Evaluating and modifying a public transport network to achieve an equitable distribution of accessibility

A comparison of accessibility distribution principles in Amstelland-Meerlanden

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Master Thesis Report

October 2022

TU Delft

Evaluating and modifying a public transport network to achieve an equitable distribution of accessibility

A comparison of accessibility distribution principles in Amstelland-Meerlanden

by

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This research is done in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering – Transport and Planning

To be defended publicly on October 17th, 2022

Student number: 5233844

Project duration: February 2022 – October 2022

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Acknowledgements

This thesis represents the culmination of my master's studies at TU Delft. I am very grateful that I had the opportunity to follow my passion for public transport in the T&P program and the Smart Public Transport Lab, and to do internships with organizations that contribute to the excellent Dutch public transport system. Coming from the US, where public transport is not a priority, I am thankful for the opportunity to live in the Netherlands, a country where the level of investment in public transport is so high. To read about public transport innovations in a book or research paper is one thing, but to experience them as part of daily life is another level. There are several people to whom I would like to extend my sincere gratitude for helping me throughout the course of this thesis.

First, I would like to express my appreciation to the members of my thesis committee. To Oded, thank you for your assistance in helping me develop an interesting research topic and keeping me motivated with the PT master's catch-up meetings. To Niels, thank you for your guidance and detailed feedback through every stage of the research process, and for connecting me with so many opportunities, from internships to the mobility podcast to the OV magazine article. To Panchamy, I am grateful for your feedback and the sharing of your expertise in working with data. To Stefan, I appreciate the time you took to discuss the research every week and provide detailed feedback on every draft. To Machiel, thank you for your feedback and for providing an additional perspective. Finally, to Matthew, I am grateful that you were able to be a part of the committee and I enjoyed our conversations about our shared research and culture.

I would also like to extend my gratitude to the Amsterdam Transport Region and the resources that the organization was willing to invest in this research. Thank you to everyone who helped me any time I needed data or had a question, with a special shout-out to Theo for your quick responses to my countless data requests. I would also like to mention the help I received from Lourentz at Goudappel, for helping me with VENOM and answering my many questions along the way.

I would like to pass a heartfelt thank you to my family and friends. First, many thanks to my parents Svetlana and Paul, for their encouragement and support of my education and other pursuits throughout my life. I am appreciative for the friends I have made at TU Delft from all over the world, with a special thank you to Stavros and Gudrun for being such wonderful assignment partners and friends these past two years. To Cornelis, thank you for the fun times going to take the cover photo and for your help with proofreading. I am also grateful to Gondelijn, for helping me manage my stress during the most difficult times of this thesis. Finally, thank you to Michalis for your constant encouragement and patience throughout this process, and for being there to make me laugh whenever I needed it.

I hope that what I have learned from TU Delft, and the research in this thesis, will allow me to contribute to the future of public transport.

Monica van Luven
Delft, October 2022

Executive Summary

The provision of good accessibility is an important characteristic of a well-functioning public transport (PT) system. The quality of the PT system affects the ability of people to access opportunities such as employment, education, healthcare, and other basic needs, and acts as a lifeline for people who cannot use other modes of transport (Litman, 2022). The accessibility of the PT system also contributes to society through outcomes relating to urban efficiency, sustainability, public health, and social inclusion (Saif, Zefreh, & Torok, 2019). Given these outcomes, it is important that PT accessibility and its benefits are distributed in a fair, or equitable, way. To assess this, it is necessary to establish what an equitable distribution of PT accessibility means and determine how to measure, evaluate, and achieve it.

Two research gaps were identified after reviewing the public transport equity analysis literature:

1) The equity of a PT accessibility distribution depends on the distribution principle used to evaluate it. These distribution principles, also referred to as justice principles, are alternative ideas of what is considered a "fair" distribution of PT service (Bills & Walker, 2017). Existing studies in PT equity evaluation currently evaluate the fairness of PT accessibility distribution according to a single distribution principle or combination of principles. Different distribution principles have not yet been compared over the same PT service area using the same accessibility measurement.

2) There is limited understanding of how the results of equity evaluation can be used in the PT network planning process. Existing research generally performs equity evaluation ex-post and does not use the evaluation results to make network modifications. Some research (Camporeale, Caggiani, & Ottomanelli, 2019; Kim, Kho, & Kim, 2019) incorporates equality into the Transit Network Design Problem (TNDP), but this approach is currently impractical outside of research settings due to its complexity and large computational requirements. Additionally, the TNDP is currently only capable of improving equality, which is only one of many distribution principles and does not necessarily equate with equity.

Based on these research gaps, this thesis has the following three study objectives:

- Objective 1: Identification of different distribution principles and determination of their corresponding equity evaluation methods.
- Objective 2: Application of the evaluation methods to a selected case study area, and comparison of the locations and magnitude of inequities for each distribution principle.
- Objective 3: Examination of the feasibility of using the equity evaluation results for guiding network modifications, for each distribution principle.

This leads to the formulation of the main research question:

How do the outcomes of public transport equity evaluation vary for different accessibility distribution principles, and how can this inform the network planning process?

This research is performed in cooperation with the Amsterdam Transport Region using the 2014 Amstelland-Meerlanden (AML) PT network and concession as the study area. The data for this research comes from the Noordvleugel Traffic Engineering Model and Statistics Netherlands. This data consists of skim matrices containing the PT and car generalized travel costs between origin-destination pairs in the Noordvleugel area of the Netherlands, and socioeconomic data on average income, population, households, addresses, and employment.

Research methodology and results

This research consists of three main parts. First, the equity evaluation is performed according to each distribution principle, to identify zones of accessibility surplus and deficit and the magnitude of their deviations from the ideal accessibility level. Second, these results are used to try to make cost-neutral modifications to the AML PT network, to determine the feasibility of using the evaluation results to design a more equitable PT system according to each distribution principle. This is done by modifying the frequencies of bus routes, by increasing service in zones with accessibility deficits and decreasing service in zones with surpluses. Finally, the evaluation results according to each distribution principle are compared to one another.

The PT accessibility measure whose distribution is evaluated is the logsum travel cost. This measure is calculated per zone as the sum of the generalized travel costs from that zone to all other zones and represents a potential perceived cost of travel within the study area. This generalized travel cost includes both the perceived travel time and the PT fare cost. A zone in this research is a PC4 postcode, which in the AML area has an average size of 6.75 square kilometers, as this is the finest level of spatial detail available for the required data. From the distribution principles identified in the literature review, three distribution principles are selected based on their suitability for achieving the research objectives, and prior application in research and practice: egalitarianism, proportionality, and sufficientarianism.

Egalitarianism

Egalitarianism states that PT accessibility is fair if it is distributed equally and uses the Lorenz curve and Gini coefficient to determine the equality of the accessibility distribution (Martens, Bastiaanssen, & Lucas, 2019). The Lorenz curve graphically shows the distribution of PT accessibility in the population, by showing how much of the total area PT travel costs each percentile of the population experiences. The Gini coefficient is an indicator between 0 and 1 that gauges the level of inequality in the PT accessibility distribution. When the AML area is evaluated according to the principle of egalitarianism, it is found that the PT accessibility distribution is almost perfectly equal. This could be for several reasons, the first of which is that the logsum travel cost is used as the accessibility metric instead of the supply of PT service. Additionally, this could be the result of the Dutch approach to PT planning, which has historically aimed to provide at least a satisfactory level of PT service throughout the country, even in low population areas (Alonso González, Jonkeren, & Wortelboer-van Donselaar, 2022).

In this analysis, the “ideal” accessibility distribution according to egalitarianism means that every zone has the same logsum travel costs. From the equity evaluation results, it is determined which zones have unequal logsum travel costs and the magnitude of their surplus or deficit. It is then attempted to make frequency modifications to make the travel costs for each zone more equal. However, the objective of a more equal network was not achieved. This is partly because the network is already very equal, but also because of the circular calculations present in the evaluation method. The ideal accessibility for every zone in the study area is calculated as the total logsum travel costs in the area divided by the number of zones. Because the total area logsum travel costs change every time a frequency is changed, the ideal accessibility per zone also changes. This circular calculation alters which zones are considered excessive or deficient in accessibility, making it difficult to target additional frequency adjustments. This leads to the conclusion that this method is suitable for network evaluation and comparison, but not for informing network modifications.

Proportionality

Proportionality states that the distribution of PT accessibility should be based on relevant land use and/or demographic factors and uses a multiple regression model to calculate a target accessibility based on these factors (Rubensson, Susilo, & Cats, 2020). From the available data, it is found that a multiple regression model based on population density and employment density provides the best estimation for target accessibility according to the existing accessibility distribution. This target accessibility is then compared to the actual accessibility to identify surpluses and deficits.

Zones of inequitable accessibility distribution are identified, as well as the magnitude of their surplus and deficit. For the zones of accessibility surplus, it is found that many of these zones experience reduced logsum travel costs because they happen to be on-route between attractive destinations. It is therefore questionable whether it is desirable to reduce accessibility in these zones to be proportional with their population and employment density, as their accessibility is more a byproduct of their location than a deliberate design choice. The zones identified as having significantly deficient accessibility in the AML area are primarily rural and recreation zones. While these zones have low population and employment densities, they receive less PT service than what is considered justified according to proportionality. Many of these zones are located at the boundaries of the concession area, meaning that there could be a bias towards more centrally located zones that is not proportional to their population and employment density.

It is also attempted to apply the results of the equity evaluation according to proportionality to the network modification process. Like with the case of egalitarianism, the circular nature of this method leads to the target accessibility changing every time a frequency is modified. This is because the target accessibility is calculated from a multiple regression model that is estimated using the current accessibility distribution as the dependent variable. This shifting target accessibility makes it difficult to make frequency adjustments with the desired impact. While it is not recommended to use this method to make targeted frequency modifications, it remains useful as a network evaluation and comparison tool. Equity evaluation according to proportionality could also be used to identify zones that could potentially have high PT demand according to the selected factors but currently do not receive a high level of service.

Sufficientarianism

Sufficientarianism states that PT accessibility must meet a minimum threshold where everyone can access their basic needs (Lucas, van Wee, & Maat, 2016). It is evaluated by determining a minimum accessibility threshold and comparing it to the actual accessibility. In this analysis, the minimum level of accessibility is based on a verplaatsingtijdfactor (VF) value, or in English the displacement time factor. The VF value in this research is calculated as the ratio of the logsum travel cost for PT to the logsum travel cost for car (Projectbureau Integrale Verkeers- en Vervoerstudie, 1995). The maximum VF value is defined as the average VF value plus two standard deviations, in the absence of a previously defined standard for a sufficient VF value when the logsum travel cost is used as the accessibility measure.

For the AML case study area, the average VF value is 1.63 with a standard deviation of 0.24, leading to a maximum VF value of 2.11. This means that the level of PT accessibility in a zone is considered insufficient if the PT logsum travel cost is more than 211% of than the car logsum travel cost. The VF value for each zone is then compared to this maximum VF value to determine if the zone has a sufficient level of accessibility. For the AML area, 17 zones out of the 319 in the study area are considered to have deficient accessibility according to this threshold. Because the VF value links the travel costs of PT and car, some of the zones identified as insufficient are only classified as such due to a high level of car accessibility, despite a high level of PT accessibility. In a similar way, some zones with a low level of PT service are not considered to have an insufficient accessibility level because the travel costs for the car are also high.

The evaluation results according to sufficientarianism are then used to make frequency modifications, the objective being to improve the accessibility of the zone with the worst VF value without increasing operating resources. The objective of reducing the VF value in this target zone below the maximum VF value could not be achieved with frequency changes alone. This zone has a large accessibility deficit with a VF value of 2.4, and the impact of frequency modifications alone is limited as frequency only affects the waiting time component of travel cost. As a byproduct of the frequency modifications made for this zone, the VF values of several other insufficient zones improved, with accessibility in 5 out of 17 previously insufficient zones becoming sufficient. No zones that were previously classified as sufficient became insufficient, meaning that the equity of the network according to sufficientarianism improved overall. This demonstrates that it is technically possible to use the results of sufficientarianism equity evaluation in the network adjustment process. However, as ridership is not considered in this modification process, it cannot be immediately recommended to use these results as a primary justification for network changes.

Comparison of equity evaluation results

The geographical locations of the zones with excess and deficient accessibility according to each distribution principle can be compared to understand if there is a difference in the spatial distribution of these zones between the three principles. Figure 1 shows the locations of zones with accessibility surpluses for egalitarianism and proportionality. Sufficientarianism is excluded because this distribution principle is only concerned with achieving a minimum level of accessibility and a surplus is therefore not possible.

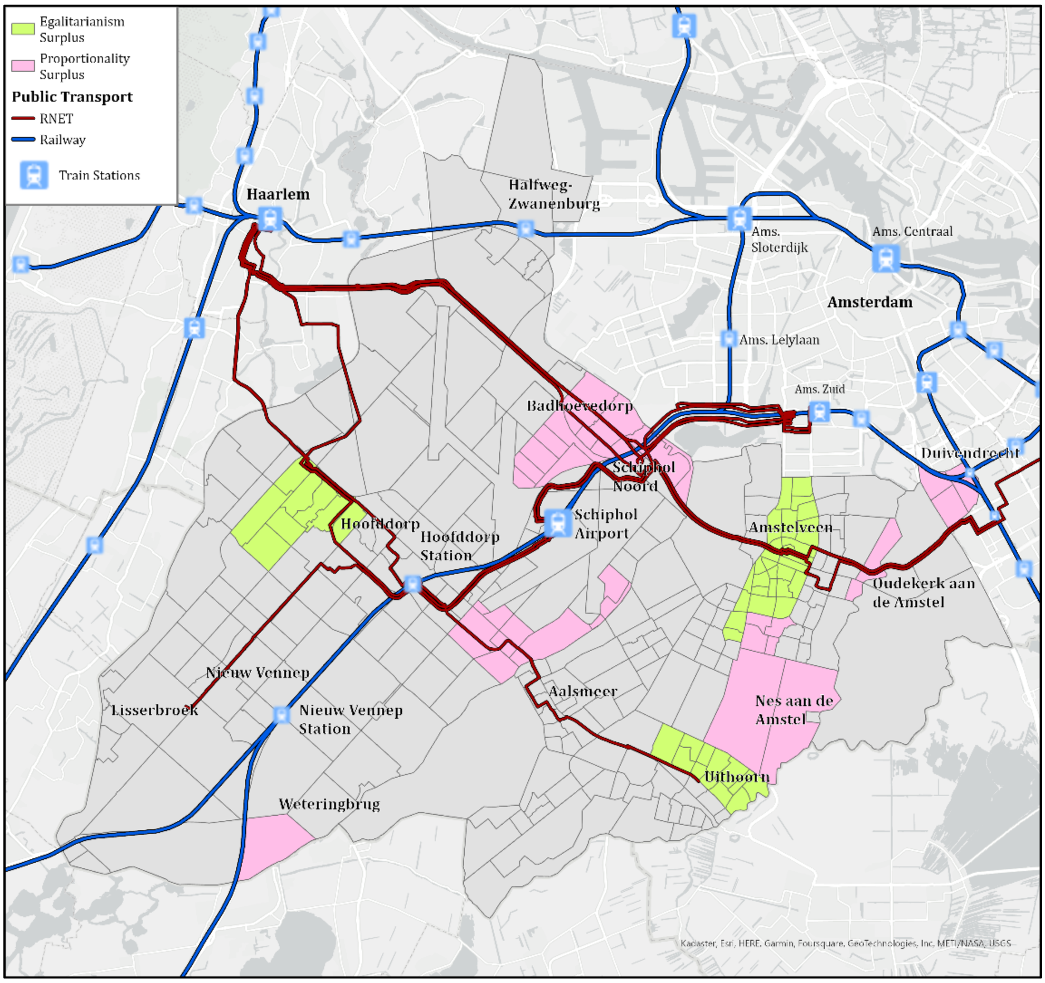

Figure 1: Comparison of zones of surplus accessibility within Amstelland-Meerlanden

As shown in the figure above, there are no zones where both egalitarianism and proportionality find an accessibility surplus. A notable pattern is that egalitarianism shows surpluses in denser zones while proportionality shows surpluses in lower density zones. This means that different area types would be affected if PT service reductions were recommended based on the locations of these surpluses. It also shows a limit of egalitarianism, as this principle could conflict with other PT objectives such as ridership.

Figure 2 compares the zones with accessibility deficits for the three distribution principles.

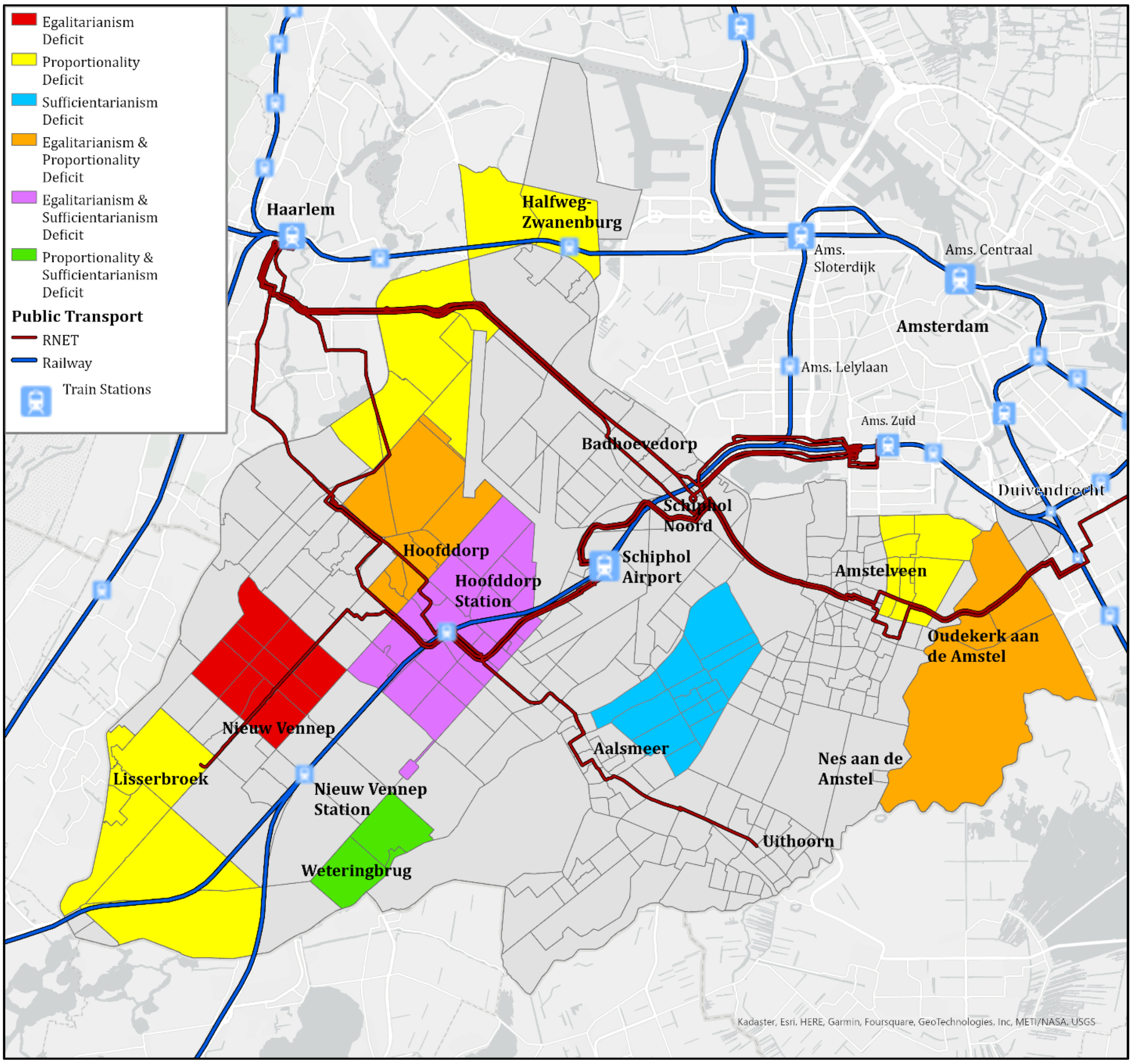

Figure 2: Comparison of zones of deficit accessibility within Amstelland-Meerlanden

Egalitarianism and proportionality have two deficient zones in common, while the egalitarianism-sufficientarianism and proportionality-sufficientarianism combinations each have one deficient zone in common. No zones are considered deficient in PT accessibility according to all three distribution principles. The majority of deficient zones according to each principle have a low density of human activity. Notably, the few zones where the density is more moderate are the zones that overlap between different principles. This indicates that there is at least some common ground between the distribution principles when identifying areas of significant PT accessibility deficit. If network planning decisions were guided by one of these principles, then it is expected that some modifications would improve equity according to more than one principle. Additionally, the peripheral areas of the concession have a disproportionate amount of PT accessibility deficit. This could indicate that peripheral areas are given less attention due to their locations at the edge of the concession area. Additional consideration should be given to these areas to keep them from being an afterthought in the planning process.

The degree of inequity also differs for the three distribution principles, as shown in Figure 3.

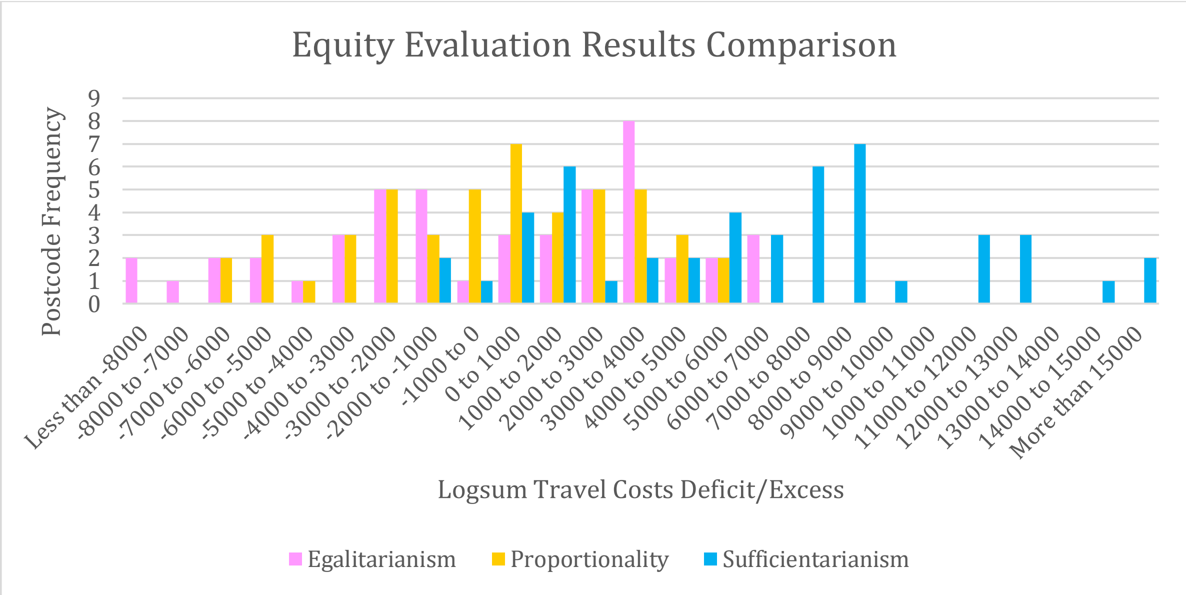

Figure 3: Comparison of accessibility surplus and deficit distribution in Amstelland-Meerlanden

In Figure 3, negative values indicate an accessibility deficit, while positive values indicate a surplus. Egalitarianism and proportionality have similar accessibility deficit/surplus distributions, while sufficientarianism is skewed, although this is dependent on the selected sufficiency threshold. A notable finding from the analysis of the surplus and deficit travel cost distribution is that the zones with the top ten deficits and surpluses are quite similar for egalitarianism and proportionality, which is expected given that the ideal accessibility per zone according to each principle is based on a linear relationship between a population-related factor and the actual accessibility.

This comparison of the equity evaluation results between the three distribution principles demonstrates that both the locations and magnitudes of accessibility surpluses and deficits differ for each principle, although there are some commonalities. This is especially relevant for the identification of PT accessibility deficits, where deficits were identified in the peripheral areas of the concession according to one distribution principle or another. This means that the borders of the concession are given less attention in the planning process, which is not warranted according to the applied distribution principles.

Of the three distribution principles studied in this research, sufficientarianism is found to be the most suitable and practical for guiding PT network modifications. However, it is not recommended to use the evaluation results independent of other inputs such as ridership data.

Scientific and practical contributions

This research provided several scientific and practical contributions. The primary contribution is the confirmation that a PT network that is equitable according to one distribution principle may not be equitable according to another. This highlights the importance of the careful consideration that is required when selecting the distribution principle to apply in equity analysis. Additionally, the feasibility of applying the equity evaluation results to PT network planning was determined for each distribution principle, which could also influence principle selection. This research is also transferrable to other study contexts, with the only potential limiting factor being the availability of data at the appropriate spatial scale.

Limitations and future research

There were some limitations present in this work that should be acknowledged. The main limitation of egalitarianism is that in the pursuit of equality, some zones receive improved accessibility at the expense of other zones, which given limited PT resources, could conflict with other PT objectives such as ridership. For proportionality, linear regression is used to calculate the target accessibility, despite non-linear regression having a better fit with the data, which could impact the identification of locations and magnitudes of accessibility surpluses and deficits. The primary limitation of the method used for the equity evaluation according to sufficientarianism is that the use of the VF value links car and PT accessibility. This can be problematic as changes in car accessibility could influence the minimum accessibility threshold for PT, which is not logical in practice. Additionally, this research did not use different VF values per area type despite various area types having different mobility goals.

A significant methodological limitation in this study is related to the selection of the logsum travel cost as the accessibility measure. This measure only considers travel within the study area and does not consider travel to and from outside areas. It is also affected by the centrality of zones within the area. Central zones will always have lower logsum travel costs than peripheral zones simply due to their physical location within the selected study area. This makes it questionable to what extent the logsum measure provides an accurate indication of the accessibility distribution in an area relative to other possible accessibility measures. There is therefore an opportunity for future research to study how the different accessibility measures affect the results of equity evaluation. For example, an location-based measure that indicates the number of opportunities reachable within a given travel time could be a more representative accessibility metric.

Additionally, the methods in this research were agnostic to existing demand patterns to avoid the influence of demand on supply determination, as this could lead to the propagation of existing inequities (Kim, Kho, & Kim, 2019). However, given the economic necessity of ridership for public transport, it would be valuable to investigate methods to consider demand in equity evaluation. Given that this research is limited to a select number of distribution principles, it would also be beneficial to develop and apply equity evaluation methods according to other (combinations of) principles. This would expand the knowledge about the applicability of other distribution principles in equity analysis. Finally, future research could investigate the impact that improved equity has on other public transport objectives, such as service effectiveness, to better understand the tradeoffs involved in equitable PT network planning.

Policy implications

This research represents an early step towards implementing more equitable public transport in the Netherlands. However, there is still more work to be done before equity can be meaningfully included in mobility policy. It is recommended for transport authorities to invest in further research to address the limitations of this study and gain a deeper understanding of the decisions required in equity evaluation, given the real-life consequences of these decisions. This will help to inform decisions regarding which distribution principle(s) are the most appropriate given the societal context of the area and how accessibility should be measured.

