## *Appendix D*

---

# Code

## D.1 Assign Omnitrans Model

```

1  #=====
2  writeln "Inlezen_parameter_bestanden ..."
3  #=====
4  include Parameters_rtd
5  #=====
6
7  toedelenVracht          = false
8  toedelenAutoSpits     = true
9  toedelenAutoRdVa     = true
10 toedelenOV              = true
11 toedelenFiets         = false
12 #
13 toedelenAutoRdAon     = false
14 toedelenVracht_etm    = false
15 #
16 aantalThreads        = 8
17
18 writeln "=====
19 varname = $Ot.currentVariant
20 writeln "The_current_variant_is_",varname[1], " "
21 vardir = $Ot.variantDirectory
22 writeln "in_", vardir
23 writeln "=====
24
25 if toedelenVracht
26     for t in [1,2,3]
27         for m in [31,32]
28             writeln "~~~*_vrachtverkeer_",m,"/" , t
29             traffic
30                 = OtTraffic.new
31             traffic.odMatrix
32                 = [Totaal,m,t,Usercat]
33             traffic.network
34                 = [Vracht,t]
35             traffic.load
36                 = [Totaal,m,t,Usercat,Aon,1]
37             traffic.routeFactors
38                 = [
39                 VrachtCostAfstand,VrachtCostTijd,0,0]
40             traffic.numberOfThreads
41                 =
42                 aantalThreads
43             traffic.execute
44
45         end
46         writeln "~~~*_vrachtloads_bewerken"
47         network = OtNetwork.new
48         network.updateResults ([Totaal,Middelzwaar,t,Usercat,Aon
49             ,1],
50             [Totaal,Zwaar,t,Usercat,Aon,1],[Totaal,Vracht,t,Usercat
51             ,Aon,1],1.0,1.0)
52         network.copyLoad ([Totaal,Vracht,t,Usercat,Aon,1],
53             [Totaal,Vracht,t,Usercat,Pae,1],2.0)
54         network.copyLoad ([Totaal,Middelzwaar,t,Usercat,Aon,1],
55             [Totaal,Middelzwaar,t,Usercat,Pae,1],2.0)
56         network.copyLoad ([Totaal,Zwaar,t,Usercat,Aon,1],
57             [Totaal,Zwaar,t,Usercat,Pae,1],2.0)
58     end
59 end
60
61 if toedelenVracht_etm
62     writeln "~~~*_vrachtverkeer_etmaal"
63     for m in [31,32]
64         traffic
65             = OtTraffic.new
66         traffic.odMatrix
67             = [
68             Totaal,m,Etmaal,Usercat]

```

```

55         traffic.network                                = [
56             Vracht, Restdag]                            = [
57             Totaal, m, Etmaal, Usercat, Aon, 1]        = [
58             traffic.routeFactors                       = [
59                 VrachtCostAfstand, VrachtCostTijd, 0, 0]
60             traffic.numberOfThreads                    = aantalThreads
61         end
62     end
63
64     if toedelenAutoSpits
65         for t in [2, 3]
66             writeln "%%*_personenauto's_tijd_", t
67             traffic
68                 = OtTraffic.new
69             traffic.assignMethod                        =
70                 VOLUMEAVERAGING
71             traffic.iterations                          = 20
72             traffic.junctions                          = true
73             traffic.junctionParameters                 = [0.5, 1.0]
74             #traffic.junctionVersion                    = 25 #RVMK3 IN
75                 P1833: VERSIE 25
76             traffic.epsilon                             =
77                 0.00000001
78             traffic.functionType                       = 19
79             traffic.bprPerType = [[1..14, 71..73], [0.5, 4.0]], \
80                 [[20, 21, 23, 25, 62, 68..70, 74, 75], [1.0, 4.0]],
81                 [[22, 24, 26..28, 35..39, 42, 63, 65], [1.5, 4.0]],
82                 [[40, 41, 64, 66], [2.0, 4.0]], \
83                 [[51, 67], [4.0, 4.0]], \
84                 [[52, 53, 55..58], [0.0, 4.0]]]
85             traffic.network                            = [Auto
86                 , t]
87             traffic.routeFactors                       = [
88                 AutoCostAfstand, AutoCostTijd, 0, 0]
89             traffic.odMatrix                           = [
90                 Totaal, Auto, t, 103]
91             traffic.load                                = [
92                 Totaal, Auto, t, 103, Va, 20]
93             traffic.preLoad                            = [
94                 Totaal, Vracht, t, Usercat, Pae, 1]
95             traffic.numberOfThreads                    = aantalThreads
96
97             traffic.skimMatrix = [Totaal, Auto, t, Usercat, [1, 2, 0], 20]
98             traffic.execute
99         end
100     end
101
102     if toedelenAutoRdAon
103         writeln "%%*_personenauto's_restdag_AoN"
104         traffic
105             = OtTraffic.new
106         traffic.load
107             = [Totaal, Auto,
108                 Restdag, 101, 151, 1]
109         traffic.routeFactors                           = [AutoCostAfstand,
110             AutoCostTijd, 0, 0]
111         traffic.numberOfThreads                        = aantalThreads
112         traffic.execute
113     end
114
115     if toedelenAutoRdVa
116         writeln "%%*_personenautoverkeer_restdag"
117         traffic
118             =
119         traffic
120             = OtTraffic.new
121         traffic.assignMethod                            = VOLUMEAVERAGING