At the Amsterdam Transport Region, equity evaluation according to the selected distribution principle(s) could become part of PT concession requirements, both in terms of submitting the initial bid and for network changes throughout the duration of operations. Equity is currently considered in service planning by the Amsterdam Transport Region in concession documents by specifying that PT provision is required in certain area types, which is a form of sufficientarianism. This could be extended by specifying a certain level of PT accessibility that must be achieved per area type. This could result in multiple levels of equity requirements, depending on the accessibility metric used. For example, if a location-based measure is used, the requirement could state that residents of a zone of a certain area type must be able to reach a minimum number of employment opportunities, educational opportunities, etc. within a specified travel time, with different requirements for various area types. In the bid evaluation process, network designs proposed by different operators could be compared and the degree to which equity is considered could be used as an additional scoring criterion. However, adding this criterion requires careful development, and it is crucial that consistent socioeconomic and accessibility data are used.

Equity can also be considered throughout the execution of the concession agreement. It could be required that in the case of a major service change, such as rerouting or frequency modifications of a certain magnitude, an equity evaluation must be performed to determine the impact of the modifications on equity. If the service changes negatively affect the equity of the PT network, then it could be required to examine alternatives with more favorable equity impacts. This would make the balancing of equity with other PT objectives part of the planning process, with equity being considered without being the main motivation for network modifications. Considering equity both in the initial design of the network and in subsequent network changes would help ensure that PT accessibility is distributed in a fair way.

In these ways, equity can be considered throughout the entire planning process, from the conception of the network design to future PT system changes. Further investment in PT equity research and fine-tuning of evaluation methods will allow for the thoughtful and meaningful incorporation of equity in mobility policy in the Netherlands.

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Introduction

An efficient and effective transport system is a necessary component of a well-functioning society. The transport system can have a significant impact on one's ability to access economic opportunities, education, healthcare, and other services (Litman, 2022). However, efficiency and effectiveness do not guarantee that the costs and benefits of the transport system are equitably distributed. Some commonly identified costs and benefits in transport are mobility and accessibility, traffic-related pollution, traffic safety, and public health. These impacts can be unevenly distributed within the population, due to land use patterns, transport service provision, and individual or group characteristics (Martens, Bastiaanssen, & Lucas, 2019).

Accessibility, defined as the ability and convenience to reach destinations or activities, is considered the most important outcome of the transport system, capturing the interaction between land use and transport (Deboosere & El-Geneidy, 2018). Public transport (PT) has an especially important role in accessibility, as a critical mobility option for people who cannot use other modes of transport to access important destinations and basic needs. PT accessibility has been shown to be connected to outcomes relating to public health, employment, sustainability, urban efficiency, and social exclusion (Saif, Zefreh, & Torok, 2019). Therefore, it is important to consider the distribution of PT accessibility during the planning process, as this can have various significant outcomes for the quality of life of citizens.

It is not a simple task to determine the "appropriate" or "fair" distribution of accessibility, as this is a debate that has to do with the goals and ideals of society and policymakers (Rubensson, Susilo, & Cats, 2020). However, if transport planning decisions are made solely based on demand and cost efficiency, then spatial bias and existing inequities will continue to be perpetuated in society (Kim, Kho, & Kim, 2019). Therefore, it is important to evaluate the equity of PT networks and address any inequities to achieve a more equitable accessibility distribution. By better understanding how equity can be evaluated and actively considered in PT network planning, governments and public transport operators can help provide a better quality of life to citizens through fairly distributed accessibility.

1.1 Research gaps

This thesis aims to address two gaps in the existing research on PT equity analysis. The first research gap is the comparison of different distribution principles, in the context of PT accessibility. The second research gap is the demonstration of a practical proactive approach to equitable PT network planning.

1.1.1 Research gap 1: Comparison of accessibility distribution principles

Distribution principles in PT equity analysis are competing ideas that indicate if the distribution of a resource, which in this thesis is PT accessibility, is distributed in a "fair" way (Bills & Walker, 2017). There are many of these distribution principles, and there is a gap in the research relating to how the results of equity evaluation according to different distribution principles compare within the same spatial area when the same accessibility measurement is used. Most existing research only applies an equity evaluation method with a single distribution principle; however, it would be interesting to investigate how equitable the same PT network is according to various distribution principles. This thesis will compare how the identified location of areas of PT accessibility surpluses and deficits, as well as their magnitude, differs between different distribution principles. This way, it would be easier to understand the implications of the adoption of different distribution principles in equity analysis and mobility policy.

1.1.2 Research gap 2: Proactive and practical approach to equitable PT network planning

Equity analysis is the method used to assess whether a PT network distributes accessibility in a fair way and is usually performed ex-post (Camporeale, Caggiani, & Ottomanelli, 2019). The most common types of equity analysis are the use of needs-gap analysis and the Gini coefficient (Carleton & Porter, 2018). Needs-gap analysis identifies spatial mismatch between PT demand and supply, while the Gini coefficient is a single indicator that expresses the overall equality of PT service provision in an area (Carleton & Porter, 2018). These methods are helpful for evaluating existing situations and comparing different areas or socioeconomic groups, but they do not go beyond evaluating equity ex-post (Camporeale, Caggiani, & Ottomanelli, 2019). Once service gaps and surpluses are identified, it is often stated that an area with gaps needs more PT resources diverted to it (Adli, Chowdhury, & Shiftan, 2019; Aman & Smith-Colin, 2020). However, this is easier said than done, especially given the limited resources available for PT service provision, and there is often no further guidance on exactly how resources can be reallocated.

A method identified in the literature for a proactive approach to equitable PT network planning is mathematical optimization in the Transit Network Design Problem (TNDP), where an equity constraint is included for the optimization to consider equality (Camporeale, Caggiani, & Ottomanelli, 2019). However, this approach has several limitations that make it difficult to implement in practice. Large computational requirements lead to an excessive solution time even for a single iteration of a small network (Camporeale, Caggiani, & Ottomanelli, 2019), making this method currently impractical for use outside of a research setting. This approach also aims for greater equality between socioeconomic groups, spatial areas, and/or modes, but equality does not necessarily equate to equity. It also requires determination of a minimum Gini coefficient based on the existing Gini coefficient (Camporeale, Caggiani, & Ottomanelli, 2019), so the extent to which equality can be improved is limited. It is also difficult to say what is objectively considered a "good" or "bad" Gini coefficient, as this measure is only useful for comparison (Carleton & Porter, 2018). Therefore, there is a gap in the research for a practical and proactive network planning approach considering equity that lies between needs-gap analysis and the TNDP, which can go further than simply evaluating without requiring a complicated optimization process.

1.2 Research Objectives

The goal of this thesis is to understand how the results of equity evaluations performed according to different distribution principles compare in terms of the location and magnitude of PT accessibility surpluses and deficits. An additional objective is to evaluate the useability of these evaluation results in the PT network planning process. This will be done through the steps outlined in the following research objectives:

- Objective 1: selection of different distribution principles and determination of their corresponding equity evaluation methods.

- Objective 2: application of the evaluation methods to a selected case study area, and comparison of the location and magnitude of inequities for each distribution principle.
- Objective 3: examination of the feasibility of using the equity evaluation results for guiding network modifications, for each distribution principle.

1.3 Research Questions

Based on the identified research gaps and study objectives, this thesis aims to answer the following research question:

How do the outcomes of public transport equity evaluation vary for different accessibility distribution principles, and how can this inform the network planning process?

This research question is supported by the following sub-questions:

- What distribution principles can be used to define an equitable distribution of PT accessibility, and how can their use in equity evaluation be quantified?
- How does the spatial distribution and magnitude of PT accessibility deficits and excess identified in equity analysis differ based on the selected distribution principle?
- How can the results from PT equity evaluation be used in PT network planning?

1.4 Research Approach

The problem in this research was identified through a preliminary literature review to identify gaps in public transport equity research. A more extensive literature review will be performed in Chapter 2, which will define important concepts in the field of PT equity research and introduce the components of equity evaluation, as well as existing approaches to equity analysis. The various measures of accessibility will be presented to help identify the most suitable accessibility metric for this study. The case study area will also be determined from the possible concession areas of the Amsterdam Transport Region to define the spatial scope of the research. This will help to understand the state of existing research on PT equity evaluation and planning, from which a conceptual framework to achieve the research objectives can be developed.

From the distribution principles identified in the literature review, three will be selected based on the availability of evaluation methods developed in previous research. Chapter 3 will describe the methodology that will be used to evaluate a PT network according to each distribution principle. After introducing the background of the case study area in chapter 4, chapter 5 will discuss the data that is required for equity analysis according to the methods from chapter 3. In chapter 5, the equity evaluation results for each distribution principle will be analyzed individually and compared to the evaluation results for the other distribution principles, in terms of the location and magnitude of inequities. These results will then be used as the basis for making network modifications in the case study area, to explore the feasibility of the use of the results for each principle in PT network planning.

Finally, chapter 6 is devoted to summarizing the study's main findings by answering the research questions presented in chapter 1.4. The implications of this research for science and practice will be discussed, and the limitations of the study are presented. This is followed by recommendations for mobility policy and future research in this area. The research approach is outlined in Figure 4 below.

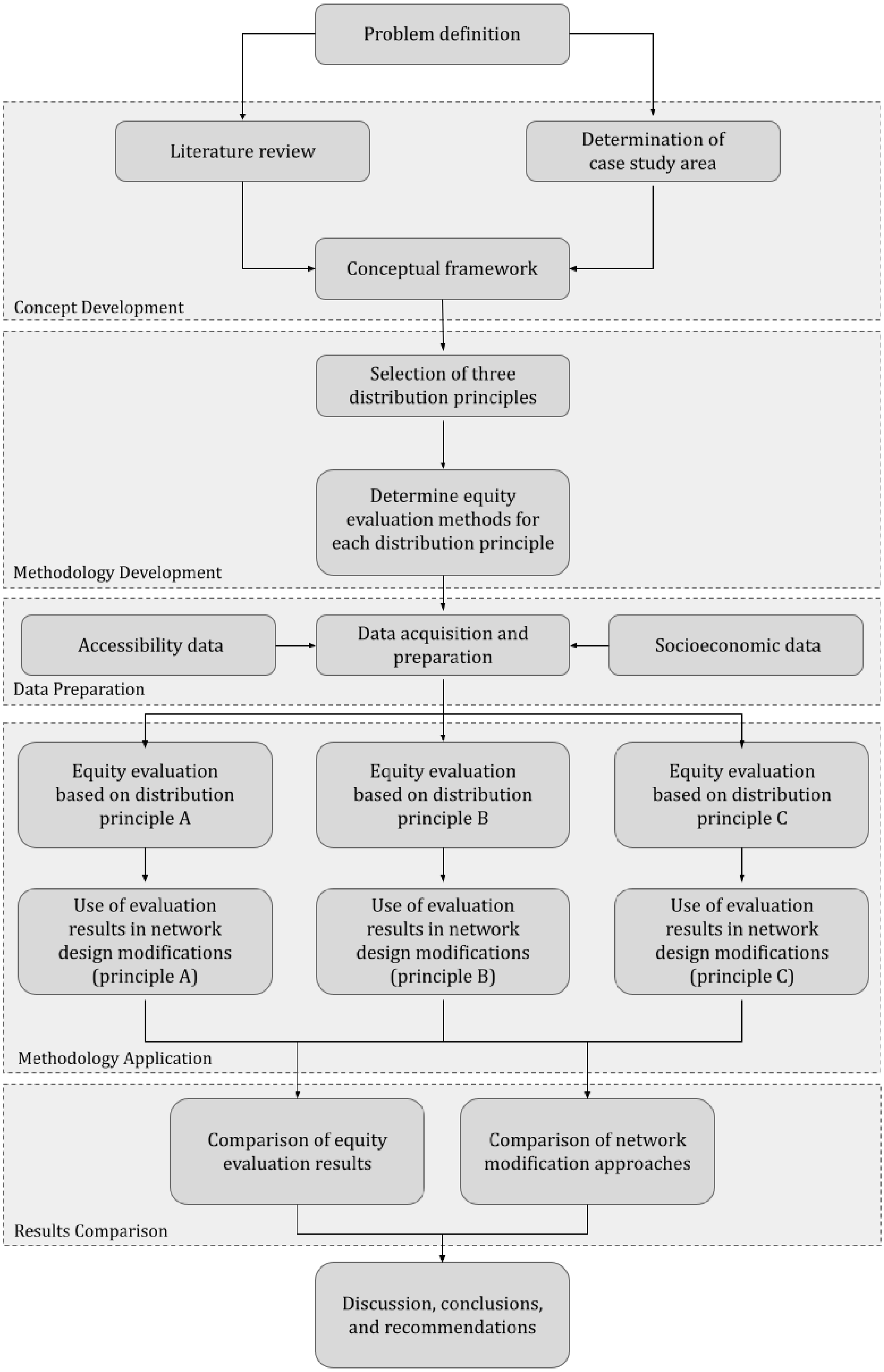


Figure 4: Research workflow

2

Literature Review

The following literature review will define some important concepts relevant to the scope of the thesis and outline the existing state of the research. First, as this thesis relates to equity in public transport (PT) network design, the concepts of equity and network design will be defined. Next, the primary components of equity analysis will be discussed, followed by the most common approaches to equity evaluation and equitable PT network planning practices. The final section of this literature review will discuss the motivations of the decisions required for the development of the methodology.

Google Scholar, ResearchGate, and ScienceDirect were used to find papers to consider for inclusion in this literature review. The following keywords and related words were used in various combinations: public transport network/system/service, accessibility, distribution, equity, justice, equality, fairness, inclusive mobility, income, disadvantage.

2.1 Defining Equity and Equality

This section clarifies the distinction between equity and equality and outlines the different types of equity identified in the literature. It is easy to confuse equity with equality, therefore it is important to clarify the distinction between the two terms.

2.1.1 Equality definition and limitations

Equality assumes that all people have the same rights and opportunities and should therefore receive equal treatment. In the context of PT, this means that everybody should receive an equal level of PT service (Carleton & Porter, 2018). The goal of equal distribution of costs and benefits in PT is problematic because it does not consider the effects of existing disparities and can therefore still be unfair, both for evaluating an existing state and assessing an intervention. In other words, social disparities within a neighborhood can lead to an equal distribution producing an unequal outcome (Martens, Bastiaanssen, & Lucas, 2019). For example, two neighborhoods can have the same level of PT service, but due to differences in geography or personal abilities, this will not result in equal accessibility for residents. Equality is also generally not a suitable benchmark because of the spatial dimension of transport, which makes it infeasible to equally distribute resources across space due to the localized nature of stop and route locations (Martens, Bastiaanssen, & Lucas, 2019).

2.1.2 Equity definitions and types

In contrast to equality, equity takes into account that not all people have the same opportunities and involves provisioning resources in a way that is considered fair or appropriate (Carleton & Porter, 2018; Litman, 2022). Equity can be further divided into horizontal and vertical equity. Horizontal equity refers to how impacts are distributed across groups with equal ability and need, while vertical equity considers the distribution between groups with different ability and need

(Bills & Walker, 2017). With vertical equity, the goal is to provide more resources to groups with a higher need to achieve a more equal outcome (Carleton & Porter, 2018).

It is also possible to think about different types of equity, such as spatial, longitudinal, and modal equity. Spatial equity refers to the provision of equal mobility for all residents living in a given area (Kim, Kho, & Kim, 2019). Longitudinal equity involves comparison of past and present distributions between social groups. Modal equity is associated with differences in access for different modes between the same zones (Kim, Kho, & Kim, 2019).

2.2 Defining network design

This section defines the various components of network design, which is necessary to understand the different mechanisms through which the distribution of PT accessibility can be changed.

2.2.1 Routes

The first component of network design is the alignment of routes, as this can affect the in-vehicle time for travellers (Camporeale, Caggiani, & Ottomanelli, 2019). Some other characteristics of routes are the total number, length, redundancy, and diversity (Camporeale, Caggiani, & Ottomanelli, 2019; Kim, Kho, & Kim, 2019; Wang, Liu, & Zhang, 2022). Aman & Smith-Colin (2020) also consider the route coverage, which is the ratio of the route length compared to the street length in a given area (Aman & Smith-Colin, 2020). Wang et al. (2022) propose a similar measure of service area ratio, which is the ratio of the service area in the zone to the total area of the zone. This study also considers route diversity, which is the number of routes in a zone, as more routes in an area equates to more access opportunities (Wang, Liu, & Zhang, 2022). Another characteristic of route design is circuity, which is the ratio of the network distance and Euclidian distance for an origin-destination pair, with high circuity being associated with lower PT ridership (Dixit, et al., 2021). Routing can therefore have a significant impact on the accessibility that can be achieved by a PT network.

2.2.2 Stops

A related component of network design is the location of transit stops, which impacts travellers' abilities to access the system and the time for access and egress, as well as in-vehicle time, as higher speeds can be achieved with fewer stops (Camporeale, Caggiani, & Ottomanelli, 2019). The catchment area of a stop can be influenced by the quality of the PT services there, with travelers willing to travel further to a PT stop with higher quality services, for example more directness, less in-vehicle time, reduced transfer time, and lower costs for bicycle parking (Brand, Hoogendoorn, van Oort, & Schalkwijk, 2017). It also depends on what mode is being used for access and egress, which is especially relevant in the Netherlands due to the common use of the bicycle as an access and egress mode for PT (Shelat, Huisman, & van Oort, 2018).

2.2.3 Frequency

Frequency is considered as part of the network design definition, as it affects the waiting time for travellers (Camporeale, Caggiani, & Ottomanelli, 2019). Frequency is generally defined per time interval, as this allows for the possibility to study the variations in accessibility during different times of day (Camporeale, Caggiani, & Ottomanelli, 2019; Aman & Smith-Colin, 2020). This can be measured by the number of arrivals for all stops in an area within a defined amount of time (Wang, Liu, & Zhang, 2022). Coordination of transfers can also be relevant to network design (Camporeale, Caggiani, & Ottomanelli, 2019) because as previously mentioned, the presence of a transfer and the transfer time influence the catchment area of PT stops (Brand, Hoogendoorn, van Oort, & Schalkwijk, 2017). Additionally, PT service types can be grouped into fixed route and demand-responsive transport, which also relate to the flexibility of the service (Giuffrida, Pira, Inturri, & Ignaccolo, 2021).

2.3 Components of equity

Martens et al. (2019) defines three components of equity:

1) The benefits and costs that are being distributed
2) the socioeconomic groups over which they are being distributed
3) the principle of distribution that determines if a distribution is fair

By specifying the unit of measurement for each of these components, it becomes possible to quantify and operationalize equity (Martens, Bastiaanssen, & Lucas, 2019).

2.3.1 Benefits and Costs

Martens et al. (2019) identified four dimensions of benefits and burdens in transport: mobility/accessibility, traffic-related pollution, traffic safety, and health (Martens, Bastiaanssen, & Lucas, 2019). PT accessibility is generally what is being evaluated in PT equity analysis as the benefit (Adli, Chowdhury, & Shiftan, 2019). Mobility is different from accessibility in that mobility refers to ease of movement through space, while accessibility refers to the ability and ease to reach opportunities. Better mobility does not necessarily indicate improved accessibility and being able to access a certain destination does not mean that the destination is considered useful or valued (Martens, Bastiaanssen, & Lucas, 2019).

PT has additional accessibility components that differentiate it from other modes. A holistic view of PT accessibility includes consideration of both the proximity and destination characteristics, in other words, the ability to access the PT system and then how PT functions once you access it (Aman & Smith-Colin, 2020). An increase in access *to* transit therefore increases access *by* transit, improving the overall mobility of the individual and increasing the accessibility of important destinations (Carleton & Porter, 2018). The other major difference between PT and other modes is its schedule—unless PT runs where and when it is needed, it does not provide any accessibility benefits (Adli, Chowdhury, & Shiftan, 2019).

A commonly cited work by Geurs and van Wee (2004) provides an overview of accessibility, the different types, and the benefits and drawbacks of each one. Geurs and van Wee (2004) define accessibility as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)." The authors identify four types of accessibility measures: infrastructure-based, location-based, person-based, and utility-based (Geurs & van Wee, 2004).

Infrastructure-based measures of accessibility measure the performance of the transport network, for example average speeds or hours lost in congestion. While it has the benefit of being simple, this measure does not consider the land use component of accessibility (Geurs & van Wee, 2004).

Location-based accessibility measures can add this spatial component, for example the number of opportunities reachable within a given time or distance, known as a contour measure. This measure also has the benefit of simplicity, but it does not consider the interaction between transport and land use, as all opportunities are considered equally desirable and competition effects are not taken into account. This can be accounted for in a gravity-based measure, which uses an impedance function to assign further or smaller destinations diminishing attractiveness. This added layer of complexity can make this measure less understandable for decision-makers. There have been several approaches for incorporating competition effects into gravity models, taking into account for example competition between employees for jobs, and/or competition between companies for employees. Methods for adding competition can add complexity to the calculations, so not all of them are frequently used (Geurs & van Wee, 2004).

Person-based accessibility measures calculate accessibility on the individual level, taking into account space and time restrictions. Of course, with a disaggregate approach there is the benefit of a stronger theoretical basis, but more data requirements and complexity (Geurs & van Wee, 2004).

Finally, utility-based accessibility measures compute accessibility as the sum of the utilities for all choices available to the traveller, known as the logsum. Although this measure may be complex, it is based on theories of travel behavior and can be calculated from the standard 4-step transport model (Rubensson, Susilo, & Cats, 2020). The selected measure of accessibility is dependent on the purpose of the study, and it should be determined what balance of complexity and theoretical soundness is adequate to address the research objectives.

2.3.2 Socioeconomic groups

The second component of equity outlined by Martens et al. (2019) is the socioeconomic groups for whom the distribution is evaluated. There are many socioeconomic groups that have been identified and used in PT equity analysis, which are divided into two relevant categories: income and social class, and mobility need and ability (Carleton & Porter, 2018; Aman & Smith-Colin, 2020; Ricciardi, Xia, & Currie, 2015). Socioeconomic variables related to income and social class include median income, race/ethnicity, employment status, gender, local language fluency, immigrant status, single parent status, housing rent, illiteracy, job level, and education (Carleton & Porter, 2018; Aman & Smith-Colin, 2020). Income is almost always included in equity analysis, as the mobility of this group is especially sensitive to the cost of travel. Poor PT services further isolate low-income individuals, limiting their opportunities and perpetuating existing inequities (Martens, Bastiaanssen, & Lucas, 2019; Kim, Kho, & Kim, 2019). Socioeconomic variables related to mobility need and ability are people with a structural, logical, or physical constraint on mobility, such as youth, the elderly, spatially or temporally isolated populations, unlicensed or non-driving individuals, people with disabilities, tourists, and people without car availability (Aman & Smith-Colin, 2020; Martens, Bastiaanssen, & Lucas, 2019). Current research uses various combinations of the previously listed socioeconomic variables, with the most common being car availability, income, age, gender, (dis)ability, and ethnicity (Martens, Bastiaanssen, & Lucas, 2019).

An important consideration for the inclusion of socioeconomic variables is whether to evaluate each variable separately or combine them into an aggregate index. Some studies use income as the only equity variable but indicate that their methodology can be applied for other indicators (Adli, Chowdhury, & Shiftan, 2019; Rubensson, Susilo, & Cats, 2020). Camporeale et al. (2019) uses a social indicator of Public Transport Need (PTN) developed by Ruiz et al. (2014) that is the sum of the products of the considered social equity variable and an associated weight based on its relative importance in the study area (Ruiz, Segui-Pons, Mateu-Lladó, & Reynés, 2014). Carleton & Porter (2018) argue against this type of aggregation, saying the benefit of increased simplicity of such a measure is outweighed by the muddiness of the result. The authors show this by comparing three aggregation types for several socioeconomic groups: a disaggregate measure, an aggregate measure with equal weighting for all groups, and total population. The results showed that some socioeconomic groups experience greater disparities than others, and that a disaggregate approach provides a better way to identify over- and under-served areas (Carleton & Porter, 2018). This can also be seen in Figure 5 below from Wang et al. (2022), where the Lorenz curves for each socioeconomic group show a different degree of inequity experienced by each group when compared to the total population (Wang, Liu, & Zhang, 2022).

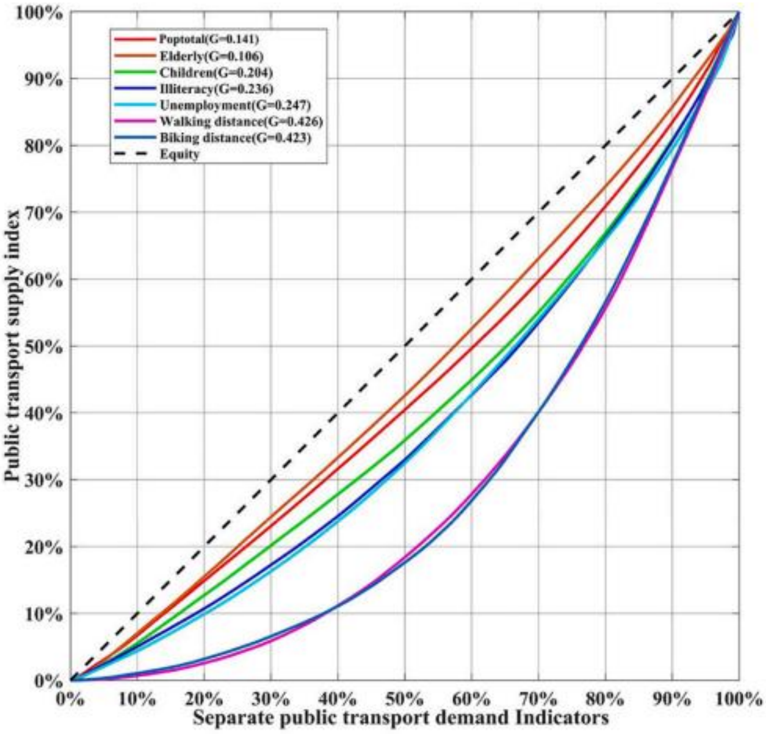


Figure 5: Lorenz curves for socioeconomic groups in Shanghai (Wang, Liu, & Zhang, 2022)

2.3.3 Distribution principles

Distribution principles provide alternative ideas of what resource distribution is accepted as fair (Bills & Walker, 2017). The standards identified in the literature review are listed in the table below and are grouped into two types: standards for assessing an existing distribution and standards for assessing an intervention (Martens, Bastiaanssen, & Lucas, 2019). The definitions and examples in Table 1 below are from (Lucas, van Wee, & Maat, 2016; Adli, Chowdhury, & Shiftan, 2019; Martens, Bastiaanssen, & Lucas, 2019; Litman, 2022; Pereira, Schwanen, & Banister, 2016). Table 1 below lists the distribution principles identified in the literature, and provides their general definitions and applications in the context of PT accessibility.

Table 1: Definitions and examples of distribution principles

Standards for Assessing an Existing Distribution		
Standard	Definition	PT Accessibility Application
Utilitarianism	A distribution is morally right if it maximizes the total benefits for society.	The accessibility distribution should result in the maximization of the total accessibility in the study area. It is acceptable for some people to have poor accessibility if society overall has a high accessibility.
Sufficientarianism	A distribution is fair if it meets the basic needs of everyone and guarantees their continued well-being. This is also known in the literature as a minimum standards approach.	Everyone should have some minimum threshold of PT accessibility to reach their basic needs and important destinations, and a goal of public policy should be to improve the accessibility of

		people who are below this threshold.
Egalitarianism	A distribution is fair if all people are treated equally.	All people should receive equal levels of PT accessibility.
Libertarianism	A fair distribution should be determined by the free market through consumer choice.	The PT accessibility distribution should be based on where and when the most ridership is.
Rawl's Theory of Justice	Resources should be allocated in a way that provides the greatest benefit to the most disadvantaged groups in society. This is also known as a vertical equity approach.	PT accessibility should be higher in areas with a high proportion of the population that is low-income, ethnic minority, disabled, etc. (or other relevant socioeconomic characteristics)
Proportionality	Resources should be distributed among groups in rough proportion to the groups' share of population, with an acceptable range in deviations.	PT should be allocated based on the distribution of the total population and/or mode share of PT.
Maximum Gap Standard	Acceptance of inequality as long as disparities are within an acceptable predefined range. It is not practical to achieve equal distribution, because disparities may be a result of personal preferences, for example, a middle-income household accepting a lower level of accessibility for lower housing costs in an outlying area.	PT accessibility can be distributed in an unequal way as long as the differences in accessibility for different socioeconomic groups are not too large.
Equal Opportunity	Resources should be distributed in a way that guarantees equality of opportunity in outcomes.	PT accessibility should be distributed in a way that everyone can reach the same number of defined opportunities within a certain PT travel time or distance.
Standards for Assessing an Intervention		
Standard	Definition	PT Accessibility Application
Equality	Applies if egalitarianism is the desired approach by attempting to intervene in a way that distributes resources equally for everyone. However, it is likely to perpetuate existing inequities.	Any changes to the PT system should move towards the provision of the same level of service for everyone.
Do No Harm	Nobody should be worse off as a result of an intervention. However, this approach can also enforce existing inequities, because even though no groups will be harmed, benefits may continue to be provided to the most well-off groups.	Any changes to the PT system should not reduce the accessibility for any groups.
Equalization	Goal of this standard is to move towards the reduction of existing disparities and does not require	Changes to the PT system should aim to increase the accessibility of

	the selection of an ultimate equity goal as long as disparities are reduced.	disadvantaged socioeconomic groups.

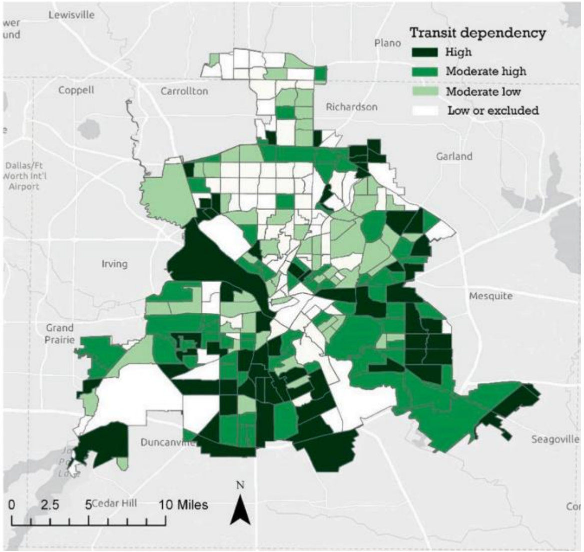
These equity standards can also be combined, for example, Adli et al (2019) recommends a combination of sufficientarianism and egalitarianism to evaluate transit equity. This approach adopts the perspective that there should be a minimum level of accessibility for all, but since equality is unavoidable, the provision of accessibility should benefit the least-well-off groups more (Adli, Chowdhury, & Shiftan, 2019).

2.4 Existing approaches to equity analysis

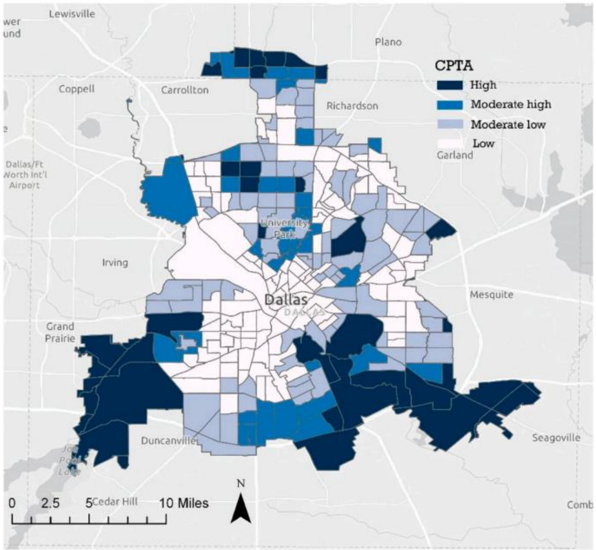
The three components of benefits/costs, socioeconomic groups, and distribution principles are the ingredients of equity analysis (Martens, Bastiaanssen, & Lucas, 2019). The selected distribution principle dictates what is a fair distribution of PT benefits over the population, which can then be compared to the actual distribution to determine the degree of equity. The primary approaches to equity analysis are gap analysis, accessibility distribution comparisons, use of Lorenz curves and Gini coefficients, and Transit Network Design Problem (TNDP) optimization. There have also been recent efforts in the Netherlands to include equity analysis as a part of mobility policy.

2.4.1 Needs-gap analysis

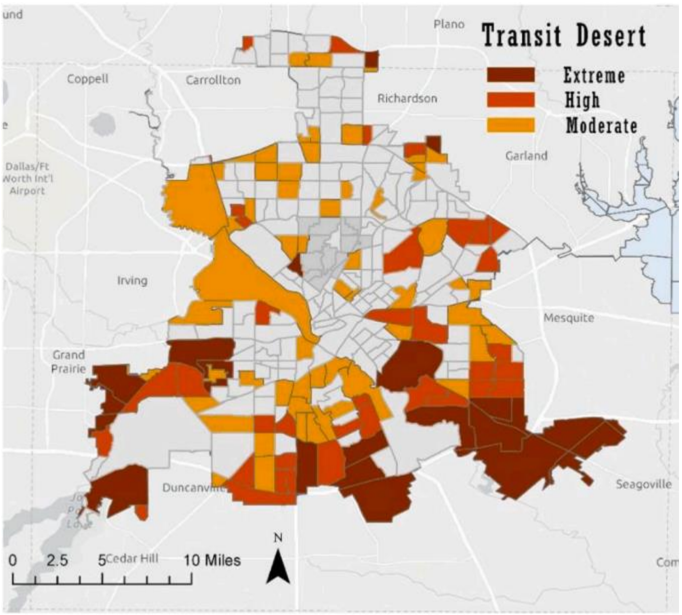
Needs-gap analyses identifies spatial mismatch between PT service supply and mobility needs of the transit-dependent population. Gap analysis works well for spatially targeted interventions, but it less useful for comparing changes overall in accessibility distribution (Carleton & Porter, 2018). Aman & Smith-Colin (2020) use a needs-gap analysis to identify transit deserts, which are defined as areas where the public transport supply is low despite the presence of a large transit-dependent population. A Comprehensive Public Transit Accessibility (CPTA) score is constructed by dividing transit supply data for each zone into quantiles and assigning the lowest quantile a value of 1. This is done for several supply measures, the scores for which are then summed to construct an overall supply score. A similar process was applied with standardized socioeconomic data to identify areas with high transit dependency characteristics, to classify zones into one of four combinations: high demand- high supply, high demand – low supply, low demand – high supply, and low demand – low supply (Aman & Smith-Colin, 2020). The results of this analysis are visualized in Figure 6 below. Adli et al. (2019) performs a gap analysis by clustering areas based on their level of accessibility and income, to identify areas that should be prioritized for PT improvements. In this study, areas with low income and low PT accessibility, with low vs. high being separated based on the mean of each variable, should be prioritized for PT improvements (Adli, Chowdhury, & Shiftan, 2019).



(a) Distribution of transit dependent populations



(b) Distribution of PT accessibility



(c) Transit deserts showing mismatched PT demand and supply

Figure 6: Spatial analysis of transit dependent populations (a) and PT service supply (b) being used to identify transit deserts (c) (Aman & Smith-Colin, 2020)

2.4.2 Accessibility distribution comparison

Another method of equity analysis is to compare accessibility distributions for different groups, either to the total population or to other disadvantaged groups. Deboorse & El-Geneidy (2018) developed a specific measure of PT accessibility of vulnerable residents to low-income jobs and compared this to PT accessibility of both the total population and vulnerable residents to all jobs, for eleven major cities in Canada (Deboosere & El-Geneidy, 2018). Bills & Walker (2017) propose the use of distributional comparisons for different population segments to evaluate the transport system before and after an intervention affecting the travel time. In this approach the change in the monetized logsum accessibility can be computed for several socioeconomic groups of interest, and then plotted as a smoothed frequency distribution to assess the impacts of changes on different groups (Bills & Walker, 2017), as shown in Figure 7 below.

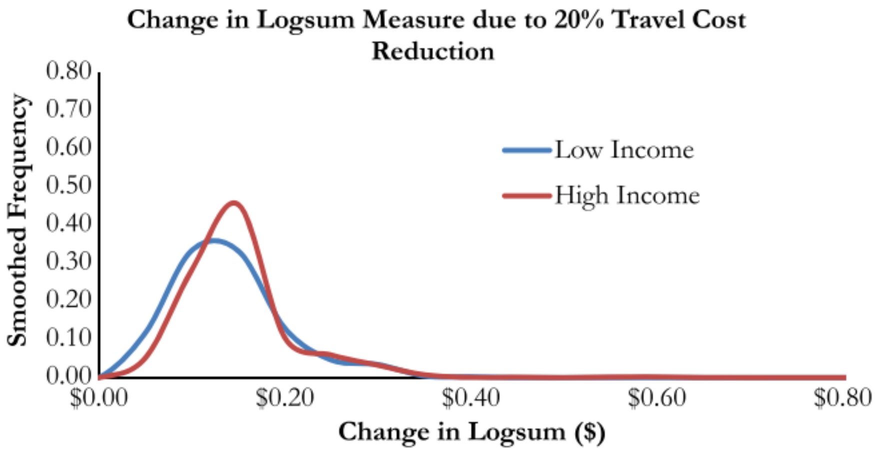


Figure 7: Distribution of accessibility changes for low-income vs. high-income groups resulting from a 20% reduction in travel time for autos and transit (Bills & Walker, 2017)

2.4.3 Lorenz curve and Gini coefficient

Another approach to equity analysis, the use of Lorenz curves and Gini coefficients, provides an indication of the equality of a distribution. A Lorenz curve graphically displays the distribution of resources, with the cumulative share of the population on the x-axis and the cumulative share of resources on the y-axis (Lorenz, 1905). An example of a typical Lorenz curve can be seen in Figure 8. The Gini coefficient, which is calculated from the Lorenz curve, has a value of 1 when everyone has equal resources and a value of 0 when the top percentile has all the benefits (Gini, 1912). While the Gini coefficient measures horizontal equity, it can be appropriated to measure vertical equity by combining this approach with data on socioeconomic characteristics of the population (Rubensson, Susilo, & Cats, 2020). Ricciardi et al. (2015) examined the distribution of PT accessibility for the three socially disadvantaged groups of elderly, low-income, and no-car households, finding their distribution to be less equitable than for the total population. The Gini coefficient was also computed for the study area and used to compare to another area (Ricciardi, Xia, & Currie, 2015). Wang et al. (2022) constructs separate Lorenz curves for each socioeconomic group of interest, to identify which groups suffer most from PT inequity, previously shown in Figure 5 (Wang, Liu, & Zhang, 2022). The optimization literature includes equality in the Transit Network Design Problem by setting a maximum Gini coefficient as a constraint (Camporeale, Caggiani, & Ottomanelli, 2019).

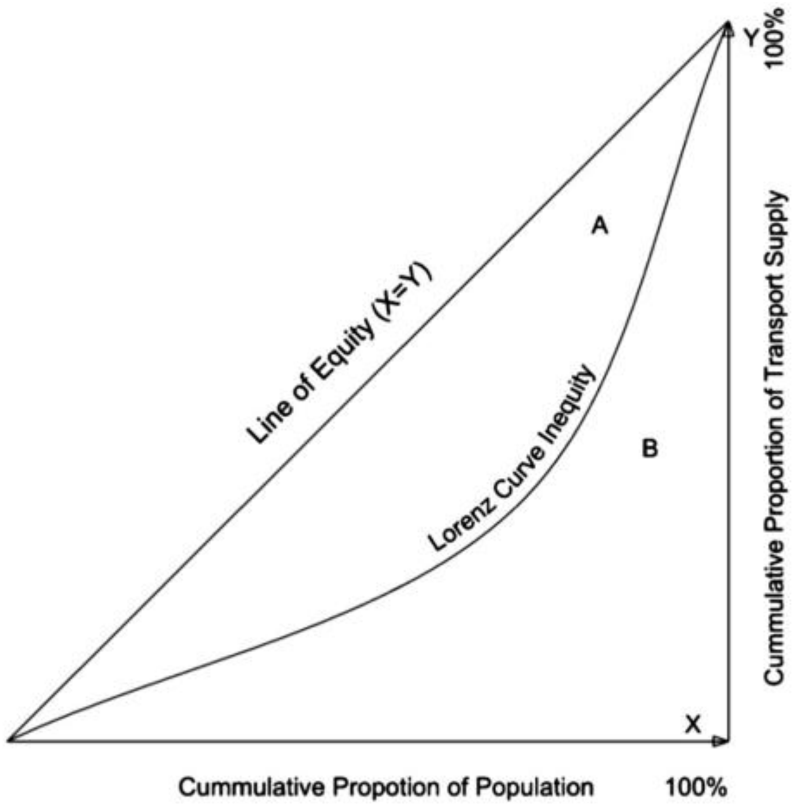


Figure 8: A typical Lorenz curve (Ricciardi, Xia, & Currie, 2015)

The strengths of the Gini coefficient are that it allows the analysis of resource allocation to various socioeconomic percentiles, and because a single number is calculated for the entire study area, it is good for comparison studies. However, the Gini coefficient is a measure of equality and not necessarily equity, and just because a distribution is unequal does not necessarily mean it is inequitable (Carleton & Porter, 2018). Additionally, there is no spatial component, which is important for considering changes to the PT network. Therefore, the recommended approach from the literature is to use both needs-gap analysis and Gini coefficient for a thorough equity analysis (Carleton & Porter, 2018).

2.4.4 Transit Network Design Problem (TNDP)

A more proactive approach to the evaluation and planning of equitable PT systems is through finding the mathematically optimal solution in the Transit Network Design Problem (TNDP). The objective function is the weighted sum of the overall social cost, composed of as user cost, operator cost, and unsatisfied demand (Camporeale, Caggiani, & Ottomanelli, 2019). Constraints are related to the number of routes, minimum and maximum headways, fleet size, minimum amount of demand that must be served, and the maximum Gini coefficient, which represents the equality component of the problem. This TNDP results in the design of a new PT network from the input data (Camporeale, Caggiani, & Ottomanelli, 2019). Kim et al. (2019) uses the same objective function, but without the component of unsatisfied demand (Kim, Kho, & Kim, 2019). In contrast to Camporeale et al. (2019), Kim et al. (2019) applied this method to improve routes with poor equity, instead of completely redesigning the network from scratch. Modal equity was calculated by comparing the travel time with public transport to that in a car, and spatial equity was calculated by comparing the modal equity between different zones in the study area (Kim, Kho, & Kim, 2019). PT constraints were related to line length, circuity, redundancy, frequency, and equity, although it is mentioned that both the objective function and the constraints can be modified depending on the study purpose (Kim, Kho, & Kim, 2019).

2.4.5 Public Transport Equity in the Netherlands

Increasing attention is being directed towards equity of transport in the Netherlands. Equity in service planning is currently mentioned in concession documents, where it is required that certain types of areas receive some form of PT service and that certain areas are connected by PT (Programma van Eisen: Concessie Amstelland-Meerlanden 2018, 2018). A report by the Dutch Knowledge Institute for Mobility Policy (KiM) published a memorandum to clarify the inclusion of fairness in mobility policy (Alonso González, Jonkeren, & Wortelboer-van Donselaar, 2022). This policy document proposes a plan for policymakers to include equity, as a goal supplementary to effectiveness and efficiency, in mobility policy. First, justice must be identified as a goal of policy, followed by the determination of which distribution principle is most suitable based on the policy goal. Depending on the distribution principle, decisions regarding selection of socioeconomic groups and thresholds may have to be made. Indicators must be chosen to quantify the distributional effects of the policy, and then expected changes to these indicators before and after policy implementation can be evaluated to determine the fairness of the policy. This report provides a practical guide for the inclusion of equity in mobility policy in the Netherlands, although some of the decisions that must be made in this process are subjective and often political, especially that of distribution principle selection (Alonso González, Jonkeren, & Wortelboer-van Donselaar, 2022).

2.5 Synthesis

This literature review has defined important terms and concepts in the realm of PT equity and presented the existing approaches to equity analysis. This understanding of past research helps to support the methodology and further define the scope of this research. This requires the three components of equity analysis identified by Martens et al. (2019) to be identified in the context of this research.

The first component, the benefits or costs that will be measured, is PT accessibility, which can be measured in various ways. From the accessibility measures identified by Geurs & van Wee (2004), it is decided to use the logsum accessibility in this research. This measure is selected because it considers travel behavior and is easy to calculate from a four-step transport model (Rubensson, Susilo, & Cats, 2020). Additionally, it represents a potential accessibility regardless of destination type, therefore avoiding assumptions of what types of destinations travelers want to access. The inclusion of the second component, the socioeconomic groups to be measured, depends on the distribution principle that is being selected. Based on the literature review, it is decided to use a disaggregate measure, from which income is selected due to its high prevalence in other PT equity research. The final component is the selection of the distribution principles to compare in equity analysis. In this research, egalitarianism, proportionality, and sufficientarianism are selected for comparison. Egalitarianism and proportionality are selected because their evaluation methods do not require arbitrary decisions to be made, for example for the selection of an accessibility threshold. Sufficientarianism is selected because although it requires the determination a threshold, it is commonly mentioned in existing mobility policies. This literature review also helps define the network modifications that will be considered in this research.

Regarding network design, this research will only focus on frequency modifications, which are simple to implement in a transport model and have the most predictable effect on travel times within the network, as waiting times are calculated as half of the headway. With the relevant terms clarified and the scope of the research defined, the methodology can be developed.

3

Methodology

The following chapter will outline the methodology used for the equity evaluation for each accessibility distribution principle. Section 3.1 will discuss the general data requirements for equity evaluation. Section 3.2 will discuss the selection and calculation of the measure of logsum generalized travel costs as the accessibility measure. Sections 3.3 through 3.5 will discuss the method used to evaluate an existing PT accessibility distribution for each of the three selected distribution principles: egalitarianism, proportionality, and sufficientarianism. Egalitarianism and proportionality are selected because their evaluation methods do not require the selection of arbitrary thresholds, while sufficientarianism is chosen because it is commonly mentioned in existing mobility policies. These prior applications in research and practice make these three distribution principles the most suitable for supporting the research objectives.

3.1 Data Requirements

The first type of data required for equity analysis is that of accessibility data, which can vary based on the accessibility measure used. In this thesis, the selected accessibility measure is the logsum generalized travel cost, the calculation of which requires the generalized travel costs between all origin-destination zone pairs. This data is available from the skim matrices of 4-step transport models and can be used to calculate logsum travel costs, which will be explained in further detail in section 3.2.

The required demographic data depends on the distribution principle being used in the equity analysis. For the principle of egalitarianism, data on population and average income per zone are required. For an equity analysis based on proportionality, data relating to factors that could influence PT ridership are needed. Depending on data availability, this could include data on population density, address density, and employment density per zone. To evaluate equity based on the principle of sufficientarianism, no demographic data is needed in addition to the accessibility data.

It is required for the accessibility and demographic data to be at the same spatial scale, or at least able to be transformed to the same spatial scale. Additionally, data at a smaller spatial scale is preferred over data at a larger scale, as smaller areas allow for more spatial resolution in the analysis. The spatial scales for each type of data should also have the same primary key, so that the accessibility and demographic data can be associated with the same zones.

3.2 Accessibility Measurement

This study uses the logsum as the accessibility measurement, due to its availability in a standard 4-step transport model and consideration of travel behavior in perceived travel costs. It should be noted that in equity analysis, the actual accessibility is less important than the accessibility differences between zones, as equity analysis is an assessment of the distribution of resource (Rubensson, Susilo, & Cats, 2020).

The logsum is the sum of all utilities for a set of choices available to the decision-maker (Williams, 1977). In the context of this study, the logsum accessibility for each zone is the sum of the utilities to travel from the origin zone to all other zones. The equation for the logsum is shown in Equation 1 below (Williams, 1977):

$$Logsum = \left(ln \sum_i e^{V_i} \right) + C \qquad (1)$$

Where:
V_i = utility of choice *i*
C = unknown constant representing the uncertainty of the accessibility value

However, in this case the C can be disregarded as this study is concerned with relative and not absolute accessibility (Rubensson, Susilo, & Cats, 2020). The total utility V_i for all destination zones *j* accessible from origin zone *i* is calculated with equation 2 below (Williams, 1977):

$$V_i = \sum_j V_{ij} = \sum_{rj} \beta_r x_{rij} \qquad (2)$$

Where:
x_{rij} = travel cost for selected transport utility component *r*
β_r = relative weight of the transport utility component *r*

The transport utility components in a PT generalized travel cost function could be in-vehicle time, walking time, waiting time, a transfer penalty, and fare (Willigers, 2020).

The logsum accessibility measurement is referred to in this thesis as the logsum travel cost. A high logsum travel cost indicates low accessibility, while a low logsum travel cost indicates high accessibility. This is an important distinction given that a high value implying a low accessibility may seem counterintuitive.

3.3 Egalitarianism Equity Evaluation

The first principle that can be applied to assess the distribution of PT accessibility is egalitarianism. As mentioned in chapter 2, an egalitarian perspective in the context of PT accessibility states that the distribution of PT accessibility is fair if all people receive the same level of PT accessibility (Litman, 2022). This principle therefore evaluates the equality of the PT accessibility distribution, which can be done using the Lorenz curve and the Gini coefficient.

3.3.1 The Lorenz curve

Lorenz curves are used to understand the distribution of a benefit or cost over a population, by showing the accumulated share of the resource that each percentile of the population has (Lorenz, 1905). An example of a Lorenz curve is shown in Figure 9 below.

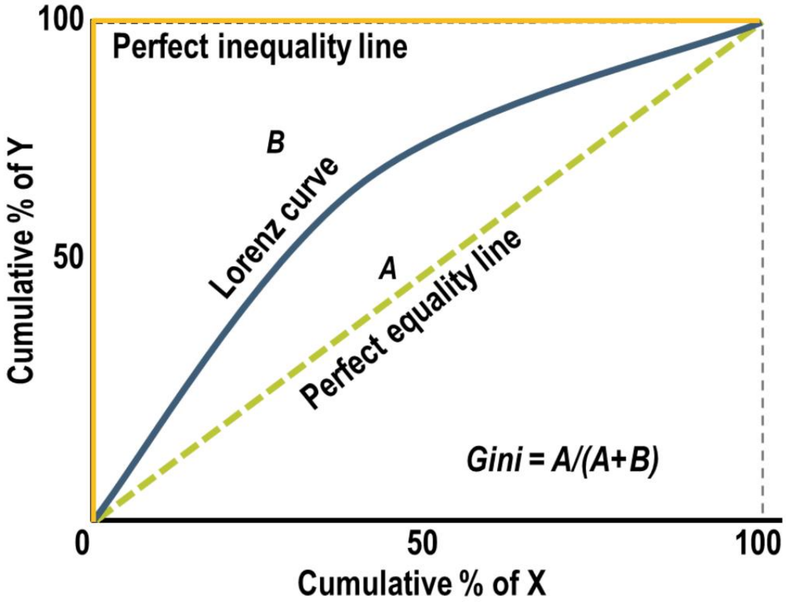


Figure 9: Example of a Lorenz curve (Rodrigue, 2020)

When travel costs are equally distributed, the Lorenz curve will follow the line of equality, shown in green in Figure 9 above. This would mean that the 10th percentile of the population has 10% of the travel costs, the 50th percentile of the population has 50% of the travel costs, and so on. The Lorenz curve shown as the blue line in the figure above therefore shows an unequal distribution of resource Y among population X. In this method, a Lorenz curve above the line of equality indicates that that percentile of the population bears excess logsum travel costs, while a curve below the line indicates that this percentile experiences lower costs (Rodrigue, 2020).

The Gini coefficient measures the equality of a distribution, with a value of 0 representing perfect equality (everyone receives the same resources) and a value of 1 representing perfect inequality (the top percentile receives all the resources) (Gini, 1912). In this evaluation, the population will be ordered by average income and the distribution of the total logsum travel costs will be evaluated as the resource. The following methodology is based on that applied in previous research, namely Delbosc & Currie (2011) and Rubensson et al. (2020).

The data required for equity evaluation according to egalitarianism in this method is the average income, population size, and logsum travel cost per zone. First, the data is ordered based on lowest to highest average income. With the data in this order, the population of each zone is divided by the study area population to obtain the proportion of the population that each zone compromises. These proportions are then added cumulatively to obtain a cumulative sum from 0 to 1 as seen in equation 3 below, which is used as the data for the x-axis.

$$x_1 = \frac{pop_1}{\sum_1^n pop_n},\ x_2 = \frac{pop_1 + pop_2}{\sum_1^n pop_n},\ x_3 = \frac{pop_1 + pop_2 + pop_3}{\sum_1^n pop_n}, \text{etc.} \qquad (3)$$

Where:
pop_n = the population of zone n
x_n = the cumulative proportion of population of zone n

The logsum travel cost for each zone times the zone population is also divided by the sum of the logsum travel costs multiplied by the population per zone for all zones in the study area to obtain for each zone its weighted proportion of logsum travel times. These proportions are then added to obtain a cumulative sum from 0 to 1 as seen in equation 4 below, which is used as the data for the y-axis.

$$y_1 = \frac{LTC_1 \times pop_1}{\sum_1^n LTC_n \times pop_n},\ y_2 = \frac{LTC_1 \times pop_1 + LTC_2 \times pop_2}{\sum_1^n LTC_n \times pop_n},\ y_3 = \frac{LTC_1 \times pop_1 + LTC_2 \times pop_2 + LTC_3 \times pop_3}{\sum_1^n LTC_n \times pop_n}, \text{etc.} \qquad (4)$$

Where:
LTC_n = the logsum travel cost of zone *n*
pop_n = the population of zone *n*
y_n = the cumulative proportion of logsum travel cost of zone *n*

The final step to obtain the Lorenz curve is to plot the data, with the cumulative percentage of the population ordered by income on the x-axis and the cumulative percentage of the weighted logsum travel costs on the y-axis. It is reiterated here that a higher logsum travel cost corresponds to poorer accessibility. This is because a higher logsum travel cost indicates that the travel costs are higher, so the accessibility is therefore lower.