```

```

106     traffic.iterations                = 20
107     traffic.junctions                = true
108     traffic.junctionParameters       = [0.5, 1.0]
109     #traffic.junctionVersion         = 25 #RVMK3 IN P1833: VERSIE
110     traffic.epsilon                   = 0.00000001
111     traffic.functionType              = 19
112     traffic.bprPerType = [[ [1..14, 71..73], [0.5, 4.0]], \
113                            [ [20, 21, 23, 25, 62, 68..70, 74, 75], [1.0, 4.0]],
114                            [ [22, 24, 26..28, 35..39, 42, 63, 65], [1.5, 4.0]],
115                            [ [40, 41, 64, 66], [2.0, 4.0]], \
116                            [ [51, 67], [4.0, 4.0]], \
117                            [ [52, 53, 55..58], [0.0, 4.0]]]
118     traffic.network                   = [Auto, Restdag
119         ]
119     traffic.routeFactors              = [AutoCostAfstand,
120         AutoCostTijd]
120     traffic.odMatrix                 = [Totaal, Auto,
121         Restdag, 101]
121     traffic.pcuFactor                = 1.0/
122         RD_factor_auto
122     traffic.load                     = [Totaal, Auto,
123         Restdag, 141, Va, 20]
123     traffic.preLoad                  = [[Totaal,
124         Vracht, Restdag, Usercat, Pae, 1], (1.0/RD_factor_vracht)]
124     traffic.numberOfThreads           = aantalThreads
125
126     traffic.skimMatrix = [Totaal, Auto, Restdag, Usercat, [1, 2, 0], 20]
127     traffic.execute
128
129     #bewerken loads restdag autoverkeer (ophogen naar totaal
130     #restdag en verwijderen tussenload (nr 141)
130     writeln "~~~~~*~autoloads_restdag_bewerken"
131     network = OtNetwork.new
132     network.copyLoad ([Totaal, Auto, Restdag, 141, Va, 20], [Totaal, Auto,
133         Restdag, 101, Va, 20], RD_factor_auto/1.0)
133     network.deleteResults ([Totaal, Auto, Restdag, 141, Va, 20])
134
135 end
136
137 if toedelenOV
138     for t in [1, 2, 3]
139         writeln "~~~~~*~Openbaar_vervoer_", t
140         transit=OtTransit.new
141         transit.network                = [Ov, t
142             ]
142         transit.logitParameters        = [0.5, 0.1, 0.1]
143         transit.load                    = [
144             Totaal, Ov, t, Usercat, Aon, 1]
144         transit.routeFactors           =
145             [[0, 1, 60, 60, 60, 1]]
145         transit.minProbability         = [0.02, 0.02]
146         transit.minFind                = [[
147             Lopen, 1]]
147         transit.searchRadius           = [[Lopen
148             , 2.00]]
148         transit.maxInterchanges        = 5
149         transit.numberOfThreads        = aantalThreads
150
151         transit.skimMatrix = [Totaal, Ov, t, Usercat, [1, 2, 3, 4, 0], 20]
152         transit.execute
153     end
154 end
155
156 if toedelenFiets
157     for t in [1, 2, 3]

```

```

158         writeln "%f%iets_",t
159         traffic
                = OtTraffic.new
160         traffic.load
                Totaal,Fiets,t,Usercat,Aon,1]
                = [
161         traffic.numberOfThreads
                = aantalThreads
162
163         traffic.skimMatrix = [Totaal,Fiets,t,Usercat,[1,2,0],20]
164         traffic.execute
165     end
166 end
167
168 writeln "Einde_toedelingen"

```

## D.2 Omnitrans To Skim

```

1  # =====
2  writeln "Inlezen_parameter_bestanden..."
3  # =====
4  load $Ot.dirJob+'Simjobs\parameters_rvmk3_rtd2010.rb'
5  include Parameters_rtd
6  # =====
7  # schrijft tekstfiles met reistijden
8  # =====
9  writeln "DUMP_REISTIJDEN_NAAR_TEXT_FILE"
10
11  skimmat=OtSkimCube.open()
12
13  # Parameters
14  aantalzonesh=[1..3700].to_a.unreduce.sort           # 1-3700 is Regio
15  aantalzonesb=[1..3700].to_a.unreduce.sort
16
17  varianttxt = "var1"
18  todomats= [[1,2,1,3,2,20],[1,2,3,3,2,20],[1,4,1,3,2,20],
19  [1,5,1,3,2,20],[1,2,1,3,1,20],[1,4,1,3,1,20],[1,5,1,3,1,20]] #alles
20
21  writeln "*_writing_files..."
22  todomats.each { |pmturi|
23    skm=skimmat[*pmturi]
24    filenaam='D:\\skimdump_2015_'+varianttxt+ pmturi.join("-") +' .csv'
25    unit1 = File.new(filenaam, 'w+')
26
27    for i in aantalzonesh
28
29      for j in aantalzonesb
30        #unit1.print i, ";", j, ";",
31          skm[i, j],
32          unit1.print i, ";", j, ";",          skm[i, j], "; \n"
33
34
35      end #j
36    unit1.print "\n"
37  end #i
38
39  unit1.close
40  writeln "*matrix_written..."
41 }
42
43 writeln "Einde_script"

```

## D.3 Data Preparation

```

1 # DATA PREPARATION
2 #
3 # -----
4 # This part reduces the OD Matrices to a much faster and more
5 # manageable size in Step 1, and calculates the PMI indicator
6 # in Step 2 (since this only needs to be done once).
7
8
9 #Load packages and set directories
10 import csv, os, csv, arcpy, math, scipy.stats
11 import numpy as np
12
13 currentdir = os.path.dirname(os.path.realpath(__file__))
14 studyareadir = os.path.join(currentdir, "Source_Files", "StudyArea.csv"
15 )
16 savedir = os.path.join(currentdir, "Skims")
17 zonesArray = np.genfromtxt(studyareadir, delimiter=',', skip_header=1)
18 numZones = len(zonesArray)
19
20 # -----
21 # Step 1
22 #
23 # Reduce OD Matrices to only the necessary rows to improve
24 # performance
25
26 #Generate a list of the zones actually within the study area
27 zonesList = []
28 with open(studyareadir, 'r') as zonesfile:
29     z = csv.reader(zonesfile, delimiter=';')
30     for row in z:
31         zonesList.append(row[0])
32
33 #Get rid of the headers in the CSV
34 del zonesList[0]
35
36 #Generate a smaller list of only the relevant travel times per PMTURI
37 #combination
38 #The result is a CSV per PMTURI combination with nothing but travel
39 #times,
40 #saved as 'skimmts_[combination].csv'.
41 def ODReduce(var):
42     # restdag, avond, PT, fiets
43     # Time: [
44         '1-2-1-103-2-1','1-2-3-103-2-1','1-4-1-3-2-1','1-5-1-3-2-20']
45     # Dist: [ '1-2-1-3-1-20','1-4-1-3-1-1','1-5-1-3-1-20']
46     pmturi = ['1-4-1-3-2-1']
47
48     ttList = [[],[],[],[]] #one sublist for each pmturi
49     counter = 0
50     totalcount = 0
51
52     for combination in pmturi:
53         filepath = os.path.join(savedir, "2015_var_0", ('skimdump_2015_
54             '+ combination + '.csv'))
55         #Use the following row for var 1 and var 2: e.g. ODReduce(1)
56         #filepath = os.path.join(savedir, ("2015 var " + str(var)),
57             #'skimdump_2015_var' + str(var) + combination + '.
58             csv'))
59         csvfile = open(filepath, 'r')
60         #Each row looks like: i, j, TT: ['1', '1', '0.0', '']
61         f = csv.reader(csvfile, delimiter=';')
62         for row in f:
63             if len(row) > 0 and row[0] in zonesList and row[1] in
64                 zonesList:
65                 newrow = [int(row[0]),int(row[1]),float(row[2][0:5])]
66                 ttList[combination].append(newrow)
67             else:
68                 pass