3.3.2 The Gini coefficient

The Lorenz curve is used to calculate the Gini coefficient, which measures how equal a distribution is on a scale from 0 to 1. 0 represents total equality (every percentile has the same logsum travel costs) and 1 represents total inequality (the top percentile of the population experiences all the logsum travel costs) (Gini, 1912). The Gini coefficient can be calculated using equation 5 below (Gini, 1912):

$$G = \left|1 - \sum_{i=1}^{N} (\sigma X_{i-1} - \sigma X_i)(\sigma Y_{i-1} + \sigma Y_i)\right| \qquad (5)$$

Where:
σX = the cumulative proportion of the population from 0 to 1 when ordered by income
σY = the cumulative proportion of weighted logsum travel costs

The Gini coefficient can be used as a single indicator to quantify the equality of the accessibility distribution to allow for comparisons, as opposed to the Lorenz curve which shows how accessibility is distributed within the population and can be used to identify specific zones with accessibility deficits and surpluses (Carleton & Porter, 2018).

3.4 Proportionality Equity Evaluation

The following principle to be assessed is that of proportionality, which states that the level of PT accessibility that an area receives should be proportional with factors that affect the use of PT and therefore the costs of service provision (Litman, 2022; Rubensson, Susilo, & Cats, 2020). The selection of which factors to consider is the decision of the researcher and is subject to data availability.

The following methodology for equity evaluation based on proportionality is based on the approach for accessibility distribution evaluation proposed by Rubensson et al. (2020). In this method, the actual accessibility of each zone will be compared to a calculated target accessibility. The target accessibility is the accessibility that is warranted based on factors that influence PT use, and is calculated using multiple regression, as conceptually illustrated in Figure 10 below.

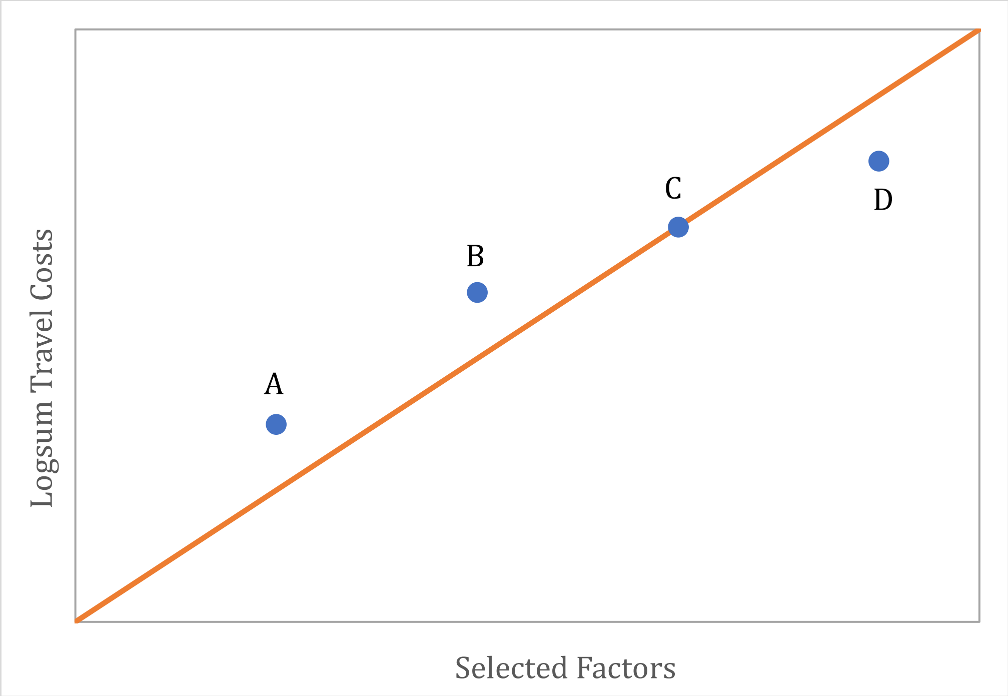


Figure 10: Target accessibility as a function of selected land use/demographic factors (Rubensson, Susilo, & Cats, 2020)

In Figure 10, the line represents the target accessibility based on the selected legitimate factors, and points A-D represent actual accessibility levels in zones A-D. In this example, points A and B have higher than proportional travel costs, C has an appropriate level of travel costs, and point D has lower than proportional travel costs. In other words, zones A and B have an accessibility deficit and zone D has an accessibility excess.

The first step is to select the relevant factors that could influence warranted accessibility levels, which is based on data availability and factors identified in previous research as affecting PT usage. Some examples of factors that may considered are population density, household density, employment density, and address density. The next step is to perform a linear regression analysis for each potential factor, which will indicate which factors could be included in the final model. It is important to note that using linear regression implies an assumption of linearity in the data. This assumption is made for the sake of simplicity of the analysis, as there are too many different types of regression to check definitively which would provide the best fit for each variable. Therefore, it is assumed that there is a linear relationship between the potential factors and the logsum travel cost, and a linear regression is performed.

The linear regressions are done with the selected factor as the independent variable and the logsum travel cost as the dependent variable. The R-square value for each potential factor, which indicates the predictive power of the model, is checked to see if it is high enough to be justified to include in the model. The p-values, which should be below 0.05, are also checked for the coefficients of each factor to check for statistical significance. Factors with relatively high R-square values and coefficients with p-values less than 0.05 should be considered for inclusion in the final regression.

A multiple regression can then be performed with the factors selected from the single regressions but this time including all the selected factors as independent variables. The resulting R-square and p-values can then be checked for goodness of fit and significance, respectively. There is a trade-off between the complexity and goodness of fit of the model, as the inclusion of more factors may improve the fit at the expense of simplicity, which should be considered when selecting which factors to include in the regression.

Once the factors have been selected, the resulting regression equation can be used to calculate the target logsum travel costs for each zone, by plugging in the values of the factor in the places of their variables. Once the target logsum travel cost for each zone is known, it can be compared to the actual logsum travel cost. If the target travel costs are higher than the actual, then a zone has an accessibility surplus, while if the target travel costs are lower than the actual, then the zone has an accessibility deficit.

3.5 Sufficientarianism Equity Evaluation

The final distribution principle discussed is that of sufficientarianism, which states that the distribution of public transport accessibility is fair if it meets a minimum threshold where everyone can access their basic needs (Lucas, van Wee, & Maat, 2016; Martens, Bastiaanssen, & Lucas, 2019). Several methods for determining the sufficient level of PT accessibility have been proposed in the literature. Van der Veen et al. (2020) proposes using descriptive statistics, for example defining sufficiency as a defined percentile of the accessibility of car users. This method requires a judgement to be made to determine the single threshold of what is a sufficient level of accessibility (van der Veen, Annema, Martens, van Arem, & Homem de Almeida Correia, 2020). In the Netherlands, a verplaatsingtijdfactor (VF), or displacement time factor in English, is used to compare travel times between different modes, for example measuring the competitive position of PT relative to the car (Projectbureau Integrale Verkeers- en Vervoerstudie, 1995). A limitation of the VF value that should be kept in mind is that it links car and PT accessibility, when in practice it is not desirable for a change in car travel times to suggest a parallel change in PT travel times.

The VF value has been shown to consistently influence mode choice, for example, when the travel times for PT and car are equal (VF factor = 1), ~60% of travelers will choose PT, and when the VF value is 1.5, ~40% of travelers will choose PT. If the VF value is more than 2, then ~20% of travelers will select PT. It is therefore important to invest in measures that reduce the VF value at least below 2, and a VF value of maximum 1.5 for commuting to major employment centers is considered ideal (Projectbureau Integrale Verkeers- en Vervoerstudie, 1995). The VF value can therefore be used to define the level of sufficiency in PT accessibility, by comparing the ideal VF value to the actual VF value. The ideal VF value can either be determined either based on thresholds defined in previous research, or determined from the existing distribution of VF values, for example by selecting a certain percentile VF value as the threshold.

The VF values can be calculated from a 4-step transport model using the skim matrices for car and PT. These matrices for each mode can then be transformed to a list and the logsum travel costs can be calculated for each zone by summing the travel times from this zone to all other zones, as described in section 3.2. For each zone, the logsum travel cost for PT can be divided by the logsum travel cost for car to obtain the VF value for that zone, as seen in equation 6 below for zone *i*.

$$VF_i = logsum_{PT,i} / logsum_{car,i} \qquad (6)$$

Where:
$logsum_{PT,i}$ = the PT logsum travel cost for zone *i*
$logsum_{car,i}$ = the car logsum travel cost for zone *i*

Each VF value can then be compared to the selected threshold VF value to determine if a sufficient level of accessibility is achieved. If a zone has a VF value above the sufficiency threshold, then the zone has an accessibility deficit. A VF value below the sufficiency threshold is acceptable, as sufficientarianism does not allow for the possibility of an accessibility surplus.

3.6 Summary

This chapter presented an equity evaluation method for each of the three distribution principles in this study. The accessibility distribution according to egalitarianism is evaluated using the Lorenz curve, and the Gini coefficient provides a single indicator of equality. Proportionality is evaluated by determining a multiple regression model to calculate a target accessibility per zone, which is then compared to the actual accessibility. For sufficientarianism, a threshold for a sufficient level of accessibility can determined based on the VF value, which is the travel time ratio between PT and car. The following chapter will introduce the case study area where these methods will be applied.

4

Background of Case Study Area

This chapter will introduce the case study area selected for the application of the methodology in this thesis: the Amsterdam Transport Region concession area of Amstelland-Meerlanden. This section will discuss general demographics and the public transport system in the area, as well as current Amsterdam Transport Region policy initiatives relating to inclusive mobility.

4.1 Demographics

The study area selected for this research is the Amstelland-Meerlanden (AML) concession of the Vervoerregio Amsterdam, in the province of North Holland. At the time of this thesis, the most recent year where all required data is available is 2014 due to the update cycle of the transport model used in this research. Therefore, the following discussion refers to the 2014 spatial boundaries and PT services. Other study areas such as the Zaanstreek Waterland concession and Amsterdam Noord were considered but were ruled out due to being in the tendering process at the time of this research and for having an insufficient number of zones, respectively, therefore AML was selected as the case study area. The location of the AML concession area relative to the Amsterdam Transport Region service area can be seen in dark purple in Figure 11 below.

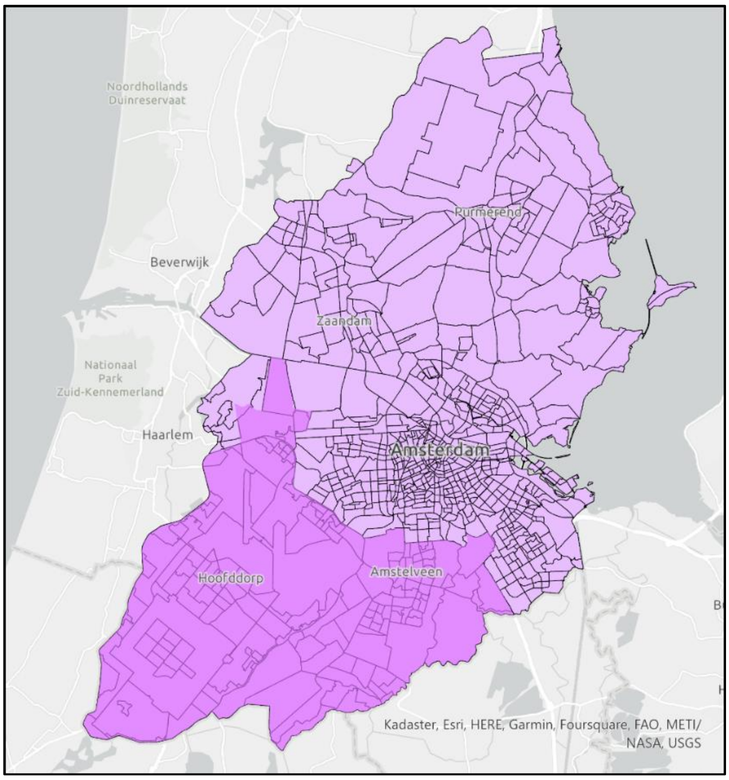


Figure 11: Location of Amstelland-Meerlanden within the Amsterdam Transport Region service area

As can be seen from the figure, the AML concession makes up a large area of the southern part of the Amsterdam Transport Region service area, and includes the municipalities of Aalsmeer, Amstelveen, Uithoorn, Ouder Amstel, and Haarlemmermeer (Programma van Eisen: Concessie Amstelland-Meerlanden 2018, 2018). The AML area can be separated into five area types, which are defined by the combined number of inhabitants and jobs per square kilometer (Gaaff, de Koning, Bonnier, van der Slot, & Mout, 2021):

- Metropolitan central urban area: > 12,500 inhabitants and jobs per square kilometer
- Central urban area: 4,000 – 12,500 inhabitants and jobs per square kilometer
- Urban living and working area: 2,000 – 4,000 inhabitants and jobs per square kilometer
- Rural living and recreation area: < 2,000 inhabitants and jobs per square kilometer
- Mainports and greenports: large working areas with little or no housing

The distribution of these areas in AML is shown in Figure 12 below.

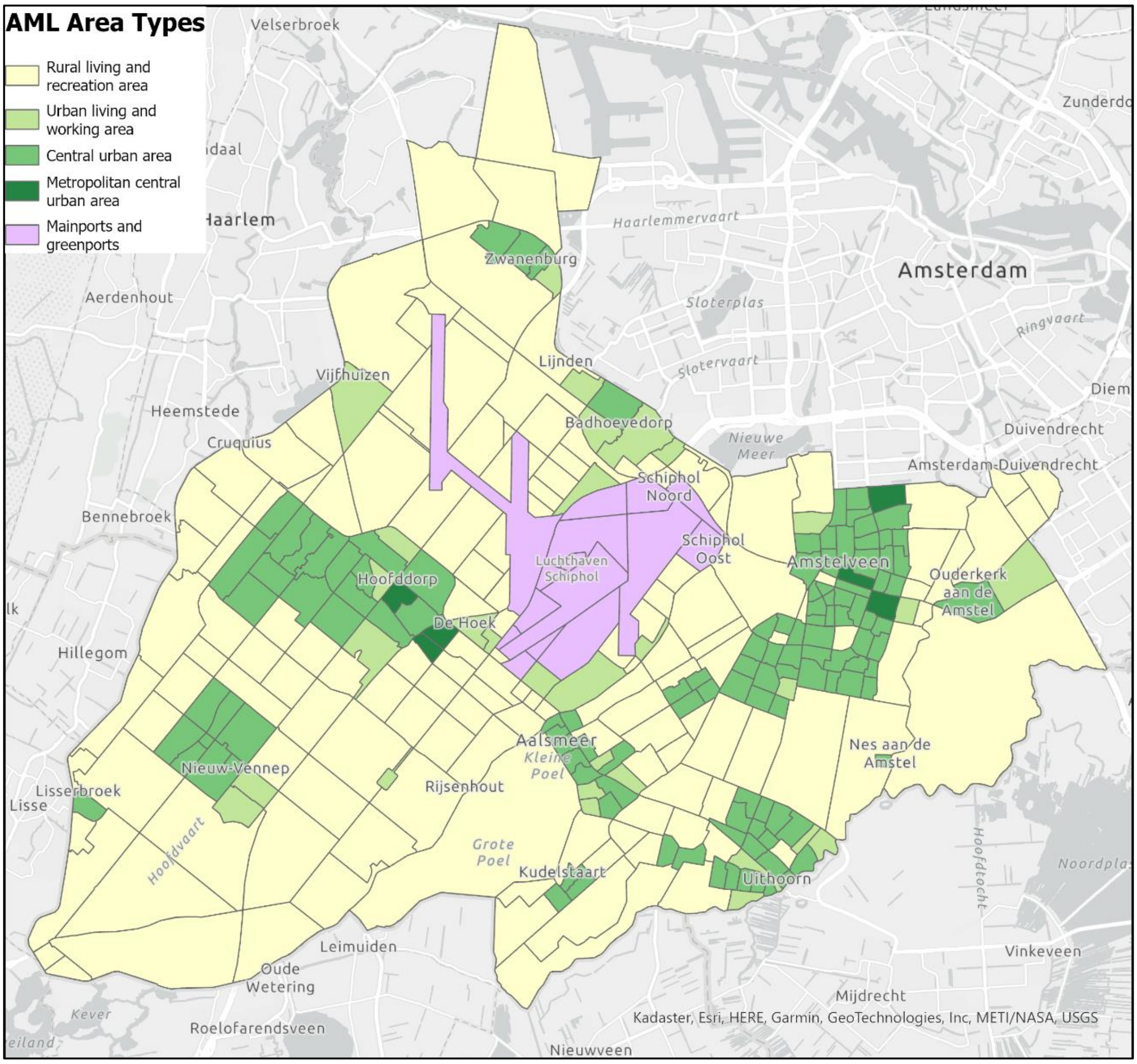


Figure 12: Classification of area types in Amstelland-Meerlanden

The land use of this area is characterized by several municipalities with agricultural and recreational land in between. The most urbanized areas are in Amstelveen and Hoofddorp, due to the high density of residential neighborhoods in these areas. An important part of the Dutch economy is located in the AML area: Schiphol Airport. The Aalsmeer flower auction, which is the largest in the world, is also important for the regional economy. This area is also located just southwest of Amsterdam, which is easily reachable with car or public transport (Programma van Eisen: Concessie Amstelland-Meerlanden 2018, 2018).

The Amsterdam Transport Region service area consists of 840 PC5 postcode zones, 319 of which belong to the AML concession area. There are two other levels of postcodes in the Netherlands: 4-digit (PC4) and 6-digit (PC6). The higher the number of digits in the postcode, the smaller the zone and therefore the higher the spatial granularity. For example, in the AML concession, the average size of a PC4 postcode is 6.75 square kilometers, while the average size of a PC5 postcode is 1 square kilometer. Additionally, postcodes in more urbanized areas are generally smaller than those in less urbanized areas.

A comparison of the population, jobs, and income between the Amsterdam Transport Region service area and the AML concession area can be seen in Table 2 below.

Table 2: Comparison of demographics between the Amsterdam Transport Region and Amstelland-Meerlanden

	Amsterdam Transport Region Service Area	AML Service Area
Total Inhabitants	1,486,491	301,979
Inhabitants per square km	1,621	952
Total Jobs	797,249	190,857
Average Annual Income	€36,088	€40,331

As can be seen in Table 2, the population density of the AML concession area is over 40% lower than that of the Amsterdam Transport Region concession area, and the average annual incomes of inhabitants in the AML area are higher than in the Amsterdam Transport Region service area. The AML area also has about a quarter of the jobs in the concession area, approximately 65,000 of which are at Schiphol Airport (Schiphol Group, 2014). The modal share for trips made in the AML concession area in 2014 relative to the Netherlands can be found in Table 3 below (Hoejnet, 2022).

Table 3: Comparison of mode share between the Amsterdam Transport Region and Amstelland-Meerlanden

	Amstelland-Meerlanden		**Netherlands**	
	#	**%**	**#**	**%**
Car as a driver	95,534,350	35.0%	5,020,966,501	32.3%
Car as a passenger	42,298,849	15.5%	2,155,925,007	13.9%
Train	4,949,217	1.8%	351,024,304	2.3%
Bus/tram/metro	14,916,269	5.5%	384,911,495	2.5%
Moped/scooter	5,927,424	2.2%	181,275,613	1.2%
Bike (electric and non-electric)	68,571,331	25.1%	4,356,259,077	28.0%
Walking	37,335,535	13.7%	2,813,572,173	18.1%
Other	3,801,276	1.4%	266,974,024	1.7%
Total	273,334,251	100.0%	15,530,908,194	100.0%

The data in the table above comes from Onderzoek Verplaatsingen in Nederland (OVin), now known as ODiN, which is a sample of about 40,000 trips taken annually by the Central Bureau for Statistics (Hoejnet, 2022). PT represents a small proportion of trips in the AML area (7.3%), and personal car remains the most used mode with more than half of the modal share. However, the modal share for bus/tram/metro in the AML area is double that for the Netherlands, which demonstrates the relatively high usage of the PT concession services in this area.

4.2 Public Transport Services

The Netherlands has been using the system of competitive tendering for PT services since 2001 (Veeneman & van de Velde, 2014). The transport operator Connexxion has been operating the bus services in this area since 1999. The concession was privately awarded to Connexxion for the period from 2002 until 2007, as the company had already been operating in this area previously (Concessie Amstelland-Meerlanden (2002-2007), 2021). Connexxion won the tender to operate services in this area from 2007 until 2015, but in 2014 it was decided to extend the concession by 2 years due to several planned projects until 2017 affecting the line network, and Connexxion operated the service until 2017 (Concessie Amstelland-Meerlanden (2008-2017), 2022). Connexxion also won the tender the following round and will continue to operate the AML service until at least 2032 (Vervoerregio Amsterdam, 2019).

The AML concession to be studied is that which was active in 2014 during the 2008 – 2017 concession period, as 2014 is the most recent year where all required data for this research is available. AML is between two high-density areas of the Netherlands, therefore the surrounding public transport is focused on Amsterdam Central and Amsterdam South on one side and Schiphol and Haarlem on the other (Programma van Eisen: Concessie Amstelland-Meerlanden 2018, 2018). The AML line network in 2014 consisted of the services shown in Table 4 (Concessie Amstelland-Meerlanden (2008-2017), 2022).

Table 4: Routes operated as part of the Amstelland-Meerlanden concession

Service Type	Number of Routes
City Service Hoofddorp	3
City Service Amstelveen	1
Regional Bus	13
Schiphol Bus	12
RNET	6
Night Bus	5
Peak Only Bus	8
Neighborhood Bus	1
School Bus	2

There are also five NS train stations in the AML concession area, at Schiphol Airport, Nieuw Vennep, Halfweg-Zwanenburg, Hoofddorp, and Duivendrecht, as well as metro services connecting Amstelveen and Amsterdam. The map for the bus services provided by Connexxion in 2014, as well as the NS and metro services, can be seen in Figure 13 and Figure 14.

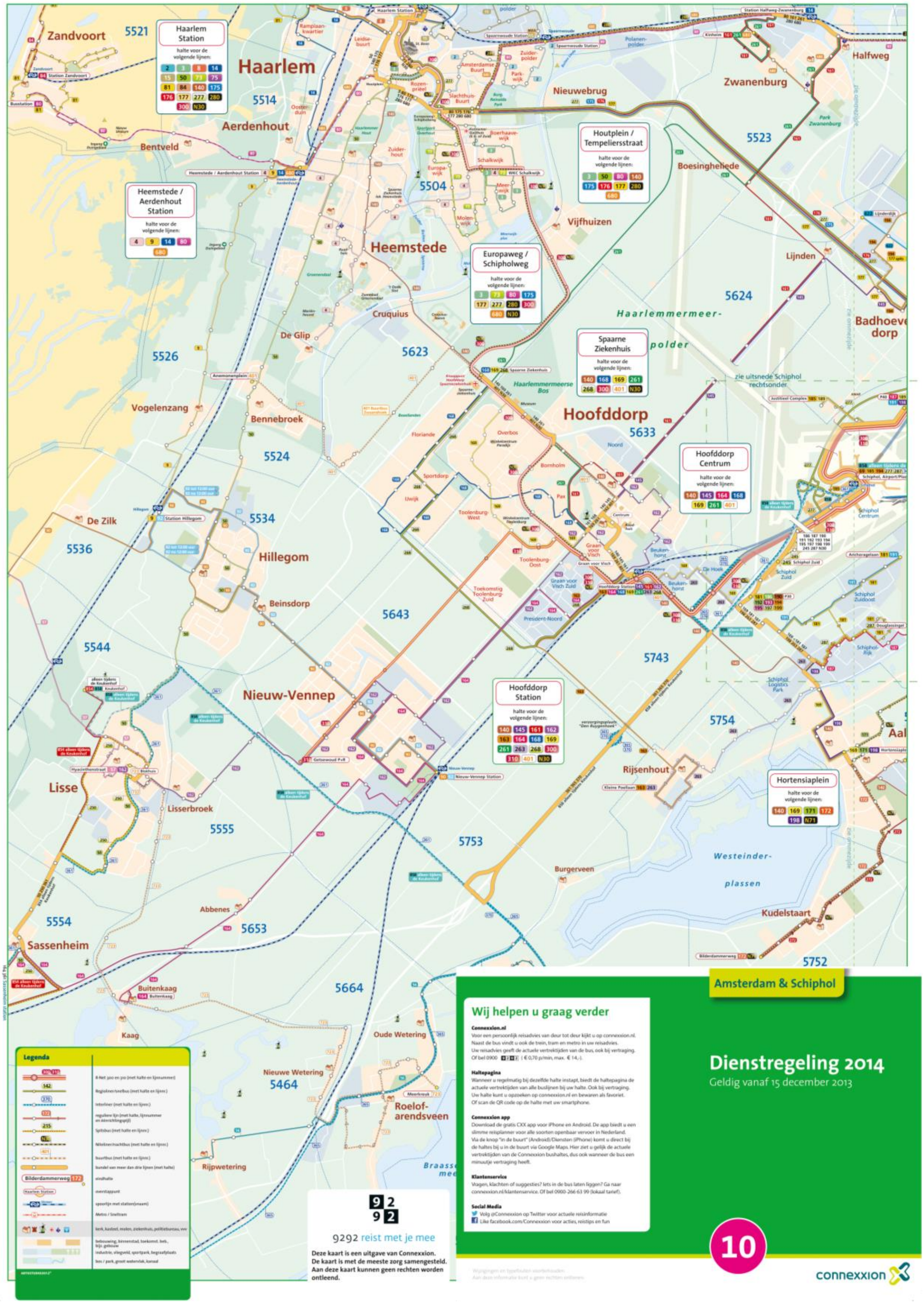


Figure 13: Amstelland-Meerlanden public transport services

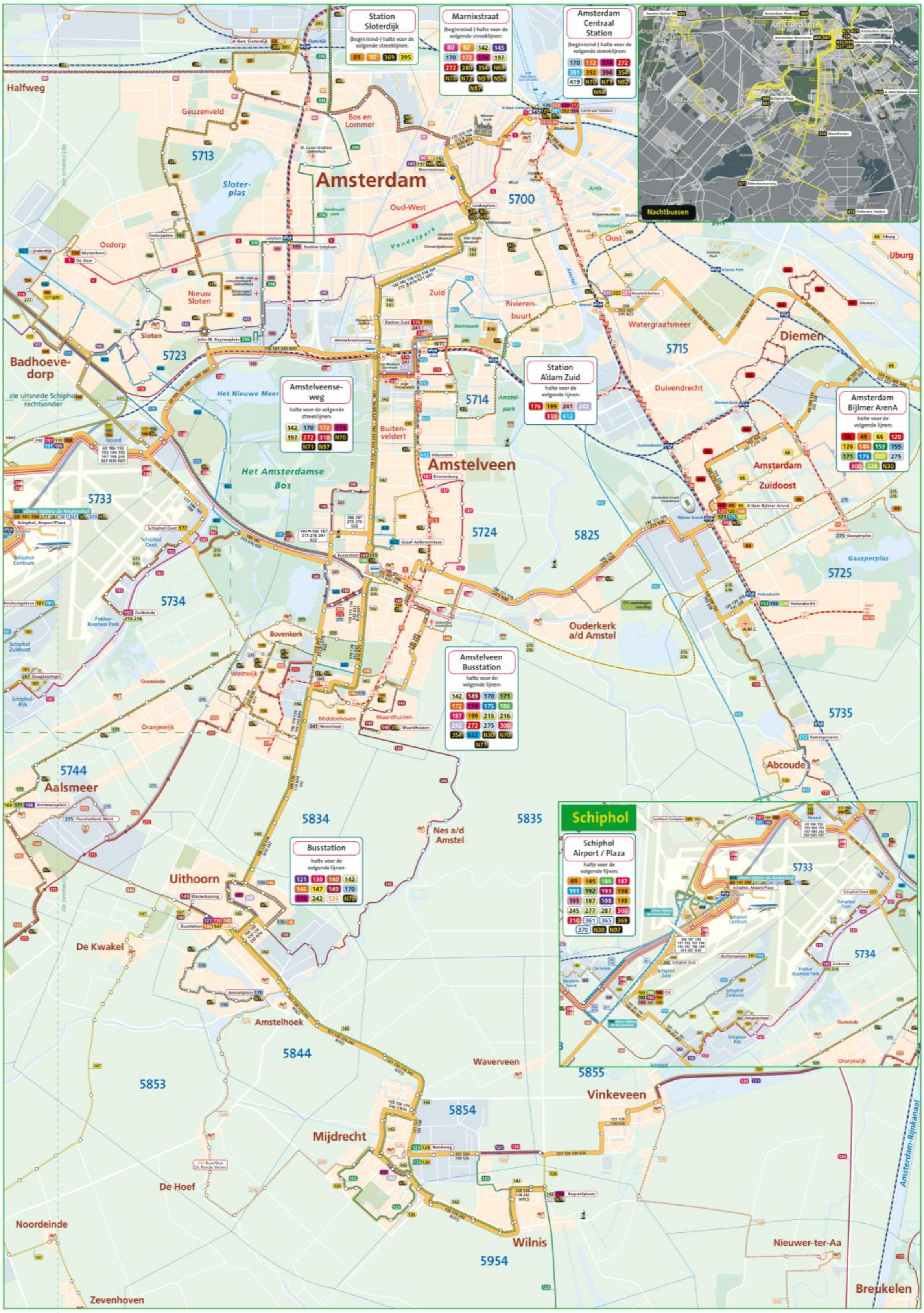


Figure 14: Amstelland-Meerlanden public transport services

4.3 Inclusive mobility and equity at the Amsterdam Transport Region

The Amsterdam Transport Region has some existing policies in place addressing equity in public transport; the Policy Framework on Inclusive Mobility and the Multimodal Network Framework both provide guidance to make PT more inclusive. The Policy Framework on Inclusive Mobility focuses on removing barriers from the PT system to make it more accessible for people with disabilities. This involves improving infrastructure accessibility, lowering the mental barriers to use the PT system and improving travel information, and increased direct cooperation of the Amsterdam Transport Region with these vulnerable populations (Vervoerregio Amsterdam, 2020). While a necessary step towards a more inclusive PT system, this policy is focused on infrastructure improvements and does not directly relate to PT service planning.

The Multimodal Network Framework provides a framework for making and justifying choices and investments in the regional PT network. This framework connects with many existing policies of the Amsterdam Transport Region, and outlines mobility goals and promotes different modes for five types of urban areas (Gaaff, de Koning, Bonnier, van der Slot, & Mout, 2021). This is a form of modal equity and closely resembles equity according to sufficientarianism.

In terms of PT service planning, sufficientarianism is applied in concession documents to guide PT service planning, although this principle is not directly named. In the AML concession, areas are classified into three types based on their population and/or employment density, and it is dictated that these area types must be serviced by some form of PT, although specific service levels are not defined (Programma van Eisen: Concessie Amstelland-Meerlanden 2018, 2018).

In addition to these policy documents, the Amsterdam Transport Region also hired a postdoc researcher in early 2022 to research causal factors relevant to inclusive mobility and to develop a framework to assess the inclusiveness of the Amsterdam Transport Region transport system, specifically for PT, active modes, and multimodal travel (Smart Public Transport Lab, 2022). The research in this thesis, which is a result of continuing cooperation between TU Delft and the Amsterdam Transport Region, will contribute further to the existing efforts of the Amsterdam Transport Region to improve equity in PT.

5

Results and Discussion

In the following chapter, the methods used to evaluate the accessibility distribution according to each of the three distribution principles are applied to the Amstelland-Meerlanden concession area of the Amsterdam Transport Region. Section 5.1 will describe the data used in this thesis, which consists of accessibility data in the form of a generalized travel cost skim matrix and related socioeconomic data. This is followed by section 5.2 which will discuss the calculation of the logsum travel costs, joining of the accessibility and socioeconomic data, and aggregation of this data on the same spatial scale. Section 5.3 will present the results of the equity evaluation according to the principle of egalitarianism, in terms of the spatial distribution and extent of inequities based on the defined equity threshold. Section 5.4 will then use these evaluation results to attempt to make cost-neutral frequency modifications to the AML network in a transport model to achieve an ideal accessibility distribution. Sections 5.5 and 5.6 will perform the same equity evaluation and planning application for the principle of proportionality, followed by sections 5.7 and 5.8, which will do the same for sufficientarianism. Section 5.9 will then compare the results of the equity evaluations and network modifications for the three distribution principles. The overall workflow can be seen in Figure 15 below.

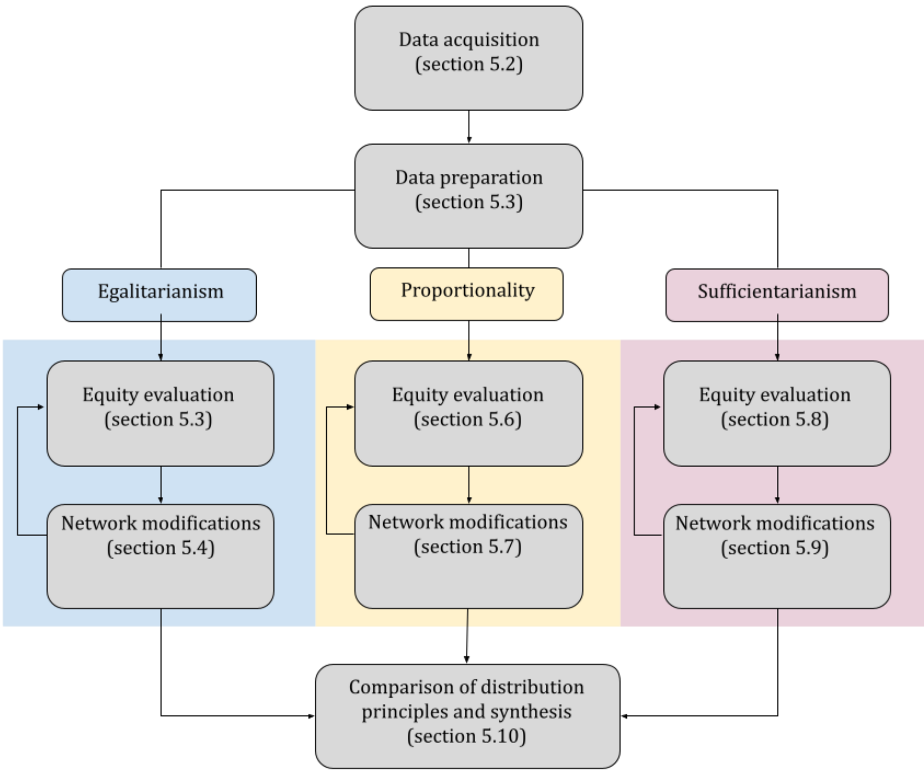


Figure 15: Results workflow

5.1 Data Acquisition

Both accessibility and socioeconomic data are required in order to apply the evaluation methods discussed in chapter 3. Both types of data used in this thesis come from the Verkeerskundig Noordvleugel Model (VENOM), or the Noordvleugel Traffic Engineering Model. The Noordvleugel area of the Randstad includes Haarlem, Zaanstad, Amsterdam, and Utrecht. The model includes the modes of passenger car, freight traffic, bus, tram, metro and train, with walking as an access and egress mode. Passenger car and freight traffic are separated from the PT modes in VENOM as separate OmniTRANS projects. The available time periods in the model, which represents an average working day, are the morning rush hour (7:00 – 9:00) and the evening rush hour (16:00 – 18:00) (Oude Wesselink & van der Linden, 2022).

VENOM has a base year (that is always in the past) and forecast years (2030, 2040, etc.) with a 4-year update cycle. This update cycle involves one major update of a new base year, and three minor updates with forecast adjustments. The current model has a base year of 2014, which at the time of this thesis is being updated for 2018. VENOM connects as much as possible to the National Regional Model (NRM) of the Netherlands, which has four regions: north, south, east, and west. NRM-West is the basis for VENOM and is the source of the socioeconomic data used in VENOM. This socioeconomic data includes zonal data on population demographics, income, employment, and education (Oude Wesselink & van der Linden, 2022).

Travel costs for PT in VENOM are calculated as skim matrices in the form of travel time, travel distance, and generalized travel cost. The skim matrices show the shortest time, distance, and cost between each set of OD pairs. Data from the generalized travel cost skim matrix is used to calculate the accessibility measure in this research, which is the logsum travel cost. Generalized travel cost includes both travel time and fare, providing a more complete representation of the cost of travel than either time or distance alone. BTM (Bus Tram Metro), train, and HSL (high-speed line) are the three categories of PT modes available in VENOM (Willigers, 2020).

The generalized travel cost calculation considers distance (which is only used to calculate the fare), the in-vehicle time, waiting time, transfer time, and the transfer penalty. The PT fares used in this study can be found in Appendix A. For all PT modes, there is a 50% penalty for waiting time, which represents the perception of waiting time feeling longer than that of other travel time components. The transfer penalty for transfers made during a trip is equivalent to 5 minutes, and the time value of money is 7.5 minutes per euro. For bus, there is an additional 15% weighting factor added for in-vehicle time and waiting time, which represents the perception of longer travel times when using the bus. The weights used in the generalized travel cost function have been estimated based on a literature survey of travel time components in the Netherlands (Willigers, 2020). By using weights in these calculations, the perceived cost of travel is captured in the accessibility measure, and the behavior of travelers is represented better than if the actual travel time were used. The following calculations for the utility of travel in VENOM were provided by Goudappel B.V (Willigers, 2020).

The utility function is based on the following generalized travel cost function:

$$V_{ij} = V_{ij,bus} * \delta_{bus} + V_{ij,nonbus} * \delta_{nonbus} \qquad (7)$$

Where:

V_{ij} = utility of traveling from zone i to zone j

δ_{bus} = dummy variable that is 1 when a bus is used for any of the trip legs

δ_{nonbus} = dummy variable that is 1 when a non-bus PT mode is used for any of the trip legs

The utility for bus trip legs is calculated in formula 8 below:

$$V_{ij,bus} = \beta_t^{bus} \cdot t_{ij}^{bus} + \beta_w^{bus} \cdot w_{ij}^{bus} + \beta_r^{bus} \cdot r_{ij}^{bus} + \beta_z^{bus} \cdot z_{ij}^{bus} + \beta_f^{BTM} \cdot f_{ij,d}^{BTM} \quad (8)$$

Where:
β_t^{bus} is the weight for the bus in-vehicle time component
t_{ij}^{bus} is the bus in-vehicle time from zone *i* to zone *j*
β_w^{bus} is the weight for the bus waiting time component
w_{ij}^{bus} is the time spent waiting for the bus from zone *i* to zone *j*
β_r^{bus} is the weight for the bus transfer walking time component
r_{ij}^{bus} is the time spent walking between transfer points from zone *i* to zone *j*
z_{ij}^{bus} is the number of transfers with bus from zone *i* to zone *j*
β_z^{bus} is the weight for the bus transfer penalty component
$f_{ij,d}^{BTM}$ is the BTM fare for distance *d* travelled with the bus from zone *i* to zone *j*
β_f^{BTM} is the weight for the BTM fare component

Each cost component is also multiplied by a conversion factor if needed to transform the unit for all components to perceived minutes. The values for the weights of each bus component in VENOM are as follows: $\beta_t^{bus} = 1.15$, $\beta_w^{bus} = 1.725$, $\beta_r^{bus} = 1$, $\beta_z^{bus} = 5$, and $\beta_f^{BTM} = 1$.

The utility for non-bus PT modes includes tram and metro, HSL, and train, as seen in formulas 9 - 12 below:

$$V_{ij,nonbus} = V_{ij,tram,metro} + V_{ij,HSL} + V_{ij,train} \quad (9)$$

Where:

$$V_{ij,tram,metro} = \beta_t \cdot t_{ij}^{tram,metro} + \beta_w \cdot w_{ij}^{tram,metro} + \beta_r \cdot r_{ij}^{tram,metro} + \beta_z . z_{ij}^{tram,metro} + \beta_f \cdot f_{ij,d}^{BTM} \quad (10)$$

$$V_{ij,HSL} = \beta_t \cdot t_{ij}^{HSL} + \beta_w \cdot w_{ij}^{HSL} + \beta_r \cdot r_{ij}^{HSL} + \beta_z \cdot z_{ij}^{HSL} + \beta_f . f_{ij,d}^{HSL} \quad (11)$$

$$V_{ij,train} = \beta_t \cdot t_{ij}^{train} + \beta_w \cdot w_{ij}^{train} + \beta_r \cdot r_{ij}^{train} + \beta_z \cdot z_{ij}^{train} + \beta_f \cdot f_{ij,d}^{train} \quad (12)$$

Where:
β_t is the weight for the in-vehicle time component
t_{ij} is the in-vehicle time from zone *i* to zone *j*
β_w is the weight for the waiting time component
w_{ij} is the time spent waiting for the bus from zone *i* to zone *j*
β_r is the weight for the transfer walking time component
r_{ij} is the time spent walking between transfer points from zone *i* to zone *j*
β_z is the weight for the transfer penalty component
z_{ij} is the number of transfers with bus from zone *i* to zone *j*
β_f is the weight for the fare component
$f_{ij,d}$ is the fare for distance *d* travelled with the bus from zone *i* to zone *j*

Again, each cost component is also multiplied by a conversion factor if needed to transform the unit for all components to perceived minutes. The values for the weights of each non-bus component in VENOM are as follows: $\beta_t = 1$, $\beta_w = 1.5$, $\beta_r = 1$, $\beta_z = 5$, and $\beta_f = 1$.

The final generalized travel costs between all zones in VENOM are provided in the form of an origin-destination skim matrix. The costs from this matrix are then used to calculate the logsum accessibility as explained in chapter 3. This provides the generalized travel costs from one zone to all other zones in the study area, for every origin zone. It should be noted that a higher logsum value represents lower accessibility, since a higher value means that the cost of travel to other zones is higher.

The logsum travel costs represent a cost for all potential, not necessarily actual, travel within the area. It is also important to consider that all zones are weighted equally regardless of demand patterns indicating the attractiveness of the zone to travelers. Therefore, travel costs to less attractive zones are considered the same as travel costs to more attractive zones with more destinations. Weighting travel cost based on travel demand is not done in this analysis because it could introduce bias from existing spatial disparities.

5.2 Data Preparation

Although the spatial zones in VENOM and their associated travel costs are at the PC5 postcode level, the sociodemographic data associated with them is only available at the more aggregated PC4 postcode level. Therefore, VENOM zones with the same PC4 postcode have the same socioeconomic characteristics and need to have their travel costs aggregated in a way that the socioeconomic data and accessibility data are at same spatial scale. Because it is not possible to separate the socioeconomic data into a more micro scale, the travel costs must be aggregated at a larger scale. This is done when calculating the logsum travel cost for each PC4 postcode as described in chapter 3. Additional sociodemographic data from Statistics Netherlands (CBS) that is not available in the VENOM dataset can also be joined to the VENOM dataset using the PC4 postcode field.

5.3 Egalitarianism Evaluation Results

The following section will apply the equity evaluation using the distribution principle of egalitarianism, which states that the distribution of PT logsum travel costs should be equal for all zones (Litman, 2022). This will be done by presenting the Lorenz curve and Gini coefficient for the AML area, followed by discussions of the geographical distribution and extent of inequality in this area according to this principle.

5.3.1 Lorenz curve and Gini coefficient

When applying the principle of egalitarianism to an equity evaluation of the AML concession area, the following Lorenz curve is obtained. The graph in Figure 16 below shows the Lorenz curve for the distribution of PT accessibility in the case study area. The x-axis represents the percentile of the population ordered by average income, and the y-axis represents the cumulative proportion of the logsum generalized travel costs.

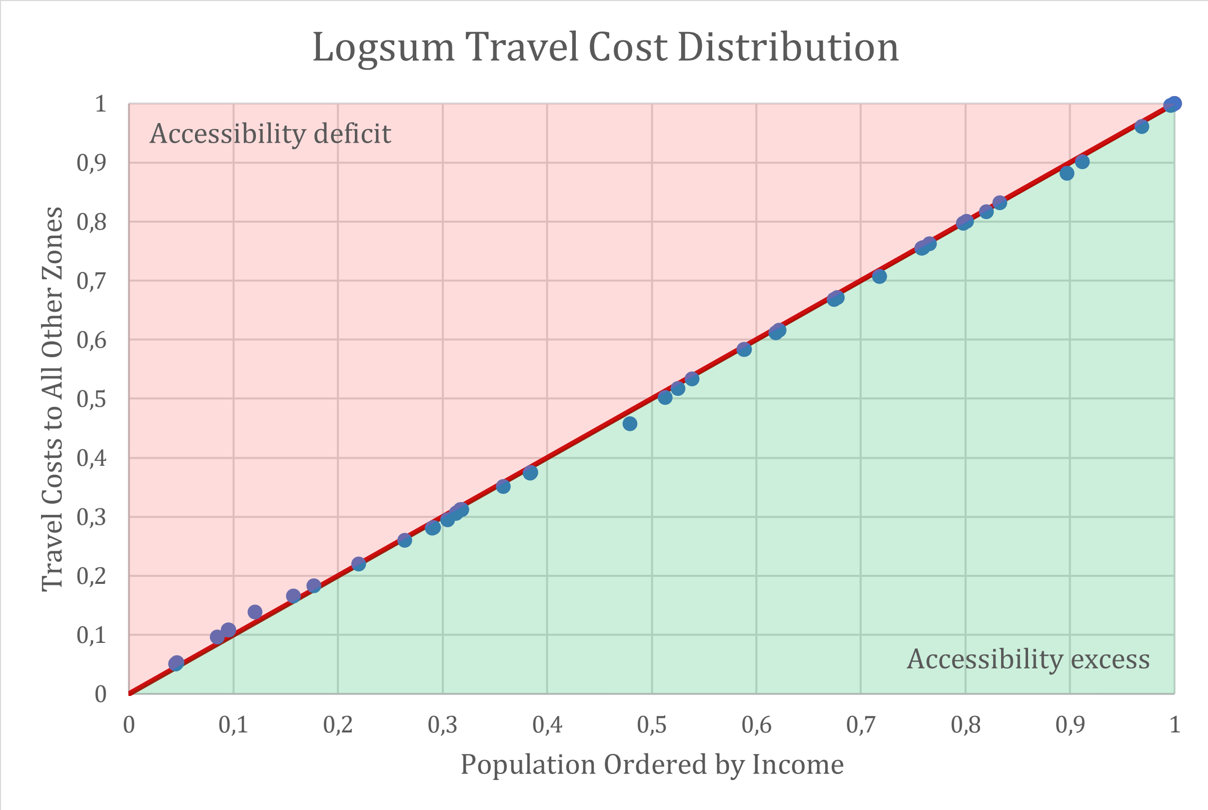


Figure 16: Lorenz curve showing distribution of logsum travel costs in Amstelland-Meerlanden

In Figure 16, each point represents a zone, which in this research is a PC4 postcode. Points below the line of equality indicate that the percentile of the population has lower travel costs, meaning that there is an accessibility surplus. Points above the line of equality indicate that the percentile of the population has higher travel costs, and therefore a deficient proportion of the total accessibility in the area.

Overall, the distribution of accessibility in the AML concession area is quite equal, with most points near the equality line. Upon closer examination of Figure 16, it is possible to see a slight pattern in the small deviations from the equality line. While the principle of egalitarianism would state that all people in the area should receive equal levels of accessibility, based on the ordering of the population by income, it is possible to gain some insight into the distribution of accessibility for different income groups within the population. This is an example of using egalitarianism to evaluate the vertical equity of a distribution, in addition to the horizontal equity. For the first 20th percentile of the population, the majority of points, which represent lower income zones, are above the line of equality, suggesting slightly increased travel costs and a lower accessibility level. For example, the 17.7th population percentile experiences 18.3% of the travel costs, exceeding the equal share of travel costs by 0.6%. Zones with middle incomes in the 20th to 60th percentile of the population are primarily on or below the line of equality, suggesting that these zones have slightly better accessibility than low-income zones. The remaining zones, which represent higher income population groups, have points primarily below the equality line, indicating that they receive a slightly increased level of PT accessibility. For example, the 89.7th population percentile has 88.2% of the travel costs, indicating a travel cost 1.5% below the value in an equal distribution. Although the distribution of logsum travel costs in the case study area is almost perfectly equal, there is slightly better PT accessibility in the middle- and higher-income zones relative to zones with low incomes.

It is also important to note the level of service in the AML area, as an egalitarian distribution does not indicate the level of service. Overall, the supply of PT service in the AML area is decent, even in zones with low densities. When looking at the maps in Figure 13 and Figure 14 from chapter 4, PT service is most concentrated in higher density municipalities and around Schiphol airport. However, comparable levels of PT service are provided in the in-between rural and recreation areas, as these zones are on-route between different municipalities and destinations. Even when these low-density zones are not on-route, PT service is still provided. For example, route 149 between Uithoorn and Amstelveen provides service 1x/hour during the morning peak along the Amstel River, despite the very low density of this area and the indirectness of this route between Uithoorn and Amstelveen. While this is not the same level of service provided at destinations such as Schiphol Airport, a fixed route service is still provided, although with a frequency proportional to its population.

The distribution of logsum travel costs is quite equal, which is further proven by the calculation of the Gini coefficient, which for this area is 0.0083, an almost perfectly equal distribution. This means that all inhabitants in the AML concession area receive comparable levels of potential PT accessibility. One possible explanation for the equality of this distribution is that the logsum travel cost is used as the accessibility metric instead of the supply of PT service. This somewhat limits the impact that a high level of PT supply has on accessibility. In-vehicle time is a major component of the generalized travel cost but is unaffected by the number and frequency of routes in VENOM. By comparing the logsum travel costs instead of the supply of PT service, the AML network appears more equal. Another possible explanation for this distribution could be the level of investment in PT in the Netherlands, where even areas with low population density receive some minimum level of PT service. A common argument against egalitarianism being the principle to evaluate accessibility distribution in PT is that the costs of PT service provision are higher in areas with lower populations (Rubensson, Susilo, & Cats, 2020). However, the AML concession shows that an egalitarian distribution is achievable if there is a willingness from society and decision-makers to invest in a high level of PT accessibility for everyone.

5.3.2 Spatial Distribution of Inequality

It is interesting to look at where zones with excess or deficient accessibility are located relative to different income groups, as this indicates who is being affected by inequality. The spatial distribution of incomes in the concession area can be seen in Figure 17 below, with each color representing a 20th percentile of the population. Areas with the red outline show zones with a travel cost excess (or accessibility deficit) of more than 0.5%, and zones with a green outline have a travel cost deficit (or accessibility excess) of more than 0.5%.

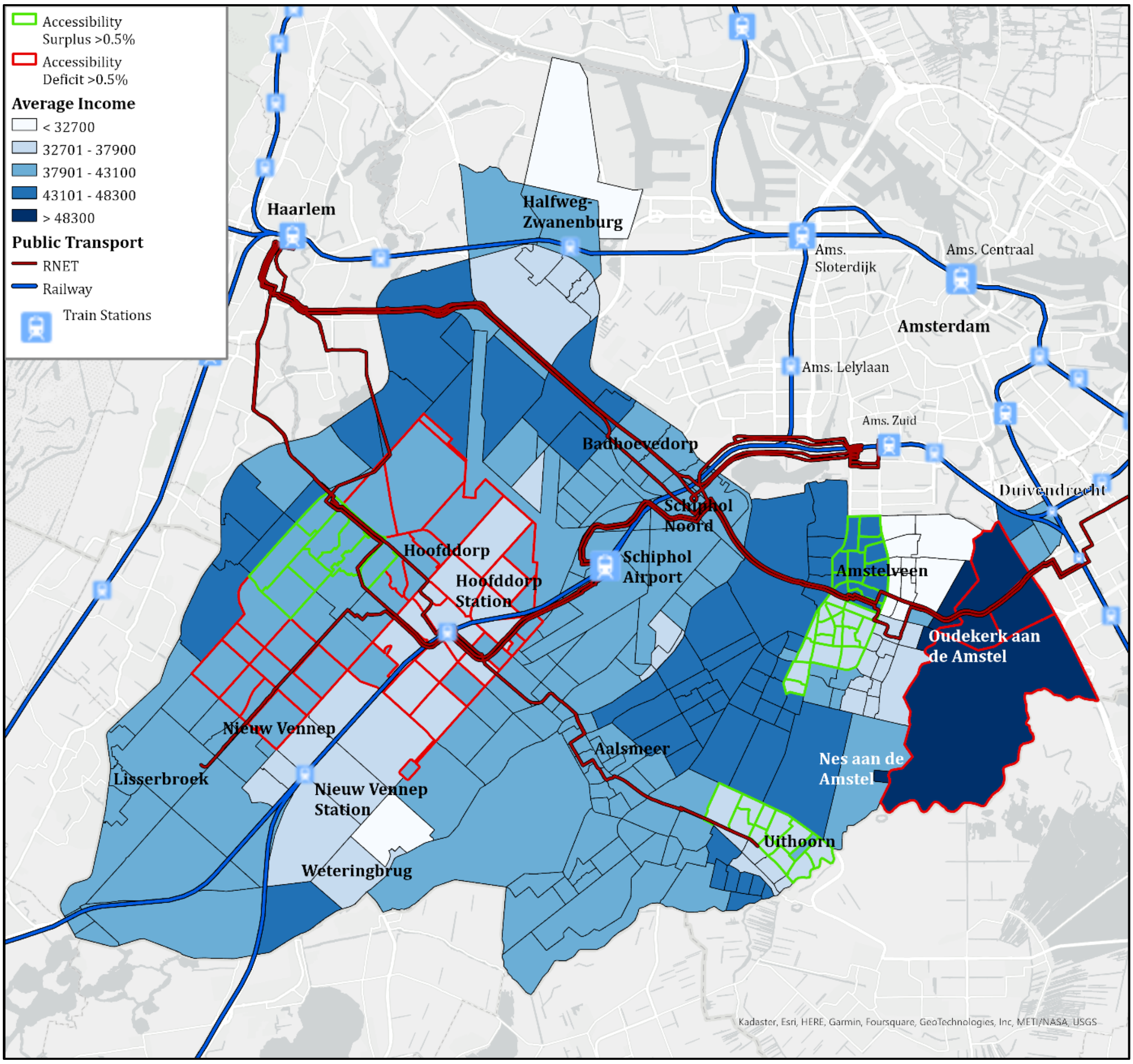


Figure 17: Areas of accessibility excess and deficit in Amstelland-Meerlanden according to egalitarianism, relative to income

As can be seen in Figure 17 above, the areas of Hoofddorp, Nieuw-Vennep, and Oudekerk aan de Amstel have logsum travel costs that exceed by more than 0.5% what is justified according to their share of the concession area population. These zones have varying population and employment densities, with Hoofddorp being the most dense of the three and Oudekerk aan de Amstel being the least. Amstelveen, Uithoorn, and the western part of Hoofddorp have logsum travel costs that are more than 0.5% lower than what is justified based on their population share. All three zones are relatively dense compared to the rest of the concession area; therefore it is expected that they would receive a higher level of PT accessibility than the equal level.