```

```

61
62         totalcount += 1
63         if totalcount % 1000000 == 0:
64             print('Processed_' + str(totalcount/1000000) + '_
              million_rows')
65         else:
66             pass
67
68         path = os.path.join(savedir, '2015_var_0', ('skimttts_2015_' +
              combination + '.csv'))
69         #Use the following row for var 1 and var 2: e.g. ODReduce(1)
70         #path = os.path.join(savedir, ('2015 var ' + str(var)),
71             #('skimttts_2015_var' + str(var) + combination + '.csv'))
72
73         f2 = open(path, 'w')
74         fw = csv.writer(f2, delimiter=';')
75         for row in ttList[counter]:
76             fw.writerow([row])
77         f2.close()
78         print(len(ttList[counter]))
79         counter += 1
80
81     csvfile.close()
82
83     ODReduce("")
84
85     # -----
86     # Step 2
87     # Calculate PMI for each of the four mode/time combinations
88
89     #First, calculate the distance part (Euclidean distances between zone
          centroids)
90     #Setting the workspace for ArcPy
91     arcpy.env.workspace = currentdir
92
93     #Define shapefile location, relevant columns in the shapefile and
          spatial reference
94     shp = os.path.join(currentdir, "Source_Files", "Shapefiles", "
          CentroidsRotterdam.shp")
95     fields = ["SHAPE@XY", "CENTROIDNR"]
96     sr = arcpy.SpatialReference(28992)
97
98     #Open the shapefile, get a list of all centroids
99     centroidlist = []
100    cursor = arcpy.da.SearchCursor(shp, fields, None, sr)
101    for row in cursor:
102        #Fill the centroid list. Each item in the Python list thus looks
          like: [centroid,x,y]
103        centroidlist.append([int(row[1]),row[0][0],row[0][1]])
104    del cursor
105
106    #Now, calculate for each centroid the distance to all other centroids
107    avgdistancelist = []
108    for i in centroidlist:
109        distancelist = []
110        for j in centroidlist:
111            #Being correctly exported to RD New, subtracting the X and Y
          coordinates
112            #and calculating the hypoteneuse returns the Euclidean distance
113            d = math.hypot(j[1]-i[1],j[2]-i[2])
114            distancelist.append(d)
115        #Calculate the sum of all Euclidean distances from the current
          centroid to all others
116        avg = sum(distancelist) / 1000 #Convert to km
117        avgdistancelist.append([i,avg])
118
119    #Output to txt file

```

```

120 path = os.path.join(currentdir, "Source_Files", "Skims", "PMI-TD.txt")
121 with open(path, 'w') as resultfile:
122     w = csv.writer(resultfile, delimiter=';')
123     for row in avgdistancelist:
124         writerow = [row[0][0], row[1]]
125         w.writerows([writerow])
126
127 #Then, calculate the network distances. Store network and Euclidean in
128 pmiD.
129 #For the network distances, use the car network distances
129 pmiD = np.zeros((len(zonesArray), 2), dtype = float)
130 pmiD[:,1] = np.genfromtxt(os.path.join(savedir, 'PMI-TD.txt'), delimiter
131                             =';')[:,1]
132
133 pmturi = ['skimtts_2015_1-2-1-3-1-20.csv']
134 counter1 = 0
135 for comb in pmturi:
136     path = os.path.join(savedir, comb)
137     dstc = np.genfromtxt(path, delimiter=';')
138     counter2 = 0
139     for zone in zonesArray:
140         pmiD[counter2, counter1] = np.sum(dstc[np.where(dstc[:,0] ==
141                                                         zone),2])
142         counter2 += 1
143     counter1 += 1
144
145 np.savetxt(os.path.join(savedir, ('PMI-TD-2.txt')), pmiD, delimiter=';')
146
147 #Then, extract the travel times from the mode CSVs and calculate TT
148 part of PMI
149
150 pmiTT = np.zeros((len(zonesArray), 4), dtype = float)
151 pmturi = ['skimtts_2015_1-2-1-3-2-20.csv', \
152           'skimtts_2015_1-2-3-3-2-20.csv', \
153           'skimtts_2015_1-4-2-3-2-20.csv', \
154           'skimtts_2015_1-5-1-3-1-20.csv']
155
156 counter1 = 0
157 for comb in pmturi:
158     path = os.path.join(savedir, comb)
159     time = np.genfromtxt(path, delimiter=';')
160     counter2 = 0
161     for zone in zonesArray:
162         pmiTT[counter2, counter1] = np.sum(time[np.where(dstc[:,0] ==
163                                                         zone),2])
164         counter2 += 1
165     counter1 += 1
166
167 np.savetxt(os.path.join(savedir, 'PMI-TT.txt'), pmiTT, delimiter=';')
168
169 #And finally, calculate the PMI for each mode twice
170 #(once regular PMI, once for the network based PMI as sensitivity)
171 pmi = np.zeros((len(pmiTT), 8), dtype = float)
172 pmi[:,0] = pmiD[:,0] / (pmiTT[:,0] / 60)
173 pmi[:,1] = pmiD[:,1] / (pmiTT[:,1] / 60)
174 pmi[:,2] = pmiD[:,0] / (pmiTT[:,2] / 60)
175 pmi[:,3] = pmiD[:,0] / (pmiTT[:,3] / 60)
176
177 pmi[:,4] = pmiD[:,1] / (pmiTT[:,0] / 60)
178 pmi[:,5] = pmiD[:,1] / (pmiTT[:,1] / 60)
179 pmi[:,6] = pmiD[:,1] / (pmiTT[:,2] / 60)
180 pmi[:,7] = pmiD[:,1] / (pmiTT[:,3] / 60)
181
182 np.savetxt(os.path.join(savedir, 'PMI-2.txt'), pmi, delimiter=';')