Depending on the priorities of the transport authority in the area, the combination of accessibility distribution and income information could be used to prioritize certain areas over others when facing limited resources. For example, if it is important to the authority for lower-income areas to not be deficient in PT accessibility, then perhaps eastern Hoofddorp would be prioritized over Oudekerk aan de Amstel for additional PT resources, as it has a lower average income.

The distribution of logsum travel costs relative to areas of accessibility excess and deficit according to egalitarianism is shown in Figure 18 below.

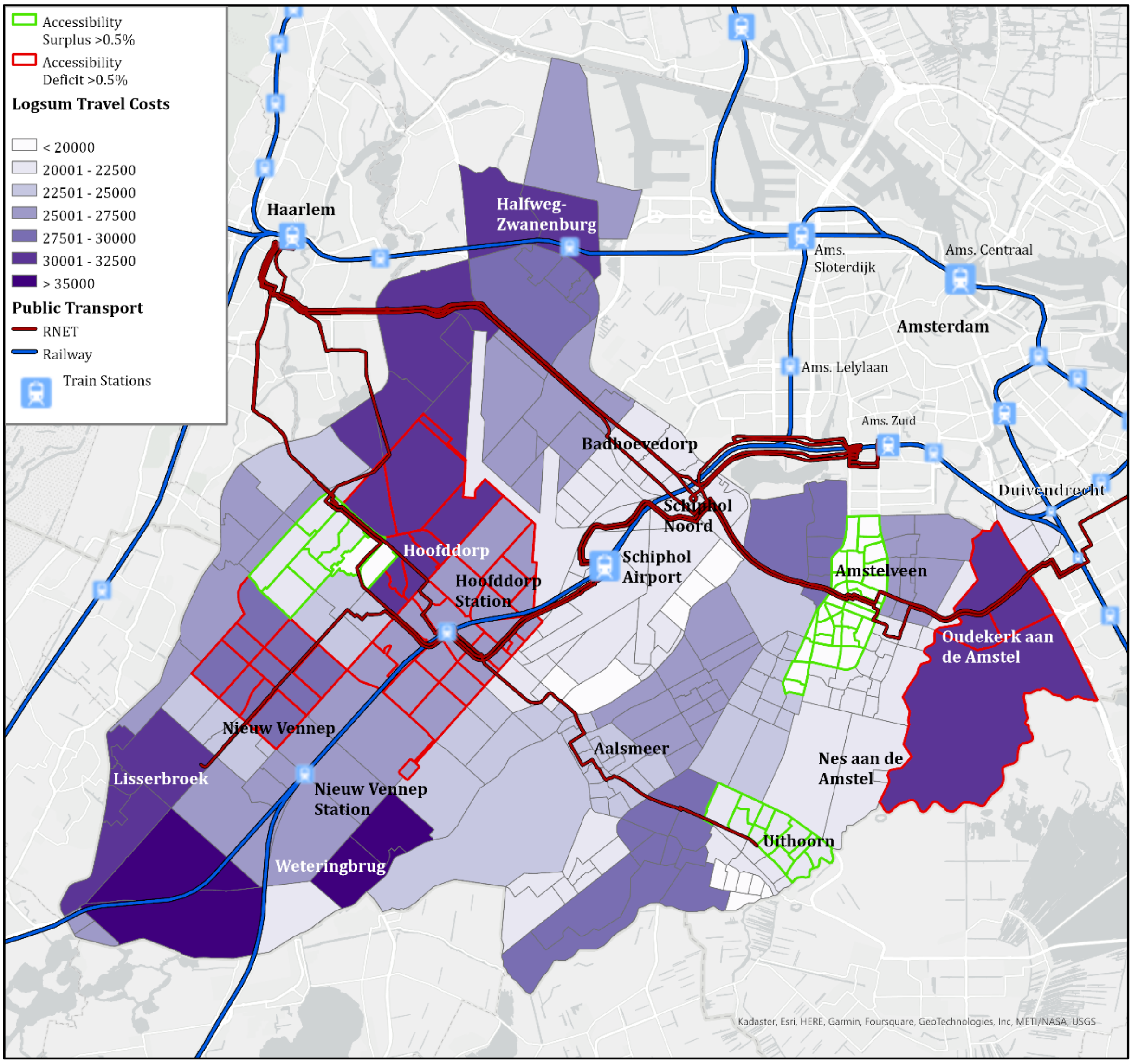


Figure 18: Areas of accessibility excess and deficit in Amstelland-Meerlanden according to egalitarianism, relative to public transport logsum travel costs

Upon examination of Figure 18, it can be seen that in areas with accessibility surpluses the logsum travel costs are lower, whereas in areas with accessibility deficits the logsum travel costs are higher. Because the logsum travel costs in the evaluation are weighted according to population, there are areas with higher logsum travel costs that are not considered to have an accessibility deficit. This means that their logsum travel costs are acceptable given these zone's share of the total area population.

5.3.3 Degree of inequality

It is also possible to look at egalitarianism in terms of the absolute surplus and deficit logsum travel costs instead of as a percentage. This can be done by calculating the ideal logsum travel cost per zone, which is what the logsum travel cost per zone would be if the distribution of accessibility in the area was perfectly equal. This ideal cost is calculated by dividing the total logsum travel costs in the area by the number of zones. Then, this ideal cost can be compared to the actual travel costs to determine how close the absolute travel costs are to that of an ideal state. The ideal target logsum travel cost for the AML area with the existing PT network is calculated to be 24,619 perceived minutes. The distribution of the degree of inequality in terms of the logsum travel costs can be seen in Figure 19 below.

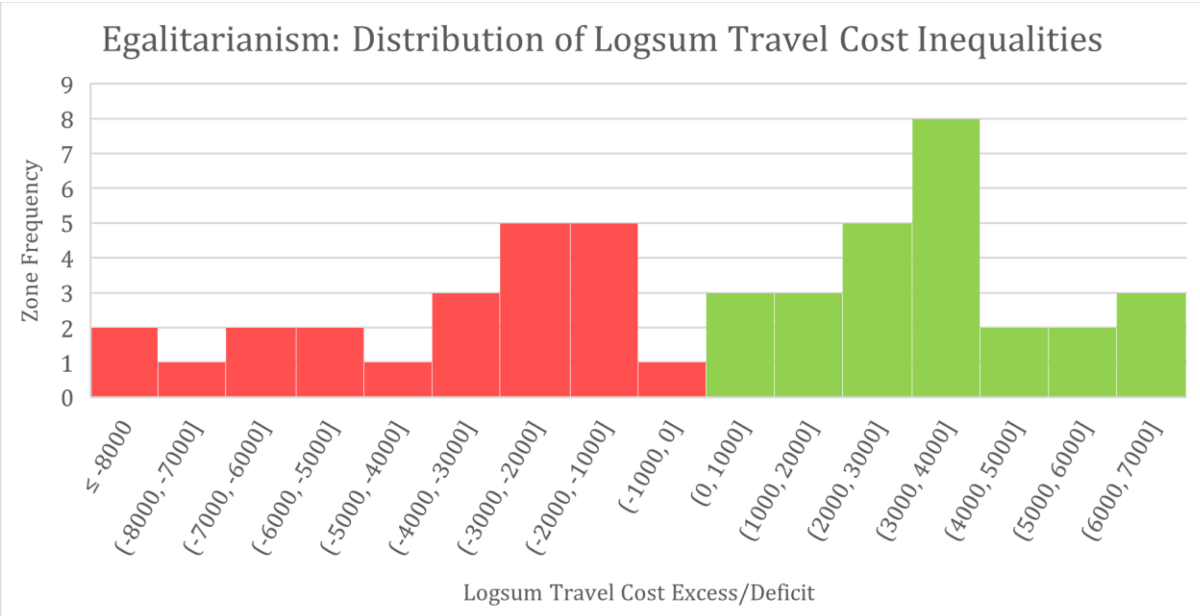


Figure 19: Distribution of surplus and deficit logsum travel costs in Amstelland-Meerlanden according to egalitarianism

Figure 19 gives an idea of how much the accessibility of each zone would have to change for the distribution to become exactly equal. While the accessibility surpluses and deficits are small when calculated for the Lorenz curve, they are larger when the actual logsum travel cost for each zone is compared to the ideal logsum travel cost for each zone. It should also be mentioned that the areas according to the absolute accessibility surplus and excess are different than the areas according to the percentage surplus and deficit. This is because the percentage differences consider the population per area, while the absolute differences do not. Therefore, the percentage differences are useful for prioritizing which areas to address based on population, while the absolute differences indicate a goal value for the logsum travel costs for each zone.

5.4 Egalitarian PT Network Design

Although the AML PT network is quite equal according to the Lorenz curve and Gini coefficient, there are areas of minor accessibility excess and deficit. Therefore, it is still possible to make modifications to the AML PT network to achieve a more egalitarian distribution of accessibility. One of the original objectives of this research was to modify the frequencies of routes in the AML PT network to achieve an accessibility distribution closer to the ideal version for each distribution principle, without increasing operating costs. However, in the case of egalitarianism, this is not possible using the traditional planning approach, which involves increasing PT service in areas with deficient accessibility and decreasing PT service in areas with excess accessibility. The steps taken to reach this conclusion will be outlined in the remainder of this section, followed by a discussion of why this approach did not work as intended.

Section 5.3.2 identified the zones with the highest accessibility deficits and surpluses. The initial goal was to address a limited selection of the zones with the largest percentage accessibility deficits. Several iterations of frequency changes were then performed in VENOM based on the locations and degree of accessibility surplus and excess. This involved increased frequencies for routes with stops in and near these postcodes, and decreased frequencies in other zones with high surpluses to compensate for the increased operating costs in the target zones. Frequency adjustments were only made for bus routes; tram and train service were not changed.

After each iteration of frequency changes, the PC5-level OD matrix was exported from Omnitrans and used to calculate the PC4-level logsum travel costs within the study area as explained in chapter 3. The distribution of travel costs between zones and the Gini coefficient were then compared to the original distribution to see how the deficient zones were affected and how the equality of the overall distribution changed, respectively. However, with this approach to frequency modifications, there were no successful iterations with a Gini coefficient lower than that with the original network.

There are several possible reasons for this, the first of which is the use of the logsum as the accessibility measure. When the frequency of a route is changed, it doesn't only change the travel costs for the zones containing that route; it will also change the travel costs for any zones with OD pairs using that route. This is the nature of the logsum accessibility measure, as it considers the travel costs to all other zones. In a similar way, changing a route significantly affects all zones within walking distance of the route, not only the targeted zone. Hence, it is not possible to affect the accessibility for only the target zones. In the case of egalitarianism specifically, it is very difficult to achieve an equal distribution using traditional planning methods because the target accessibility changes every iteration. This ideal accessibility, which in the case of egalitarianism is the same for every zone, is the total logsum travel costs in the area divided by the number of zones. The total area logsum travel costs change every time a frequency adjustment is made, therefore shifting the ideal travel cost value per zone. This circular calculation makes it unknown by how much the target travel costs for a zone should be adjusted to achieve the ideal accessibility distribution.

The combination of these reasons makes it very difficult to use the equity evaluation according to egalitarianism in the traditional network planning process. This method is therefore better suited for use in evaluation and PT network comparison than as a tool to make individual network changes. However, it could be used when network changes are made based on another goal, for example ridership. Then, the Lorenz curves and Gini coefficients of the networks can be compared to see if the changes made the network more or less equal (if equality is the objective of the transport authority or other decision-maker).

5.5 Proportionality Evaluation Results

The following section will apply the equity evaluation using the distribution principle of proportionality, which states that the distribution of PT logsum travel costs should be proportional to selected land use and demographic factors (Litman, 2022; Rubensson, Susilo, & Cats, 2020). This will be done by comparing a calculated target accessibility and actual accessibility for each zone in the AML area, followed by discussions of the spatial distribution and degree of inequity according to this principle.

5.5.1 Calculation of target accessibility

To calculate the target accessibility for each zone, it is first necessary to determine what relevant factors to include in the regression. Of the available data from VENOM and CBS, the factors selected for consideration for inclusion in the regression are population density, household density, employment density, and address density. The data for address density is not available in the VENOM dataset, and instead comes from CBS and can be joined to the VENOM data based on the PC4 postcode field. It should be noted that there were other factors that could have also been considered, but it was decided to only consider relevant factors that had been identified in the literature review and were available from the VENOM and CBS datasets.

As explained in chapter 3, an assumption of linearity is made for simplicity, although it is possible that the data may not be linear. The scatterplots of the four selected factors and their linear trendlines can be seen in Figure 20, Figure 21, Figure 22 and Figure 23 below, with each point representing a zone (PC4 postcode).

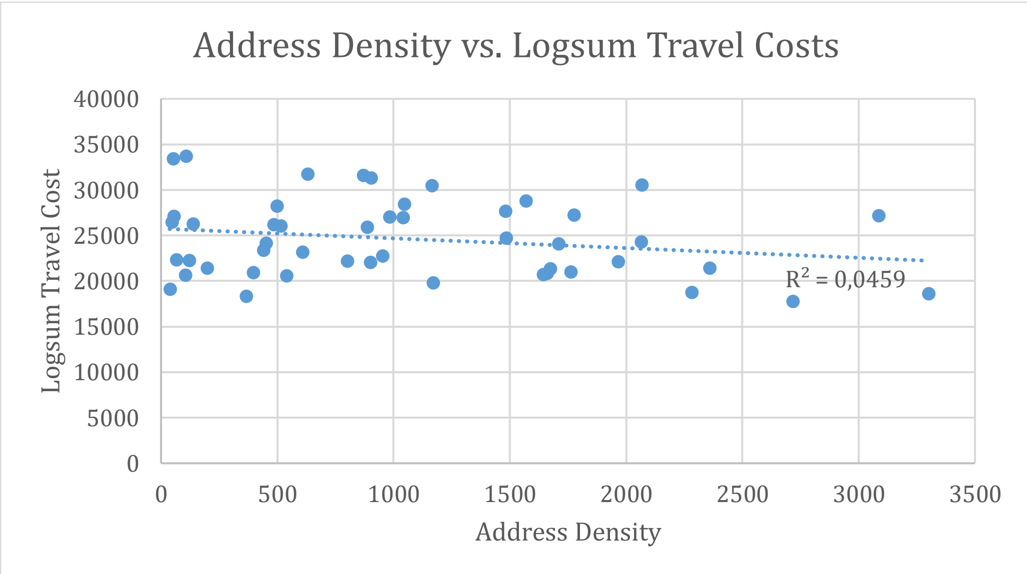


Figure 20: Scatterplot showing relationship between address density and logsum travel cost

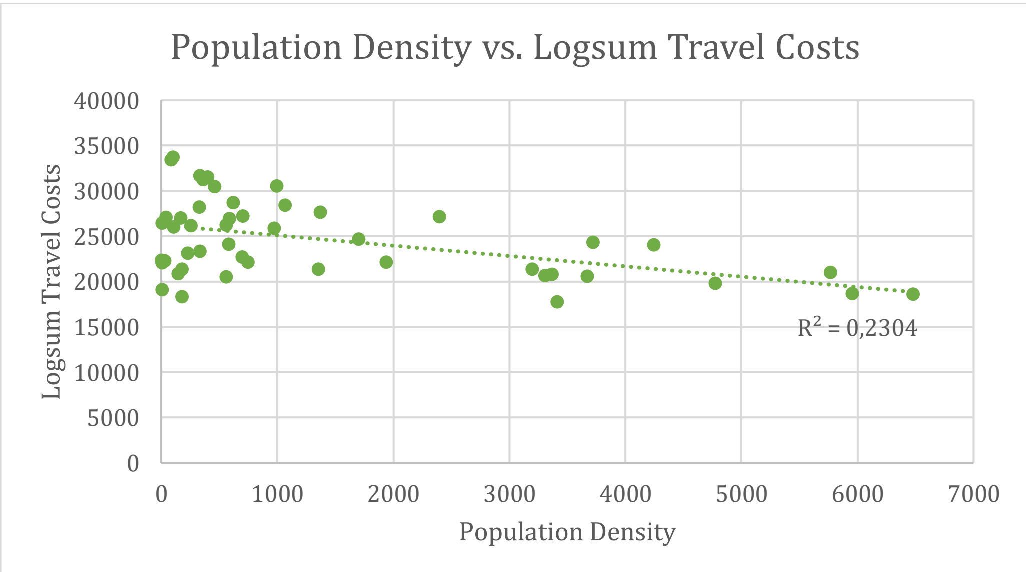


Figure 21: Scatterplot showing relationship between population density and logsum travel cost

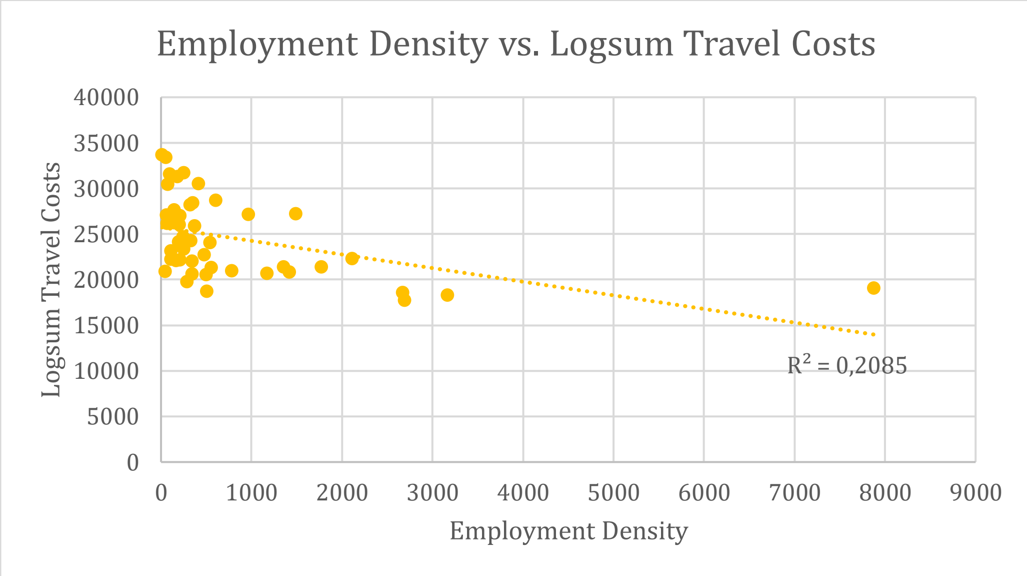


Figure 22: Scatterplot showing relationship between employment density and logsum travel cost

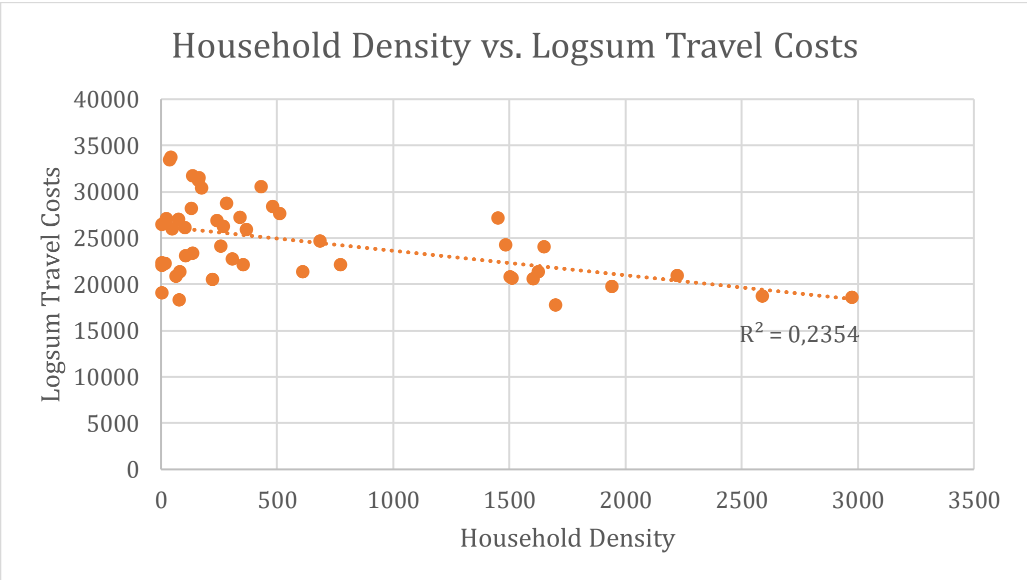


Figure 23: Scatterplot showing relationship between household density and logsum travel cost

It can be seen from the figures above that a linear relationship may not be the best fit for the data. For example, a logarithmic trendline for employment density has an R-square value of 0.364 as opposed to the linear trendline R-square of 0.209. It could be possible to test many types of non-linear regression to find the best fit for the data, but in this analysis, this is not done to maintain simplicity. This could result in more and larger accessibility surpluses and deficits than there would be for a model that fits the data better.

Regression analyses were performed for each individual potential factor to determine what factor(s) should be included in the final target accessibility calculation, with each factor as an independent variable and the actual logsum travel costs as the independent variable. The results from these tests can be found in Table 5 below, where X* represents coefficients with p-values of more than 0.05.

Table 5: R-square values for each possible model factor

Regression model	Population density	Household density	Employment density	Address density	R square
1	X				0.230
2		X			0.235
3					0.209
4			X		0.231
5				X*	0.046
6	X*	X*	X	X*	0.431
7		X	X		0.391
8	X		X		0.397

Based on its low R-square and high p-value, it was decided to exclude address density from the model. Both household density and population density have high R-squares and low p-values, but as they are highly correlated with one another, only one of these two factors should be present in the model. The model with employment density and population density provided a slightly better fit than the model with employment density and household density, therefore population density was selected as a factor over household density. While the R-square value is lower for this two-factor than in the model with all four variables included, the improvement in the R square in the four-factor model is too small to justify the increased model complexity. This leads to the following multiple regression equation based on employment density and population density:

$$Target\ Accessibility = 27111.5 - 1.343064 \times \text{Jobs density} - 1.037416 \times \text{Population density} \quad (13)$$

Equation 13 above can then be used to calculate the target accessibility, which in this case is the level of accessibility (expressed in logsum travel costs) that a zone is warranted based on the number of jobs per square kilometer and inhabitants per square kilometer. Both the actual and target accessibility in this analysis are calculated at the more aggregated PC4 level because regression at the PC5 postcode level led to very low R-square values for all factors, meaning that it would not be possible to create a useable calculation for the target accessibility using linear regression at the PC5 spatial scale.

5.5.2 Spatial Distribution of Inequity

The calculated target accessibility for each zone can then be compared to the actual accessibility to determine if a zone has an accessibility excess or deficit based on the selected factors. If the target logsum travel cost is lower than the actual, then there is an accessibility deficit, while if the target cost is higher than the actual cost then there is an accessibility surplus.

Accessibility surpluses and deficits are influenced by the target accessibility, which is based on a zone's population density and employment density, and the actual accessibility, which is impacted by the level of PT service from that zone to all other zones. The accessibility surplus and excess can be better understood by looking at the logsum travel costs and the relevant factors individually, as seen in Figure 24, Figure 25, Figure 26 and Figure 27 below.

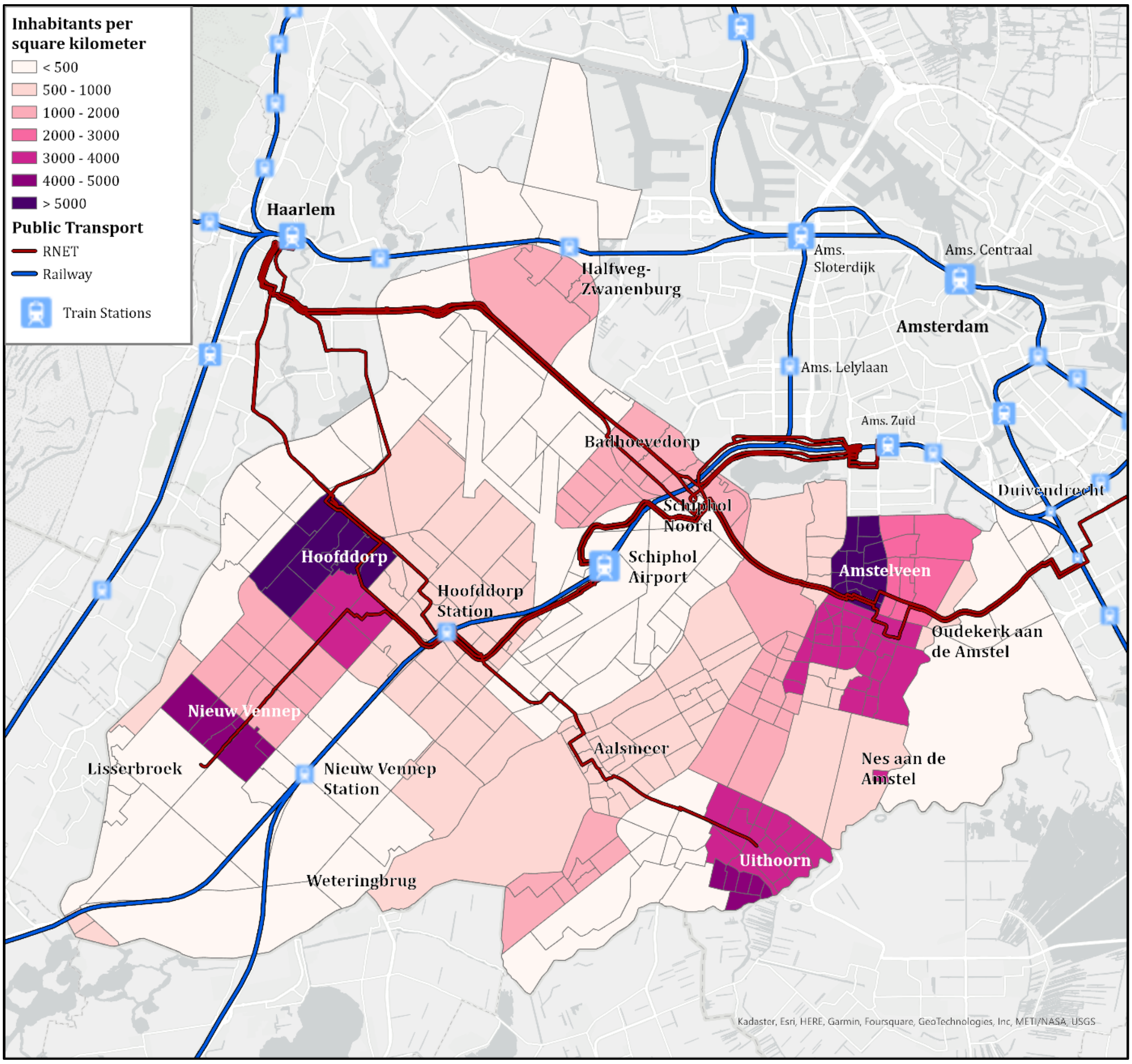


Figure 24: Population density in Amstelland-Meerlanden

The areas of high population density can be found in western Hoofddorp and Nieuw-Vennep, Amstelveen, and Uithoorn. Despite being an important destination in the study area, Schiphol has a relatively low population density, as this is not a residential area. Low population densities are also found on the periphery of the concession area.