```



## D.4 Methodology

```

1 # IMPLEMENTATION OF THE DEVELOPED METHODOLOGY
2 # -----
3 #
4 # Note: before running this code, the Data Preparation code must be run
5 #
6 # The goal of this script is to calculate all indicators for all
7 # alternatives
8 # and scenarios tested. This script is structured according to the
9 # methodology
10 # and steps defined in Chapter 4.
11 #
12 # 0. Define variables, define alternatives to test for the
13 # sensitivity
14 # 1. Identify population groups and estimate the group sizes
15 # 2. Calculate Accessibility for each identified group
16 # 2A. What is the accessibility to opportunity types per mode?
17 # 2B. What is the accessibility to opportunity categories per
18 # mode?
19 # 2C. What is the accessibility per mode?
20 # 3. Calculate Mobility and Thresholds
21 # 4. Calculate the Accessibility Fairness Index and ranks for the
22 # groups
23 # -----
24 # Step 0
25 #
26 # Importing the relevant packages, setting directories
27 # and defining the various alternatives for the sensitivity analysis
28 #
29 import os, time, csv, math, scipy.stats
30 import numpy as np
31 #
32 # Set directories for this file and for the two kinds of input files
33 # (source files for zonal and opportunity data, skims for the skims)
34 currentdir = os.path.dirname(os.path.realpath(__file__))
35 sourcedir = os.path.join(currentdir, "Source_Files")
36 skimdir = os.path.join(currentdir, "Skims")
37 #
38 # The following options are defined for the sensitivity analysis:
39 #
40 #3 selections of opportunities: 100%, 75% and 50% of opportunities
41 altOPS = [100,75,50]
42 #
43 #3 skim variants (1 null variant, 2 variants made in OT)
44 altSKIM = [0,1,2]
45 #
46 #2 methods of calculating accessibility
47 altACC = ['Cumulative', 'Gaussian']
48 #
49 #3 threshold values (100%, 50% of car accessibility)
50 altTHR = [100,50]
51 #
52 #2 different inputs for the distance for calculating PMI
53 altPMI = ['Euclidean', 'Network']
54 #
55 #3 Cutoff values
56 altCUT = [20,30,45]
57 #
58 # Each alternative has one of the options for each of the six alt__
59 # values.
60 # So, an alternative using an altCUT of 30 minutes instead of the
61 # default 20
62 # is [0,0,0,0,0,1]. Below are all 24 alternatives considered:
63 alternatives = [[0,0,0,0,0,0], [0,0,0,0,0,1], [0,0,0,0,0,2],

```

```

58         [0,0,0,1,0,0], [0,0,0,1,0,1], [0,0,0,1,0,2],
59         [0,0,1,0,0,0], [0,0,1,0,0,1], [0,0,1,0,0,2],
60         [0,0,1,1,0,0], [0,0,1,1,0,1], [0,0,1,1,0,2],
61
62         [1,0,0,0,0,0], [1,0,1,0,0,0],
63         [2,0,0,0,0,0], [2,0,1,0,0,0],
64         [0,1,0,0,0,0], [0,1,1,0,0,0],
65         [0,2,0,0,0,0], [0,2,1,0,0,0],
66         [0,0,1,0,1,0], [0,0,0,0,1,0]]
67
68 #Translating these 0-1-2 values into a list with words depicting the
69 alternative:
69 def AlternativesNumToVal( alternative ):
70     return [altOPS[ alternative [0]], altSKIM[ alternative [1]],
71            altACC[ alternative [2]], altTHR[ alternative [3]],
72            altPMI[ alternative [4]], altCUT[ alternative [5]]]
73
74     alternativestext = [AlternativesNumToVal(i) for i in alternatives]
75
76
77 #
78 # Step 1
79 #
80 # Define the differentiated groups and estimate their sizes.
81 # Considered are:
82 # - 1192 zones
83 # - 4 mode-time combinations (Car-Peak, Car-Offpeak, PT and Bicycling
84 )
85 #Firstly, create a list of all zones considered and store the number of
86 zones
87 zonesArray = np.genfromtxt(os.path.join(sourcedir, "StudyArea.csv"),
88                             delimiter=',', skip_header=1)
89 numZones = len(zonesArray)
90
91 #Define the considered modes and store the number of modes
92 modenames = [ 'CarOffPeak', 'CarPeak', 'PT', 'Bike' ]
93 numModers = len(modenames)
94
95 #Estimate the amount of people using each mode with formula 4.2 - 4.6.
96 #Create residentsArray to store this information in.
97 residentsArray = np.zeros((numZones, 4), dtype = float)
98 zonalData = np.genfromtxt(os.path.join(currentdir, "Source_Files", "
99     ZonalData.txt"),
100                             dtype=float, skip_header=1)
101 residentsArray[:,0] = zonalData[:,2]
102
103 #Calculate percentage of car-dependant residents, overwriting the
104 second column:
105 zonalData[:,1] = (zonalData[:,1]/3) + .2
106
107 #Calculate number of mode-dependant residents per zone
108 residentsArray[:,1] = zonalData[:,1] * zonalData[:,2]
109 residentsArray[:,2] = (1 - zonalData[:,1]) * .65 * zonalData[:,2]
110 residentsArray[:,3] = (1 - zonalData[:,1]) * .35 * zonalData[:,2]
111
112 print( 'Done_with_Step_2' )
113
114 #
115 # Step 2 - Calculate Accessibility
116 #
117 # For each alternative, calculate the accessibility indicators.
118 # First, grab OD info (2A). Then, aggregate opportunities per zone (2
119 B).
120 # Then, calculate accessibility (2C).
121
122 loopcounter = 0

```

```

119 starttime = time.time()
120 for currentalt in alternativestext:
121
122     #
123
-----
124     # Step 2A: Create a file with the results
125     # and create a three dimensional OD Matrix with travel times per
        mode
126
127     print('Loop_' + str(loopcounter+1) + '/22.' + 'Alternative_'
        considered:_)
128         + str(currentalt) + '_' + str(alternatives[loopcounter]) + '
        )')
129     if loopcounter > 0:
130         print('ETA:_' + time.ctime(starttime+(1/((loopcounter+1)/22)*
131             (time.time()-starttime)))
        )
132
133     #To start saving results ,
134     #define the Results matrix and fill the first columns:
135     results = np.zeros((numZones, 210), dtype = float)
136     results[:,0] = int(''.join(map(str, alternatives[loopcounter])))#
        [1,2,3]->123
137     results[:,1] = zonesArray
138
139     #Also start writing headers for the Results matrix
140     headers = ['ALT', 'ZONE']
141
142     #Import OD Matrices:
143     reducedskimfiles = ['skimtts_2015_1-2-1-101-2-1.csv',
144         'skimtts_2015_1-2-3-103-2-1.csv',
145         'skimtts_2015_1-4-1-3-2-1.csv',
146         'skimtts_2015_1-5-1-3-1-20.csv']
147     folder = '2015_var_0'
148
149     #If the current alternative concerns model changes, change folder
150     #and update filenames to match filenames in those var folders
151     if currentalt[1] == 1:
152         folder = '2015_var_1'
153         reducedskimfiles = [(r[:13]+'var1'+r[13:]) for r in
            reducedskimfiles]
154     elif currentalt[1] == 2:
155         folder = '2015_var_2'
156         reducedskimfiles = [(r[:13]+'var2'+r[13:]) for r in
            reducedskimfiles]
157
158     #Create and fill a 3 dimensional matrix with dimensions [O,D,Mode]
159     counter = 0
160     ODMatrix = np.zeros((numZones,numZones,4), float)
161     for skim in reducedskimfiles:
162         file = csv.reader(open(os.path.join(skimdir, folder, skim)),
            delimiter=',')
163         for row in file:
164             if row:
165                 i_index = np.where(zonesArray == int(row[0]))[0][0]
166                 j_index = np.where(zonesArray == int(row[1]))[0][0]
167                 ODMatrix[i_index, j_index, counter] = row[2]
168             else:
169                 pass
170             counter += 1
171             del file
172
173     #Hotfix for a trafic model error.
174     #(incorrect travel times to/from zone 63-67 are replaced with a
        nearby zone)
175     for i in range(63,67):

```

```

176     for j in range(1192):
177         for mode in range(3):
178             ODMatrix[i][j][mode] = ODMatrix[902][j][mode]
179             ODMatrix[j][i][mode] = ODMatrix[902][j][mode]
180
181     #

```

---

```

182     # Step 2B: Calculate the amount of opportunities in each zone
183     # for each of the 19 opportunity types.
184
185     #Create an array from the input Opportunities file.
186     inputdir = os.path.join(currentdir, "Source_Files", "Opportunities.
187     csv")
188     tempArray = np.genfromtxt(inputdir, delimiter=';', usecols=(0,2),
189     dtype=int, skip_header=1)
190
191     #Depending on the alternative, drop every second or every fourth
192     row:
193     indices = list(range(len(tempArray)))
194     if currentalt[0] == 50:
195         tempArray = np.delete(tempArray, indices[::2], axis = 0)
196     elif currentalt[0] == 75:
197         tempArray = np.delete(tempArray, indices[::4], axis = 0)
198
199     #Create an array with the number of opportunities in each zone of
200     each type
201     opportunitytypes =
202     [11,12,13,21,22,23,24,31,32,41,42,43,44,51,52,61,62,63,71]
203     opportunitiesArray = np.zeros((numZones, len(opportunitytypes)+1), np
204     .float)
205     opportunitiesArray[:,0] = zonesArray
206
207     #Go through the Opportunities CSV array, and count for each zone
208     and type
209     #the amount of opportunities. Store this in the opportunities array
210     for opportunity in range(len(tempArray[-1,0])):
211         #Find the correct column for this opportunity type:
212         category = tempArray[opportunity,0]
213         j = opportunitytypes.index(category)+1
214         #Find the correct row for this centroid no:
215         i = np.where(opportunitiesArray[:,0] == tempArray[opportunity
216         ,1])
217         #Increment the correct row + column with 1
218         opportunitiesArray[i,j] += 1
219
220     #

```

---

```

221     # Step 2C: Calculate accessibility for each zone
222     #
223
224     if currentalt[2] == 'Gaussian':
225         #The Gaussian accessibility formula requires a weighing
226         #of each opportunity using formula 3.8. The weight is the
227         fraction of
228         #the total amount of opportunities. So first, sum the
229         opportunitiesArray
230         #columns to get the amount of total opportunities of a type
231         totalopportunities = opportunitiesArray[:,1:].sum(axis=0)
232
233         #Then, calculate elementwise: 1 / (previous matrix /totalops)
234         weights = opportunitiesArray[:,1:]*(1/totalopportunities)
235
236         #Calculate the 't*' which is the assumed half the cutoff value
237         tstar = currentalt[5] / 2
238
239     #Only accessibility to zones with an opportunity in them matter.

```

```

231 #Create thus an index with zones that have ops in them
232 index = []
233 for optype in range(1,20):
234     index.append(np.where(opportunitiesArray[:,optype] > 0))
235
236 #Due to the hospital in Spijkenisse being large and just outside of
237     study area,
238 #add it manually to index:
239 index[1] = tuple([np.append(index[1], 261)])
240
241 #Then, calculate Accessibility per zone, per mode, and per type
242 #(summed over j by incrementing over j in the deepest loop level)
243
244 #Create matrix and fill it with the accessibility measure.
245 accessibilityMatrix = np.zeros((numZones,4,len(opportunitytypes)),
246                               dtype=float)
247
248 def accessibility(tt, optype, j, mode):
249     if currentalt[2] == 'Cumulative' and tt <= currentalt[5]:
250         #Cumulative formulation: if the destination zone is within
251             reach,
252         #return the total # of opportunities
253         return opportunitiesArray[j,optype+1]
254     elif currentalt[2] == 'Gaussian':
255         #Gaussian formulation: return distance-decayed and weighed
256             opportunities.
257         return math.exp(-(tt/tstar)**2/2) * weights[j,optype]
258     else:
259         return 0
260
261 #Calculate accessibility from i, to all j, with all modes, for all
262     optypes,
263 #and sum over j if j is in the index (so, only over zones with ops
264     in them).
265 for i in range(numZones):
266     for j in range(numZones):
267         for mode in range(4):
268             for optype in range(len(opportunitytypes)):
269                 if j in index[optype][0]:
270                     tt = ODMatrix[i,j,mode]
271                     accessibilityMatrix[i,mode,optype] +=
272                         accessibility(tt, optype, j, mode)
273
274 print('Calculated_accessibility_for_zones_1_thru_' + str(i))
275
276 #Save the accessibility per zone per opportunity type to the
277     Results matrix
278 results[:,2:78] = accessibilityMatrix.reshape(numZones,76)
279
280 #Add the appropriate headers to the growing header list
281 for mode in modenames:
282     for optype in range(len(opportunitytypes)):
283         headers.append(mode + str(opportunitytypes[optype]))
284
285 #Calculate average / sum accessibility per opportunity type
286 #(e.g. Health instead of hospitals). Columns to average:
287 columns1 =
288     [[0,1,2],[3,4,5,6],[7,8],[9,10,11,12],[13,14],[15,16,17],[18]]
289 counter = 78
290 for mode in range(4):
291     for cols in columns1:
292         value = np.zeros(numZones)
293         for j in cols:
294             actualcol = mode*19 + j
295             value += results[:,actualcol+2]
296
297 #With Gaussian, consider average accessibility; with
298     Cumulative,

```

```

290     #consider total sum of reachable opportunities
291     if currentalt[2] == 'Gaussian':
292         results[:,counter] = value / len(cols)
293     elif currentalt[2] == 'Cumulative':
294         results[:,counter] = value
295
296     counter += 1
297
298     #