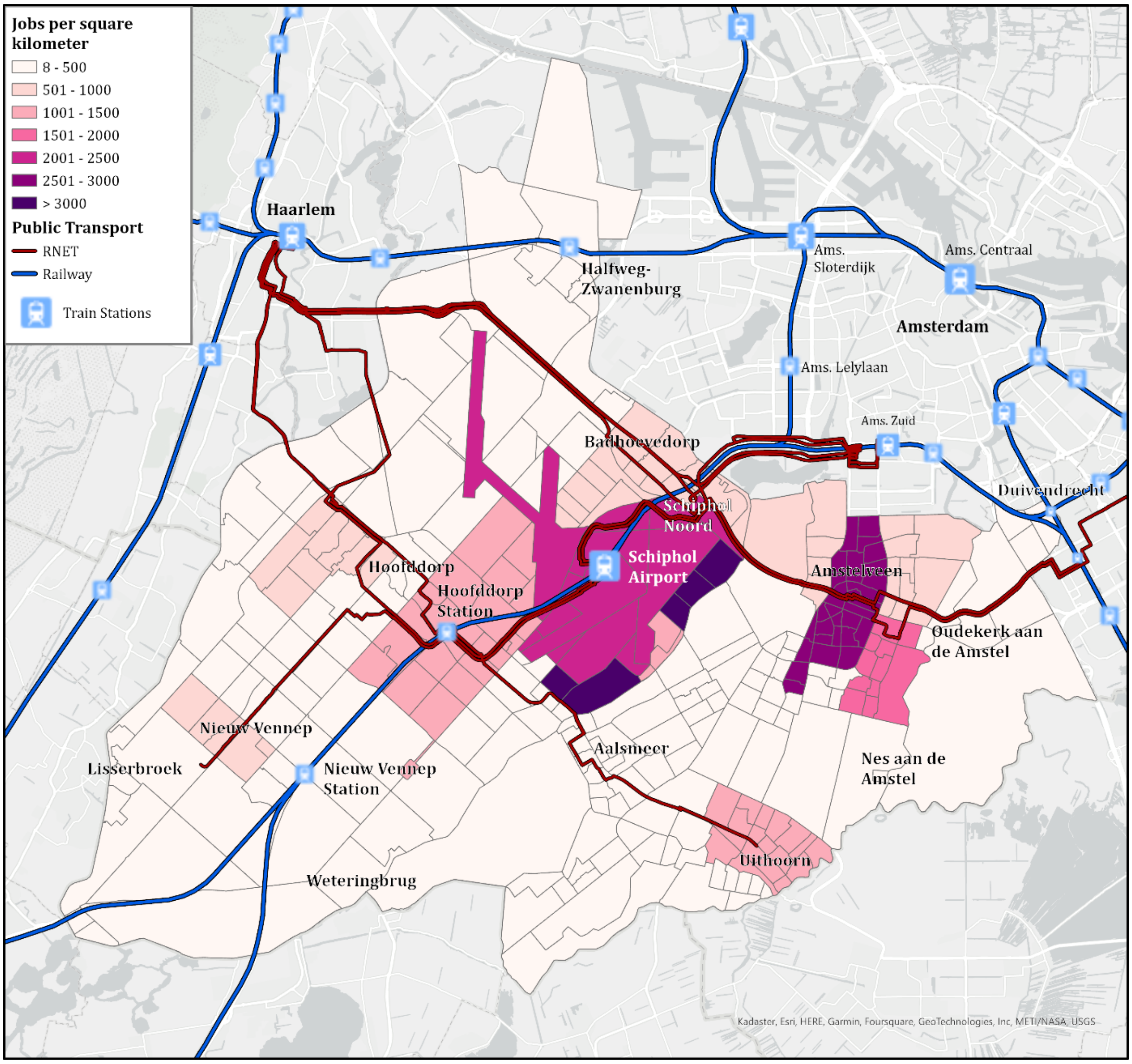


Figure 25: Employment density in Amstelland-Meerlanden

The areas with the highest employment density are Schiphol airport, its surrounding areas, and Amstelveen. Western Hoofddorp, Nieuw-Vennep and Uithoorn, which have the highest population densities in the AML area, have low to moderate employment densities. The areas on the periphery of the concession also have low employment densities, as well as some more central areas such as Aalsmeer and parts of Hoofddorp and Nieuw-Vennep.

The combination of the population density and employment density, as well as the existing accessibility levels, determine the target travel costs for each zone. The distribution of target travel costs in the AML area is shown in Figure 26 below.

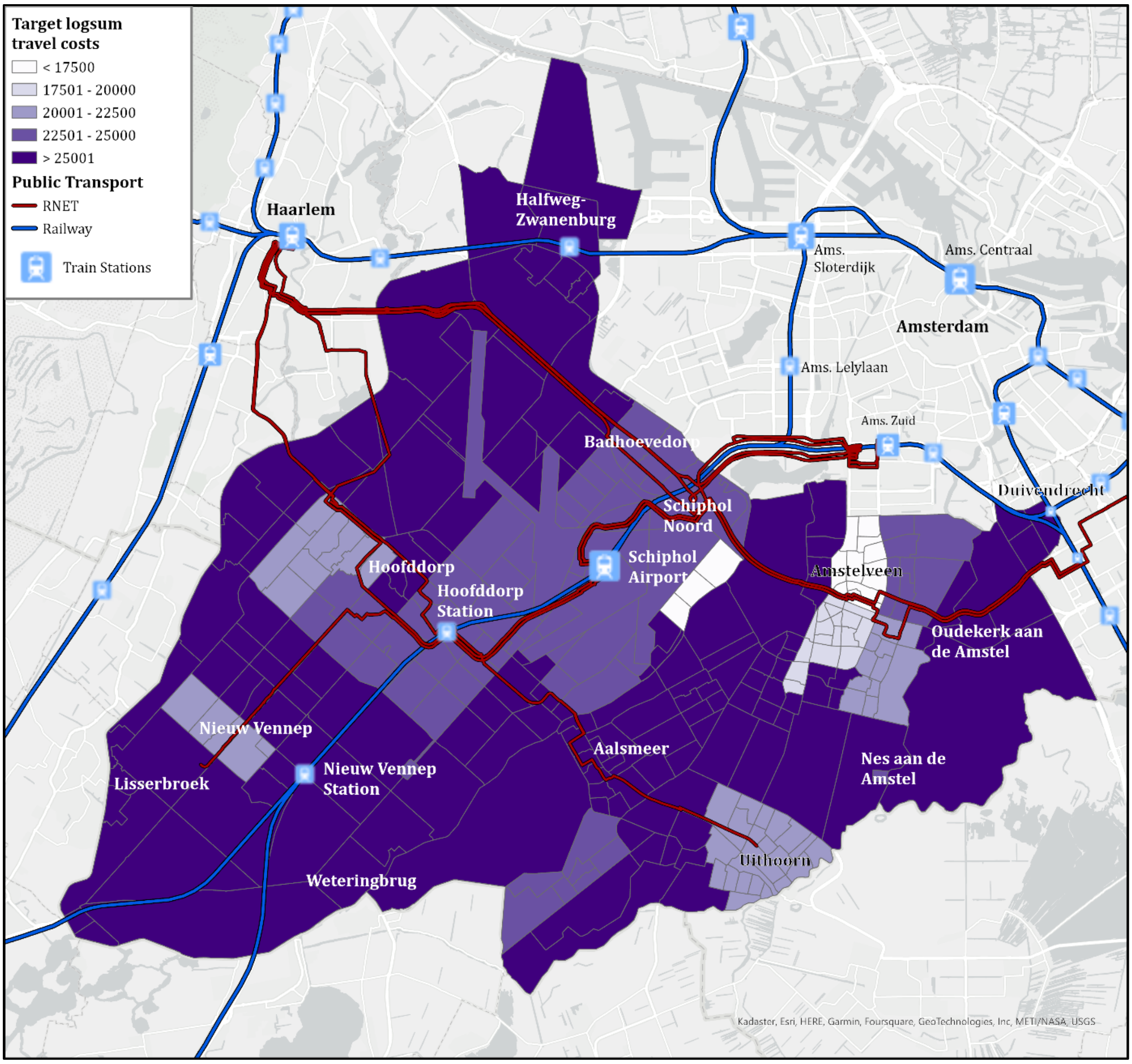


Figure 26: Target public transport logsum travel costs in Amstelland-Meerlanden

The areas with the lowest target travel costs (highest target accessibility) are Amstelveen, Schiphol Oost (east of Schiphol Airport), Uithoorn, west Hoofddorp, and parts of Nieuw-Vennep. Each of these areas either has both a high population and employment density (Amstelveen), a high population density and low employment density (Hoofddorp, Nieuw-Vennep, Uithoorn), or a low population density and high employment density (Schiphol Oost). The remaining areas with a high target accessibility have a low population density and/or employment density. For example, despite its high employment density, the low population of Schiphol Airport leads to a low target accessibility. Areas on the periphery of the concession have a low target accessibility because they have both low population density and low employment density.

The distribution of actual accessibility in the concession area can be seen in Figure 27 below.

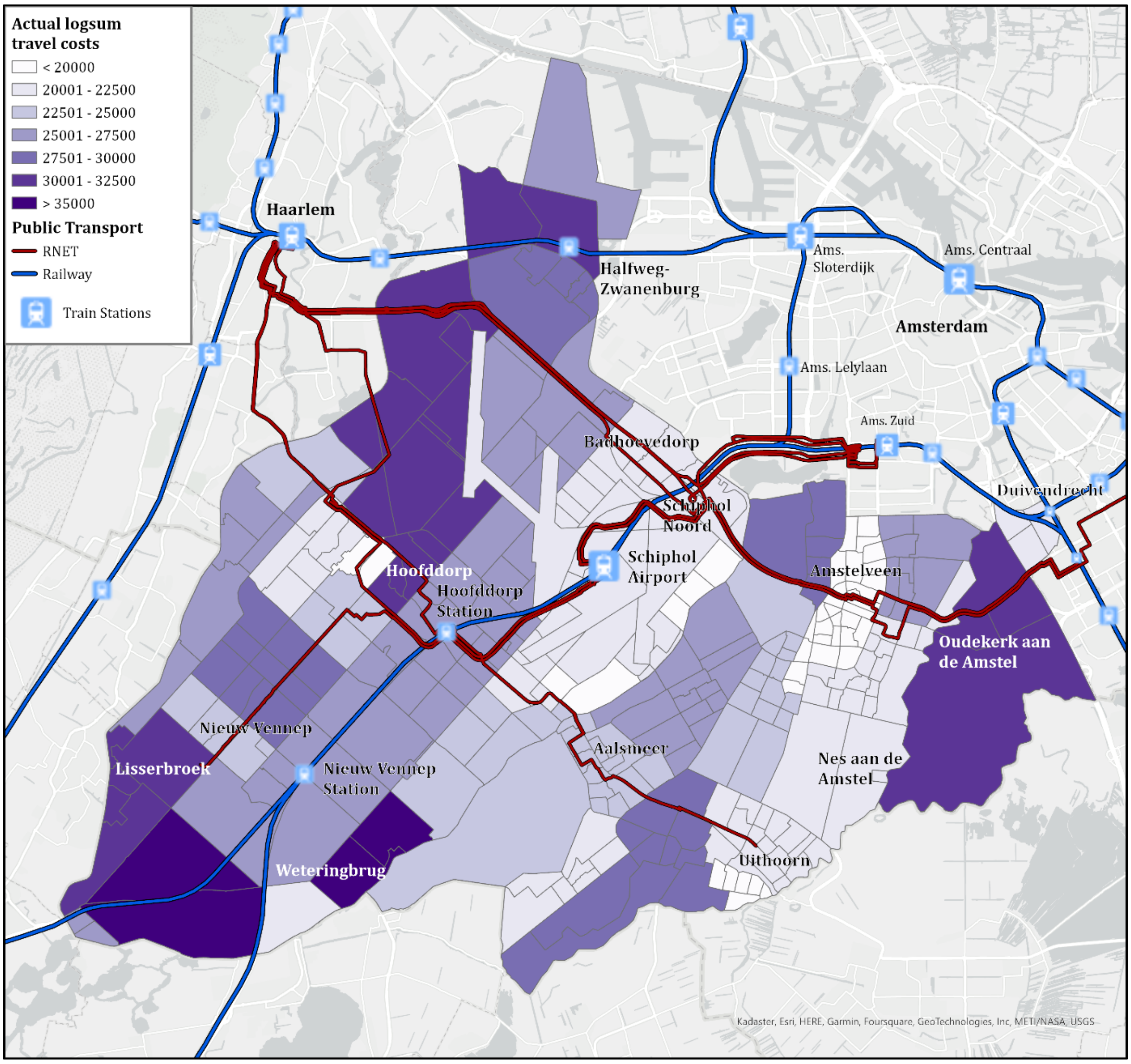


Figure 27: Actual public transport logsum travel costs in Amstelland-Meerlanden

The areas with the highest logsum travel costs, or the lowest accessibility, can be found in the in the north, east, and southwest periphery of the study area. The areas with the highest accessibility are Amstelveen, Schiphol Oost, Uithoorn, and western Hoofddorp. This distribution generally mirrors the PT service supply distribution in these areas.

The following results are obtained when the equity evaluation according to the principle of proportionality is applied to the AML area. The values in Figure 28 below represent the differences between the target and actual accessibilities at the PC4 postcode level, in perceived minutes.

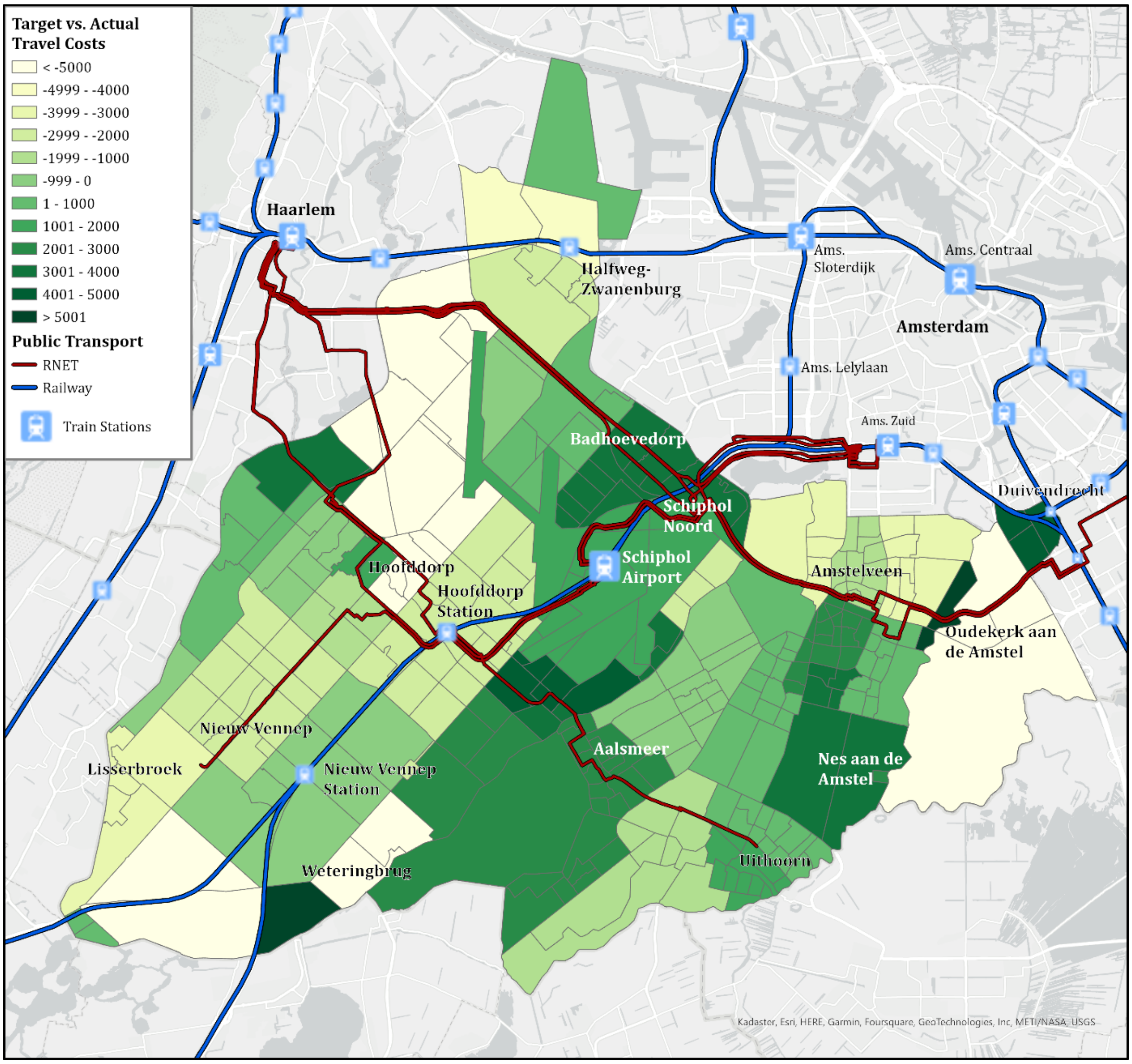


Figure 28: Areas of accessibility excess and deficit in Amstelland-Meerlanden according to proportionality

In the figure above, a negative value indicates that the actual travel costs are larger than the target travel costs, meaning that there is an accessibility deficit. A positive value indicates that the target travel costs are larger than the actual, meaning that there is an accessibility excess. In general, areas with accessibility excesses are located towards the center of the concession, while areas with deficits are more on the eastern and western periphery, with some exceptions. The areas with the largest accessibility excess are the eastern part of Amstelveen, Duivendrecht, south of Schiphol Airport, and Weteringbrug (southern part of the concession). The areas with the largest deficits are Leimuiderbrug and Abbenes (southern part of the concession), Oudekerk aan de Amstel, northern Zwanenburg, and the areas north of Hoofddorp.

Zones with high accessibility surpluses have actual travel costs less than the target travel costs. One of the areas with the highest surpluses is the eastern part of Amstelveen. This area has both low population density (Figure 24) and employment density (Figure 25) but has a large accessibility excess due to the high level of PT service in the area. This is because this area is serviced by multiple routes because it contains a main road that is the only major east-west thoroughfare in the eastern part of the concession. Therefore, this area has an accessibility excess due to the location of a main road that is used to service other destinations through it.

Weteringbrug, a zone in the southern part of the concession, also experiences excess accessibility due to a disproportionate number of routes relative to its population and employment. However, this is because the larger municipality of Oude Wetering is located just south of Weteringbrug outside of the official AML area boundary. Weteringbrug therefore receives what appears to be a disproportionately high level of PT service due to its proximity to the larger neighboring municipality, and it being on the way between this municipality and other destinations. This occurrence of areas receiving a high level of PT service due to them being on-route between attractive destinations is a common reason for excess accessibility. It is therefore questionable if it is desirable to reduce accessibility in areas of accessibility excess to be proportional with their population and employment density, as this high accessibility could be the result of justifiably high service levels in surrounding areas or a byproduct of the road network design.

The presence of NS train stations also influences the actual PT accessibility, as zones containing or near NS train stations have higher accessibility due to the low travel time for train travel. The NS station at Schiphol is an especially important station due to the high number of trains that stop there. Nieuw-Vennep, Hoofddorp, Halfweg-Zwanenburg, and Duivendrecht are regular train stations. For example, Duivendrecht is an area of surplus accessibility due to the presence of an NS train station in the area, which proportionality would not justify according to the area's low population and employment density.

Zones with accessibility deficits have actual logsum travel costs that exceed their target costs. The zones with the largest accessibility deficits can be seen in Figure 28 in the far southern, eastern, and northern parts of the AML area. Despite low population and employment densities, there is still a lack of accessibility due to the lower-than-expected level of PT service in these areas. In other words, the high actual travel costs are still considered excessive, even relative to the high target travel costs. For example, the Rondehoeppolder east of Oudekerk aan de Amstel, has a population density of 396 inhabitants per square kilometer and employment density of 92 jobs per square kilometer. Based on the multiple regression model, the target logsum travel cost is 26,557 perceived minutes, while the actual logsum travel cost is 31,593, indicating a travel cost excess of over 5,000 perceived minutes. The actual logsum for this zone is so high because during the morning peak period, the only route servicing the southern part of the area is route 149 at one trip per hour.

There are some more moderate accessibility deficits in other parts of the concession, for example the eastern part of Hoofddorp. These zones have population densities between 500 and 1,000 inhabitants per square kilometer and employment densities between 1,000 and 1,500 jobs per square kilometer. This results in a target logsum travel cost between 22,500 and 25,000, while the actual logsum costs are between 25,000 and 27,500. When looking at the route network of this area, it can be speculated that the actual logsum travel costs are higher in this area due to the low frequency of PT services. This area has many routes, but there is often only one per corridor operating 1-2 times per hour during the morning peak. While there are high frequency routes through the area, they have limited stops and therefore require more walking time to access the stop. This mismatch between the target and actual accessibilities results in a moderate accessibility deficit.

5.5.3 Degree of inequity

There are 26 postcodes with excess accessibility and 22 zones with deficit accessibility according to proportionality, the distribution of which can be seen in Figure 29 below.

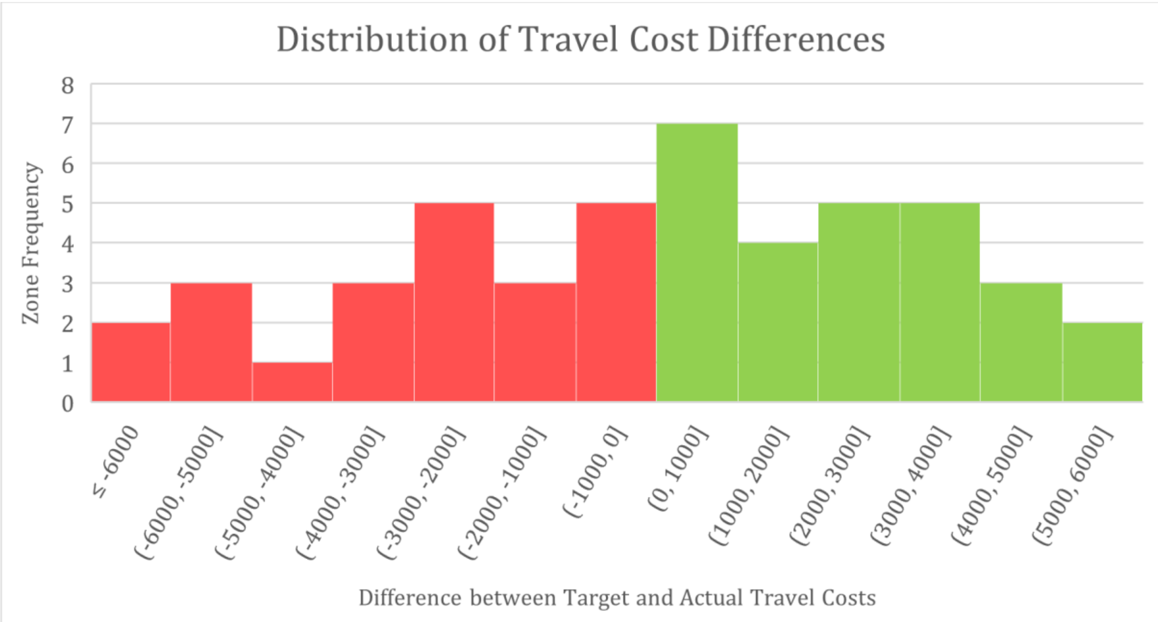


Figure 29: Distribution of surplus and deficit logsum travel costs according to proportionality

According to Figure 29, there are more zones with smaller mismatches between the target and actual travel costs than postcodes with large mismatches, indicating that there are not as many extreme deficits and surpluses as minor ones. In general, there is more variation in the actual logsum travel costs than for the target costs, as seen in Figure 30 below.

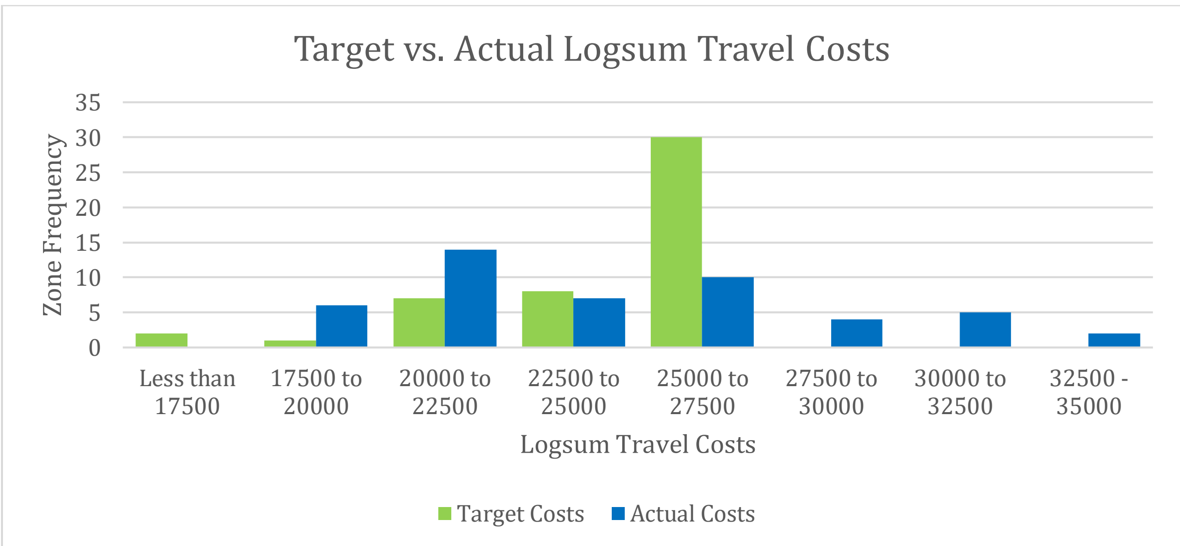


Figure 30: Comparison of target and actual travel costs according to proportionality

The actual costs range from 17,788 to 33,747 while the target costs range from 16,536 to 27,000. The majority of zones have a target travel cost between 25,000 and 27,500 perceived minutes, although the actual travel costs are more dispersed. The range for the actual travel costs is also higher, which is expected given that the range for the target travel cost distribution is more limited as it is based on a linear relationship.