```

---

```

299     # Step 2D: Calculate averages for each zone
300     #
301
302     #Then, take further averages for the accessibility per mode
303     #These are the average accessibilities per mode
304     tempArray = results[:,78:106]
305
306     if currentalt[2] == 'Cumulative':
307         #Convert cumulative sums to percentages of the total
308         #Find total ops for each of the 7 categories
309         totalOps = opportunitiesArray[:,1:].sum(axis=0)
310         totalOps2 = np.zeros((7), dtype = int)
311         counter=0
312         for cols in columns1:
313             tempsum = 0
314             for j in cols:
315                 tempsum += totalOps[j]
316             totalOps2[counter] = tempsum
317             counter += 1
318
319         if currentalt[2] != 100:
320             totalOps2 = np.array([101,289,410,103,93,48,265483])
321
322         #Divide temparray by the total amount of opportunities
323         tempArray = tempArray / np.hstack((totalOps2, totalOps2,
324                                           totalOps2, totalOps2))
325
326     #Taking into account the proposed hierarchy of activity types Work,
327     #and Leisure, average the normalised accessibilities for each mode
328     results[:,106] = (tempArray[:,0:3].sum(axis=1)/3 +
329                    tempArray[:,3:6].sum(axis=1)/3 + tempArray[:,6])/3
330     results[:,107] = (tempArray[:,7:10].sum(axis=1)/3 +
331                    tempArray[:,10:13].sum(axis=1)/3 + tempArray[:,13])/3
332     results[:,108] = (tempArray[:,14:17].sum(axis=1)/3 +
333                    tempArray[:,17:20].sum(axis=1)/3 + tempArray[:,20])/3
334     results[:,109] = (tempArray[:,21:24].sum(axis=1)/3 +
335                    tempArray[:,24:27].sum(axis=1)/3 + tempArray[:,27])/3
336
337     #Add headers for these averages
338     headers.extend([(mode + str(col+1)) for mode in modenames for col
339                    in range(len(columns1))])
340     headers.extend([(mode+'Avg') for mode in modenames])
341
342     #

```

---

```

342     # Step 3 - Calculate Mobility and Thresholds
343
344     #Because PMI is not alternative-dependent, this has been added to
345     the
346     #data preparation script. Here, import the results:
347     pmdir = os.path.join(skimdir, folder, "PMI.txt")
348     pmi = np.genfromtxt(pmdir, delimiter=',', dtype=float)
349

```

```

350 #Store PMI in results array
351 if currentalt[4] == "Network":
352     results[:,110:114] = pmi[:,0:4]
353 elif currentalt[4] == "Euclidean":
354     results[:,110:114] = pmi[:,4:8]
355
356 #For AFI, the number of people is important. Save this to the
      results too.
357 results[:,114:118] = residentsArray
358
359 #Extend headers accordingly
360 headers.extend([( 'PMI_' + mode + currentalt[4][:5]) for mode in
      modenames])
361 headers.append('TotalPeople')
362 headers.extend([(mode[:3] + 'People') for mode in modenames[1:4]])
363
364 #Then, calculate the accessibility thresholds
365 if currentalt[2] == 'Cumulative':
366     #Calculate thresholds per opportunity type based on the car
      accessibility
367     #(e.g. how many schools can you reach by car on average)
368     accthresholds = np.average(results[:,21:40], axis=0)
369     #Set the correct row offset, this will be used in line 385
370     counter = 2
371 elif currentalt[2] == 'Gaussian':
372     accthresholds = np.average(results[:,85:92], axis=0)
373     counter = 78
374
375 #Calculate mobility threshold based on the mean PMI value of car
      accessibility
376 mobthreshold = np.mean(results[:,110])
377
378 #

```

---

```

379 # Step 4 - Calculate AFI, Contribution and Rank
380 #
381
382 modes = [115,115,116,117] #refers to the Results column with no.
      of people
383 for mode in modes:
384     for thr in accthresholds:
385         tp = thr*(currentalt[3]/100) #threshold * (100%/50%)
386
387         #First, find the rows for each mode where the thresholds
      are
388         #not met (so, where accessibility deficiencies occur)
389         if currentalt[4] == "Network":
390             deficiencies = np.where((tp > results[:,counter]) &
      (pmi[:,mode-114] < mobthreshold
      ))
391
392         elif currentalt[4] == "Euclidean":
393             deficiencies = np.where((tp > results[:,counter]) &
      (pmi[:,mode-110] < mobthreshold
      ))
394
395
396 #Then, calculate fairness from column 118 onwards
397 if currentalt[2] == 'Cumulative':
398     #Acc. in col 2 corresponds to AFI in col 118 (+116)
399     displacement = 116
400 elif currentalt[2] == 'Gaussian':
401     #Acc. in col 78 corresponds to AFI in col 118 (+40)
402     displacement = 40
403 results[deficiencies, counter+displacement] = (((tp-results[
      deficiencies, counter])/
404     tp)**2)*results[deficiencies, mode]
405
406 counter += 1

```

```

407
408 #Having calculated the AFI, the loop below does three things:
409 # Sum over the seven optypes;
410 # Calculate Contribution;
411 # Calculate Rank
412 for mode in range(4):
413     if currentalt[2] == 'Cumulative':
414
415         #Sum the deficiencies per mode, store in first 4 columns
416         results[:,198+mode] = np.sum(results[:,(118+19*mode)
417                                     : (137+19*mode)],
418                                     axis=1)
419         #Contribution pts stored in columns 149:152
420         results[:,202+mode] = (results[:,198+mode] /
421                                np.sum(results[:,198+mode]+.01)) *
422                                100
423         #Ranking stored in columns 153:157.
424         #Note that ranking 1 represents the least unfairness.
425         results[:,206+mode] = scipy.stats.rankdata(results[:,198+
426                                                     mode],
427                                                     method="dense")
428
429     elif currentalt[2] == 'Gaussian':
430
431         #Sum the deficiencies per mode, store in first 4 columns
432         results[:,146+mode] = np.sum(results[:,(118+7*mode):(125+7*
433                                     mode)],
434                                     axis=1)
435         #Contribution pts stored in columns 149:152
436         results[:,150+mode] = results[:,146+mode] /
437                                np.sum(results[:,146+mode]+.01) *
438                                100
439         #Ranking stored in columns 153:157
440         results[:,154+mode] = scipy.stats.rankdata(results[:,146+
441                                                     mode],
442                                                     method="dense")
443
444     #Extend headers for step 4 accordingly
445     headers.extend([( 'AFI_' + mode + str(t)) for mode in modenames
446                    for t in range(len(accthresholds))])
447     prefixes = [ 'SumAFI_', 'Contrib_', 'Rank_' ]
448     headers.extend([(pre+mode) for pre in prefixes for mode in
449                    modenames])
450     headers.extend([' ' for i in range(len(results[1,:]) - len(headers))
451                    ])
452
453     #Save the result to txt file
454     np.savetxt('Results/resultsF_alt' + str(results[0,0]) + '.csv',
455               results,
456               delimiter=',', header = ','.join(headers))
457
458     loopcounter += 1

```

## D.5 Creating graphs

```

1 #Visualization Graphs
2
3 import matplotlib.pyplot as plt
4 import numpy as np
5 import os
6
7
8 #Set directories for this file, list files
9 currentdir = os.path.dirname(os.path.realpath(__file__))
10 files = [f for f in os.listdir(os.path.join(currentdir, 'Results'))]
11

```



```

12 #This script creates graphs for all files in the Results folder.
13 for currentfile in files:
14     results = np.genfromtxt((os.path.join(currentdir, 'Results',
15                                         currentfile)),
16                             delimiter=';', skip_header=1)
17     print(results)
18     #Correct for Gaussian / Cumulative
19     if currentfile[-10] == '1':
20         print('PINGG')
21         offset = 0
22         norm = 1
23     else:
24         offset = 52
25         norm = 1
26
27     #Colorblind Palette:
28     colbl = ['b', (0.9,0.6,0.0), (0.35,0.7,0.9), (0.0,0.6,0.5),
29             (0.95,0.9,0.25), (0.0,0.45,0.7), (0.6,0.0,0.0),
30             (0.8,0.6,0.7)]
31
32     #E69900
33     #009980
34     #0073b3
35     #990000
36
37 # #Plot amount of people per mode vs PMI
38 fig = plt.figure(figsize = (10,8))
39 ax1 = fig.add_subplot(111)
40 ax1.scatter(results[results[:,114] != 0][:,110],
41             results[results[:,114] != 0][:,146+offset], s=1, c=
42             colbl[6],
43             marker=" ", label='Car')
44 ax1.scatter(results[results[:,114] != 0][:,111],
45             results[results[:,114] != 0][:,147+offset], s=1, c=
46             colbl[5],
47             marker=" ", label='Car_Peak')
48 ax1.scatter(results[results[:,114] != 0][:,112],
49             results[results[:,114] != 0][:,148+offset], s=1, c=
50             colbl[3],
51             marker="o", label='PT')
52 ax1.scatter(results[results[:,114] != 0][:,113],
53             results[results[:,114] != 0][:,149+offset], s=1, c=
54             colbl[1],
55             marker="o", label='Bike')
56 plt.legend(loc='lower_right')
57 ax1.set_ylim([0,20000])
58 ax1.axvline(np.average(results[:,110]), c='k')
59
60 plt.xlabel('Potential_Mobility_Index_in_km/h', fontsize=14)
61 plt.ylabel('Sum_of_Accessibility_Unfairness_to_All_Opportunity_
62           Types', fontsize=14)
63
64 plt.savefig(os.path.join(currentdir,
65                           'Graphs',
66                           ('SumUnfairvsPMI'+str(results[0,0])+'.png'
67                           )),
68             dpi=300, bbox_inches='tight')
69 plt.show()
70
71 #Plot Accessibility vs PMI sized to population
72 fig2 = plt.figure(figsize = (10,8))
73 ax2 = fig2.add_subplot(111)
74 ax2.scatter(results[results[:,114] != 0][:,111],
75             results[results[:,114] != 0][:,107]/norm, s=(results
76             [:,114]/100),
77             c=colbl[6], marker="o", label='Car_Peak')

```

```

72     ax2.scatter(results[results[:,114] != 0][:,110],
73                results[results[:,114] != 0][:,106]/norm, s=(results
74               [:,114]/100),
75                c=colbl[5], marker="o", label='Car')
76     ax2.scatter(results[results[:,114] != 0][:,112],
77                results[results[:,114] != 0][:,108]/norm, s=(results
78               [:,114]/100),
79                c=colbl[3], marker="o", label='PT')
80     ax2.scatter(results[results[:,114] != 0][:,113],
81                results[results[:,114] != 0][:,109]/norm, s=(results
82               [:,114]/100),
83                c=colbl[1], marker="o", label='Bike')
84     ax2.axvline(np.average(results[:,110]), c='k')
85     ax2.axhline(np.average(results[:,106])*0.5/norm, c='k', linestyle
86                = 'dotted')
87     ax2.axhline(np.average(results[:,106])/norm, c='k')
88     ax2.set_ylim([0,1])
89     plt.xlabel('Potential_Mobility_Index_in_km/h', fontsize=14)
90     plt.ylabel('Accessibility_Indicator', fontsize=14)
91     plt.legend(loc='lower_right');
92     plt.savefig(os.path.join(currentdir,
93                             'Graphs',
94                             ('PMIvsAlpop'+str(results[0,0])+'.png')),
95                dpi=300, bbox_inches='tight')
96
97 #Plot Accessibility vs AFI
98     fig3 = plt.figure(figsize = (10,8))
99     ax3 = fig3.add_subplot(111)
100
101     ax3.scatter(results[results[:,114] != 0][:,146+offset],
102                results[results[:,114] != 0][:,106]/norm, s=(results
103               [:,114]/100),
104                c=colbl[5], marker="o", label='Car')
105     ax3.scatter(results[results[:,114] != 0][:,147+offset],
106                results[results[:,114] != 0][:,107]/norm, s=(results
107               [:,114]/100),
108                c=colbl[6], marker="o", label='Car_Peak')
109     ax3.scatter(results[results[:,114] != 0][:,148+offset],
110                results[results[:,114] != 0][:,108]/norm, s=(results
111               [:,114]/100),
112                c=colbl[3], marker="o", label='PT')
113     ax3.scatter(results[results[:,114] != 0][:,149+offset],
114                results[results[:,114] != 0][:,109]/norm, s=(results
115               [:,114]/100),
116                c=colbl[1], marker="o", label='Bike')
117     ax3.axvline(np.average(results[:,198]), c='k')
118     ax3.axhline(np.average(results[:,106])*0.5/norm, c='k', linestyle
119                = 'dotted')
120     ax3.axhline(np.average(results[:,106])/norm, c='k')
121     ax3.set_ylim([0,1])
122     ax3.set_xlim([0,12000])
123     plt.xlabel('Sum_of_Accessibility_Unfairness_to_All_Opportunity_
124                Types', fontsize=14)
125     plt.ylabel('Accessibility_Indicator', fontsize=14)
126     plt.legend(loc='lower_right');
127     plt.savefig(os.path.join(currentdir,
128                             'Graphs',
129                             ('AFIvsAI'+str(results[0,0])+'.png')),
130                dpi=300, bbox_inches='tight')
131
132 #Plot Accessibility vs PMI sized to AFI
133     fig4 = plt.figure(figsize = (10,8))
134     ax4 = fig4.add_subplot(111)

```

```

130     ax4.scatter(results[results[:,114] != 0][:,110],
131                results[results[:,114] != 0][:,106]/norm,
132                s=(results[results[:,114] != 0][:,146+offset]/100),
133                c=colbl[5], marker="o", label='Car')
134     ax4.scatter(results[results[:,114] != 0][:,111],
135                results[results[:,114] != 0][:,107]/norm,
136                s=(results[results[:,114] != 0][:,147+offset]/100),
137                c=colbl[6], marker="o", label='Car_Peak')
138     ax4.scatter(results[results[:,114] != 0][:,112],
139                results[results[:,114] != 0][:,108]/norm,
140                s=(results[results[:,114] != 0][:,148+offset]/100),
141                c=colbl[3], marker="o", label='PT')
142     ax4.scatter(results[results[:,114] != 0][:,113],
143                results[results[:,114] != 0][:,109]/norm,
144                s=(results[results[:,114] != 0][:,149+offset]/100),
145                c=colbl[1], marker="o", label='Bike')
146
147     ax4.axvline(np.average(results[:,110]), c='k')
148     ax4.axhline(np.average(results[:,106])*0.5/norm, c='k', linestyle
149                = 'dotted')
149     ax4.axhline(np.average(results[:,106])/norm, c='k')
150     ax4.set_ylim([0,1])
151     plt.ylabel('Accessibility_Indicator', fontsize=14)
152     plt.xlabel('Potential_Mobility_Index_in_km/h', fontsize=14)
153     plt.legend(loc='lower_right');
154     plt.savefig(os.path.join(currentdir,
155                               'Graphs',
156                               ('PMLvsAI'+str(results[0,0])+'.png')),
157                dpi=300, bbox_inches='tight')
158
159 #Plot Accessibility vs AFI
160     fig5 = plt.figure(figsize = (10,8))
161     ax5 = fig5.add_subplot(111)
162     ax5.scatter(results[results[:,114] != 0][:,146+offset],
163                results[results[:,114] != 0][:,106]/norm,
164                s=(results[:,114]/100),
165                c=colbl[5], marker="o", label='Car')
166     ax5.scatter(results[results[:,114] != 0][:,147+offset],
167                results[results[:,114] != 0][:,107]/norm,
168                s=(results[:,114]/100), c=colbl[6],
169                marker="o", label='Car_Peak')
170     ax5.scatter(results[results[:,114] != 0][:,148+offset],
171                results[results[:,114] != 0][:,108]/norm,
172                s=(results[:,114]/100),
173                c=colbl[3], marker="o", label='PT')
174     ax5.scatter(results[results[:,114] != 0][:,149+offset],
175                results[results[:,114] != 0][:,109]/norm,
176                s=(results[:,114]/100),
177                c=colbl[1], marker="o", label='Bike')
178
179     ax5.axvline(np.average(results[:,198]), c='k')
180     ax5.axhline(np.average(results[:,106])*0.5/norm, c='k', linestyle
181                = 'dotted')
181     ax5.axhline(np.average(results[:,106])/norm, c='k')
182     ax5.set_ylim([0,1])
183     ax5.set_xlim([0,5000])
184     plt.xlabel('Sum_of_Accessibility_Unfairness_to_All_Opportunity_
185                Types', fontsize=14)
185     plt.ylabel('Accessibility_Indicator', fontsize=14)
186     plt.legend(loc='lower_right');
187     plt.savefig(os.path.join(currentdir,
188                               'Graphs',
189                               ('AFIvsAI6k'+str(results[0,0])+'.png')),
190                dpi=300, bbox_inches='tight')
191
192 #Plot Acc/Afi for all 18 optypes
193     fig6 = plt.figure(figsize = (6,12))
194     ax6 = fig6.add_subplot(111)

```

```

195     ax6.scatter([1 for i in range(len(results[results[:,114] !=
196         0][:,106]))],
197               results[results[:,114] != 0][:,106],
198               s = 100, alpha = 0.02,
199               c=colbl[5], marker="o", label='Car')
200     ax6.scatter([2 for i in range(len(results[results[:,114] !=
201         0][:,107]))],
202               results[results[:,114] != 0][:,107],
203               s = 100, alpha = 0.02,
204               c=colbl[6], marker="o", label='Car_Peak')
205     ax6.scatter([3 for i in range(len(results[results[:,114] !=
206         0][:,108]))],
207               results[results[:,114] != 0][:,108],
208               s = 100, alpha = 0.02,
209               c=colbl[3], marker="o", label='PT')
210     ax6.scatter([4 for i in range(len(results[results[:,114] !=
211         0][:,109]))],
212               results[results[:,114] != 0][:,109],
213               s = 100, alpha = 0.02,
214               c=colbl[1], marker="o", label='Bike')
215
216     ax6.set_xlim([0.5,5])
217     ax6.set_ylim([0,1])
218     ax6.set_xticks([1,2,3,4])
219     ax6.set_xticklabels([])
220     plt.ylabel('Accessibility_Indicator', fontsize=10)
221     lgd = plt.legend(loc='upper_right')
222     for lh in lgd.legendHandles:
223         lh.set_alpha(1)
224     plt.savefig(os.path.join(currentdir,
225                             'Graphs',
226                             ('Accessibility'+str(results[0,0])+'.png')),
227               dpi=300, bbox_inches='tight')
228
229
230
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```

---

```

227 # Line Graphs
228 #

```

---

```

229
230 #Plot the line graph depicting improvements from PT to car
231 fig3 = plt.figure(figsize = (10,8))
232 ax2 = fig3.add_subplot(111)
233
234 for row in range(len(results[:,114])):
235     x = [results[row,110], results[row,112]]
236     y = [results[row,106]/norm, results[row,108]/norm]
237     plt.plot(x,y, linewidth=2)
238
239 plt.savefig(os.path.join(currentdir,
240                             'Graphs',
241                             (str(results[0,0])+'lineimg.png')),
242           dpi=300, bbox_inches='tight')
243
244 del fig2, fig3
245
246 #

```

---

```

247
248 combination = files[2:4]
249 def DifferencePlot(combination):
250

```

```
251     results0 = np.genfromtxt(combination[0], delimiter=';', skip_header
252                             =1)
253     results1 = np.genfromtxt(combination[1], delimiter=';', skip_header
254                             =1)
255     fig4 = plt.figure(figsize = (10,8))
256     ax3 = fig4.add_subplot(111)
257     #Correct for Gaussian / Cumulative
258
259     norm0 = 1
260     norm1 = 1
261     if combination[0][-9] == '1':
262         norm0 = 88700
263     elif combination[1][-9] == '1':
264         norm1 = 88700
265
266     for row in range(len(results[:,114])):
267         x = [results1[row,112], results0[row,112]]
268         y = [results1[row,108]/norm1, results0[row,108]/norm0]
269         plt.plot(x,y, linewidth=1)
270     plt.savefig(os.path.join(currentdir,
271                             'Graphs',
272                             (str(results[0,0])+'newlineimg.png')),
273               dpi=300, bbox_inches='tight')
274
275     DifferencePlot(combination)
```