A possible explanation for the disconnects between the target and actual travel costs could be the use of linear regression, as opposed to a method of non-linear regression, to determine the target accessibility. The predictive power of the model in this analysis is limited as the R-square value is only 0.397, therefore the target accessibility for many zones is very different from the actual accessibility, even though the target accessibility is calculated based on the actual data. It is also important to consider that this method of equity evaluation is highly dependent on the factors that are selected. A regression model with different factors is likely to have different target accessibility values.

This method is well suited for understanding how PT accessibility is distributed relative to land use factors that could influence its usage. It is not recommended to use this method to identify areas with accessibility surplus, as this is often the byproduct of road network design or proximity to areas requiring high levels of PT service. Additionally, it may not be suitable for determining service levels beyond identifying areas with significant deficits, depending on the R-square value. However, using a non-linear regression method to achieve a higher R-square value would allow for a better calculation of the target accessibility. This could provide a more accurate calculation of the degree of accessibility deficit per zone.

5.6 Proportionality PT Network Design

This section will discuss the application of proportionality equity analysis in PT network planning to achieve a network with services distributed more in line with the population and employment density of the area. The network changes in this case study application refer to frequency modifications for bus routes only. The frequency modifications aim to be as close to cost neutral as possible, meaning that cost increases from PT frequency increases in areas with accessibility deficits will be balanced by frequency decreases in areas with surpluses. The goal of the following frequency modifications was to reduce the gap between the target and actual logsum travel costs for selected zones with the highest accessibility deficits. While this would not result in a PT network with a proportional accessibility distribution, it would provide insights into the use of proportionality evaluation as a network planning tool.

Several frequency modifications and iterations were tested in VENOM. The evaluation method described in chapter 3 was re-applied every time new logsum travel costs resulting from frequency changes are calculated from VENOM skim matrix exports. This results in a new target accessibility and actual accessibility for each zone, the difference between which can then be compared to see how the frequency changes affected the accessibility gap in the target zones.

However, in the same way as in the case of egalitarianism, the use of the logsum travel cost as the accessibility measure makes it difficult to use this evaluation method as a network planning tool, as any changes affect many more zones than just the target zone. Additionally, sometimes network changes can have the opposite of the expected effect, for example sometimes a frequency increase in a zone led to an increase in the deficit for that zone. This is due to the target travel costs changing with each iteration in addition to the actual travel costs. This occurs because the target accessibility is determined using multiple regression based on the actual accessibility data, so when the actual accessibility changes, so does the target accessibility. This is again a similar situation to the application of the egalitarianism evaluation method in frequency adjustments, where the shifting target accessibility per iteration makes it difficult to make frequency adjustments with the desired impact.

Therefore, this method is more useful in evaluating and comparing different PT network configurations in an area. For example, it can be used in the planning process as a way of seeing if network changes according to ridership are in consistent with other factors such as population or employment density, therefore allowing for more considerations and planning goals to be taken into account. It may also be useful for identifying areas of accessibility deficits, as this could give insight into areas that could potentially have high PT demand based on the selected factors but currently do not receive a high level of service.

5.7 Sufficientarianism Evaluation Results

The following section will apply the equity evaluation using the distribution principle of sufficientarianism, which states that the distribution of PT logsum travel costs is acceptable if each zone achieves a minimum defined accessibility threshold (Lucas, van Wee, & Maat, 2016; Martens, Bastiaanssen, & Lucas, 2019). This is followed by discussion of the geographical distribution and extent of inequity according to this principle.

5.7.1 Calculation of VF values

With the available data, the equity analysis for sufficientarianism can be calculated both at the PC4 and PC5 spatial levels. The following evaluation is based on the PC5 postcode level, as this is the finest level of spatial detail available. The VF value for each zone *i* is calculated using equation 14:

$$VF_i = logsum_{PT,i}/logsum_{car,i} \qquad (14)$$

Where:
$logsum_{PT,i}$ = the logsum travel cost using public transport from zone *i*
$logsum_{car,i}$ = the logsum travel cost using car from zone *i*

It should also be mentioned that in VENOM, PT includes walking time for access, egress, and transferring, while the car does not. Once the VF value for each zone in the study area is calculated, the threshold for sufficiency is determined. This means that a maximum VF value must be set. This could be done by studying the impacts of this VF factor using the logsum travel cost accessibility measure on modal share. However, this is out of scope for this thesis, and it is not necessary to determine empirically derived thresholds to demonstrate the use of this principle. Therefore, a sufficiency threshold will be determined based on the distribution of VF values.

A limitation of the use of one VF value for all zones is that it links PT and car accessibility, which can be problematic when the goals for each mode in an area are different. For example, in a city center, the goal is to encourage PT usage and discourage car usage. But if the car accessibility in the center is poor, then the minimum sufficiency level for PT accessibility will also be poor, when the goal of the municipality may be for PT accessibility to be high. This can be somewhat mitigated, for example in the Amsterdam Transport Region policy which uses different VF factors for each area type (Gaaff, de Koning, Bonnier, van der Slot, & Mout, 2021). However, as the AML area does not have a central metropolitan urban area, it was decided that using a single measure for the whole area would be sufficient. The main limitation of the VF value, however, is that if there is a change in car accessibility, the sufficiency threshold for PT will also change, therefore the results of this analysis are interpreted with this in mind.

5.7.2 Degree of inequity

Ideally, the VF value would be determined based on the desired mode share of PT, as was done in (Projectbureau Integrale Verkeers- en Vervoerstudie, 1995). However, it cannot be assumed that these exact thresholds can be applied in this research due to the use of the logsum travel cost as the accessibility measure. Therefore, it is preferred to base the threshold VF value off the existing distribution of VF values than to select a value from previous research (Projectbureau Integrale Verkeers- en Vervoerstudie, 1995). It should be noted that there is some arbitrariness with this approach, therefore more research is needed before applying this method in practice, as this is an important choice that affects the number of zones that are classified as insufficient, as well as the degree of their accessibility deficiency. The distribution of VF values, which is calculated as the ratio of PT logsum travel cost to car logsum travel cost, can be seen for the AML area in Figure 31 below.

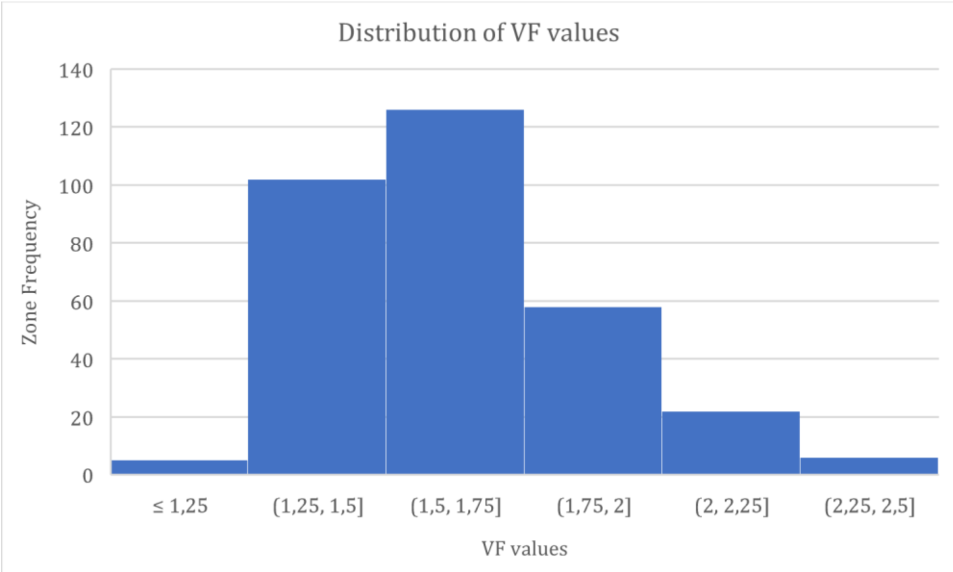


Figure 31: Distribution of VF values in Amstelland-Meerlanden

The average VF value in the AML area is 1.63 with a standard deviation of 0.24. Based on the distribution of the VF values, 2.11 is selected as the maximum VF value threshold for which to determine PT sufficiency, as this is two standard deviations above the mean VF value of 1.63. This means that the PT accessibility in a zone is considered sufficient if it is less than 211% of the car accessibility. There are 17 zones with values exceeding the threshold of 2.11 and 302 zones below this threshold. Below the sufficiency threshold, values range from 1.11 to 2.11, although the principle of sufficientarianism does not consider any of these zones to have an accessibility excess, as this principle is only concerned with all zones receiving a minimum level of accessibility.

5.7.3 Spatial Distribution of Inequity

The spatial distribution of VF values in the AML concession area according to their deviation from the mean can be seen in Figure 32 below. The areas of insufficient PT accessibility are those that are 2 standard deviations above the mean, shown in dark red.

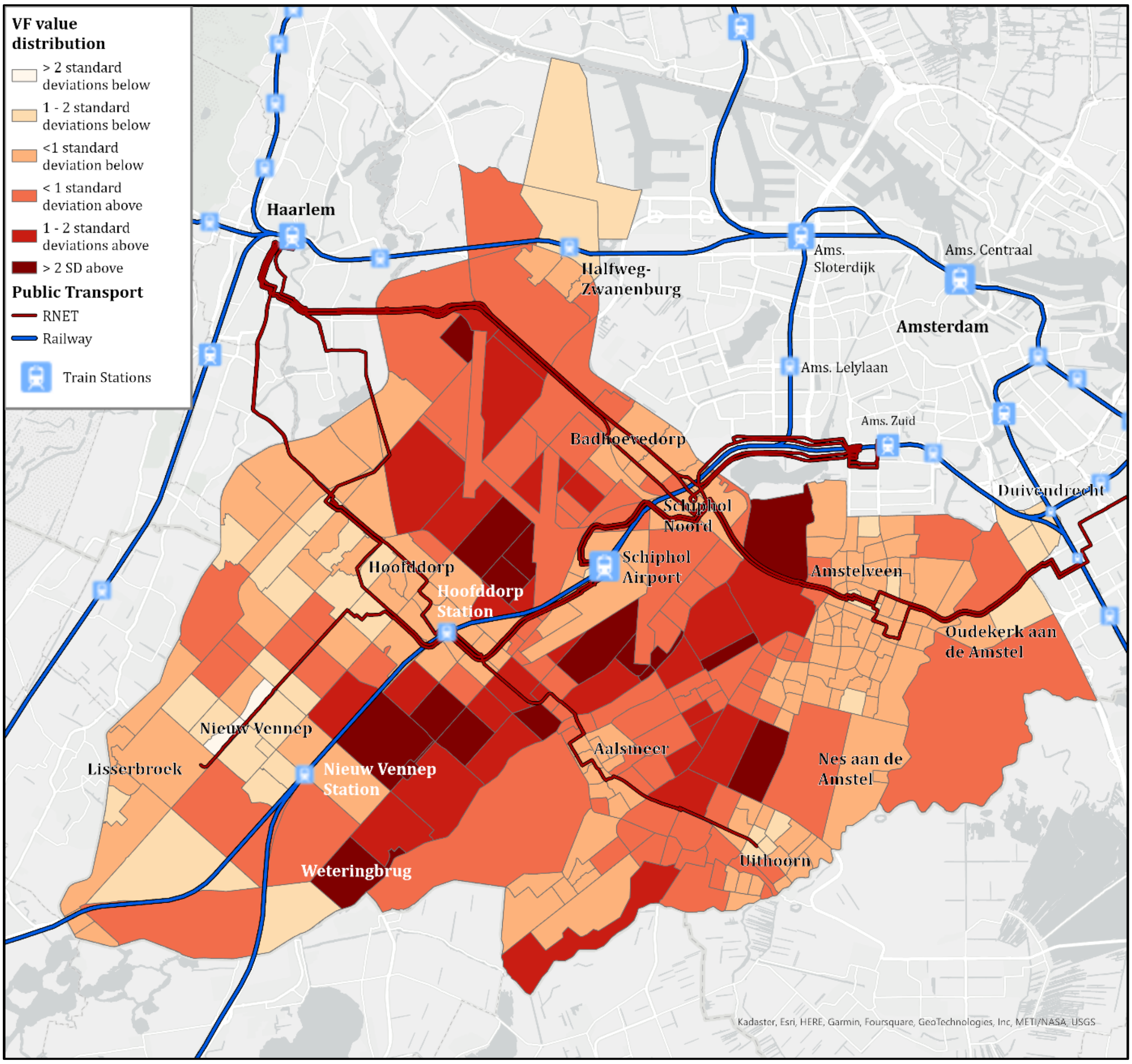


Figure 32: Spatial distribution of VF values in Amstelland-Meerlanden

As seen in Figure 32 above, the areas of insufficient PT accessibility are scattered throughout the AML concession, although most are located in the more central areas of the concession, with lower VF values in the east and west. These deficit zones include the western part of Amstelveen, zones adjacent to the airport, and the zones between Nieuw-Vennep and Aalsmeer. Examination of Figure 33 and Figure 34 can help to understand why the zones with a VF value less than 2.11 have insufficient PT accessibility.

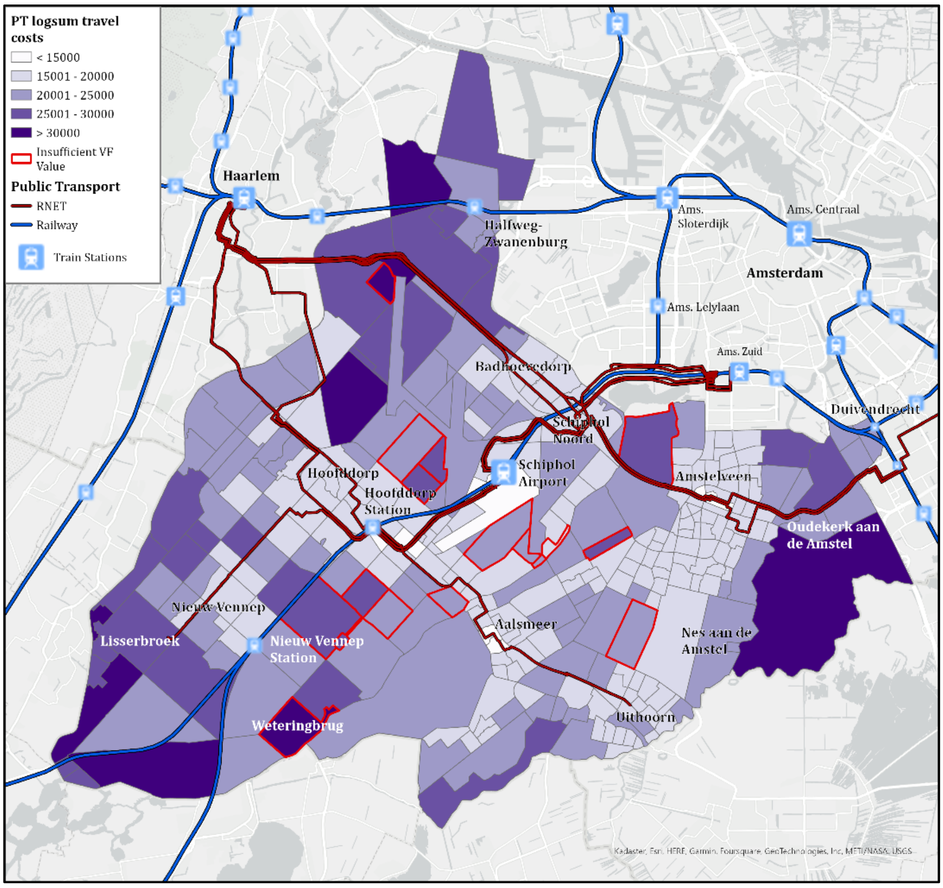


Figure 33: Zones with insufficient VF values in Amstelland-Meerlanden relative to PT logsum travel cost

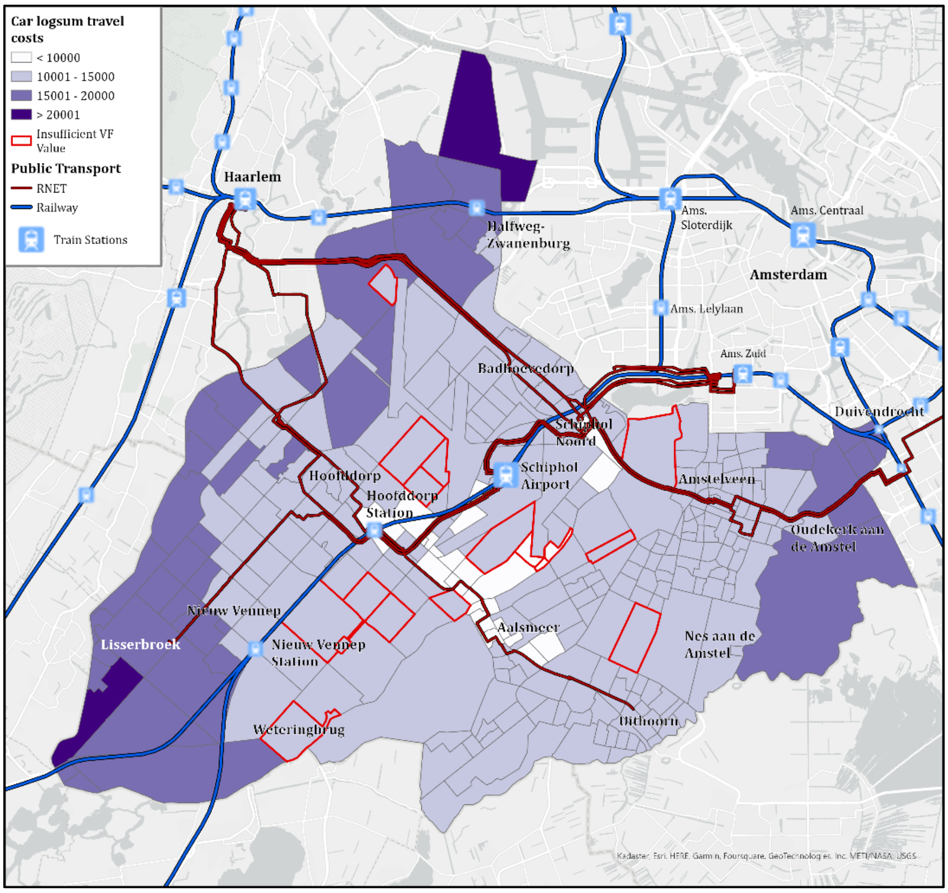


Figure 34: Zones with insufficient VF values in Amstelland-Meerlanden relative to car logsum travel cost

In the figures above, zones with a VF value greater than or equal to 2.11 are shown with a red outline. These areas are classified as rural and recreation areas, except for the zone south of Schiphol Airport, which is considered a major employment area. Most of these zones with insufficient PT accessibility have low logsum travel costs with the car and moderate logsum travel costs with PT. For the deficient zone south of Schiphol, which has decent car accessibility relative to other zones in AML, has a lower level of PT accessibility despite its proximity to high accessibility zones at Schiphol and Aalsmeer. This could be due to the structure of PT routes in this area, which go between Schiphol and Aalsmeer in an L-shape that goes around this zone.

Many of the deficient zones are located towards the central area of the concession, as this is where the car accessibility is highest due to the centrality benefit from the use of the logsum measure. Some of the zones with the highest PT logsum travel costs are not considered to be deficient in PT accessibility, because the travel costs for the car are also higher. However, in the deficient zones with the highest level of car accessibility, for example the small zones east of Schiphol airport, the level of PT service is high but PT accessibility in these zones is still classified as insufficient. This means that the deficiency in PT accessibility is more of a result of low travel costs with the car than of high travel costs with PT.

5.8 Sufficientarianism PT Network Design

The following section will demonstrate how sufficientarianism equity analysis can be used in the network adjustment process with a cost-neutral outcome. In this research, the only network modification considered is frequency changes, to limit the scope of the study. The goal is for these frequency modifications to remain cost neutral, to demonstrate the feasibility of improving equity without increasing operating costs. This will be done by attempting to address accessibility in the zone with the highest VF value through frequency adjustments. Any increase in operating resources in this target zone will be offset by a decrease in frequencies of other routes in zones with lower VF values. The feasibility of achieving the target VF value given the initial VF value will also be evaluated. While this will not achieve an ideal network according to sufficientarianism, it will give an indication of the process and insights from using sufficientarianism equity evaluation to make frequency modifications.

5.8.1 Frequency increases

The zone with the highest VF value is zone 1168, with a VF value of 2.4. This zone is shown outlined in blue in Figure 35 below.

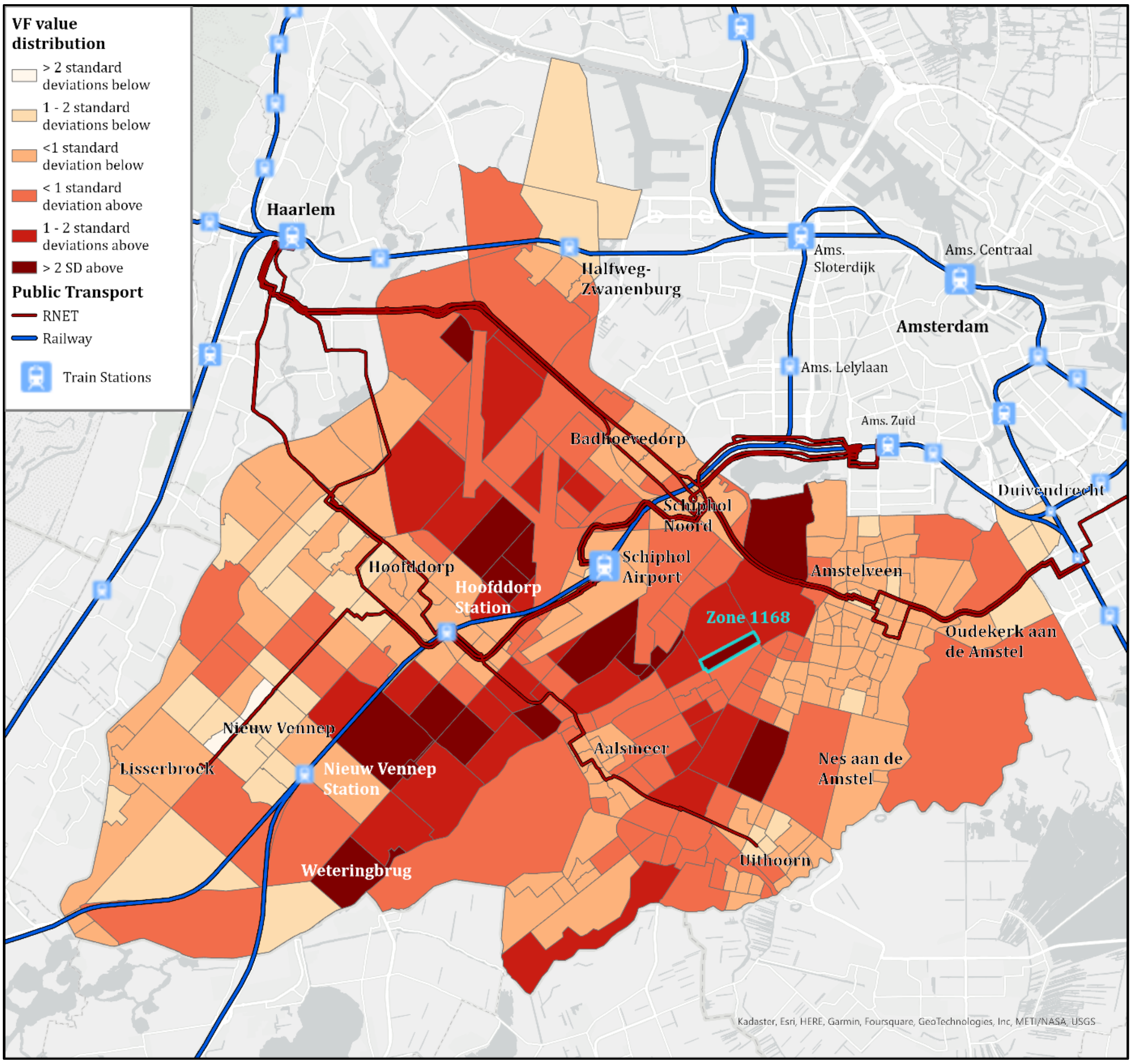


Figure 35: Distribution of VF values in Amstelland-Meerlanden relative to zone 1168

Different approaches were used to understand where and how to target frequency adjustments to affect accessibility in the target zone. First, the frequency of routes servicing stops in or near the centroid of zone 1168 were increased, as this could affect the waiting time component for trips originating in the target zone. VENOM considers all stops within 5km of the zone centroid as candidate stops for that zone, and then travelers are distributed among the access stops using multinomial logit based on the travel cost of their trip from that stop. In the case that there is no stop within 5km, a 10km search radius is then applied. Lower frequency routes are also prioritized for frequency modifications over high-frequency routes. Increasing frequency on these routes has a greater absolute impact on the waiting time component of the generalized travel cost function, since the waiting time in VENOM is calculated as half of the headway. Therefore, low-frequency routes with stops closest to the centroid of zone 1168 were prioritized for frequency increases. The results of several iterations using this approach can be seen in Table 6 below.

Table 6: Frequency modification iteration results for zone 1168

Iteration	Route	Previous iteration frequency	New frequency	Previous iteration VF value (zone 1168)	New VF value (zone 1168)
1	171	3-3.5x/hr	5x/hr	2.402	2.344 (-0.058)
	187	2x/hr	4x/hr		
	199	2x/hr	4x/hr		
2	171	5x/hr	10x/hr	2.344	2.220 (-0.124)
	187	4x/hr	8x/hr		
	199	4x/hr	8x/hr		
3	171	10x/hr	15x/hr	2.220	2.166 (-0.054)
	187	8x/hr	12x/hr		
	199	8x/hr	12x/hr		
4	171	15x/hr	20x/hr	2.166	2.133 (-0.033)
	187	12x/hr	18x/hr		
	199	12x/hr	18x/hr		

As can be seen in the table above, even large frequency increases do not have a significant enough impact on the VF value to achieve the minimum level of accessibility in zone 1168. The impact of frequency changes alone is generally limited as this will only change the waiting time component in the generalized travel cost function. Additionally, as the frequencies on the routes increase, the smaller the impact of subsequent route changes, since the waiting time in VENOM is considered as half of the headway.

Use of the logsum measure also limits the impact of frequency adjustments. In the AML area, the logsum travel cost for zone 1168 is calculated as the sum of travel costs from zone 1168 to the 318 other zones in the AML area. Only the travel costs to destination zones accessed with one or more of the modified routes will be affected; the remainder of the travel costs for OD pairs from zone 1168 will remain the same. Therefore, the impact on the total PT logsum value, and by extension the VF value, depends on how many of the OD pairs from zone 1168 use these modified routes. If many OD pairs from the target zone use these routes than the impact will be more significant, whereas if only a few OD pairs use these routes then the effect on the VF value will be minimal.

Another possibility for decreasing the VF value for a zone is to increase frequencies in other zones. Use of the logsum value as the accessibility measure also means that a zone's accessibility can be impacted by frequency adjustments made in other zones, if the adjusted routes are used for travel between those zones. Figure 36 below shows the logsum travel costs from zone 1168, shown in the blue outline, to all other zones in the study area prior to any frequency adjustments.

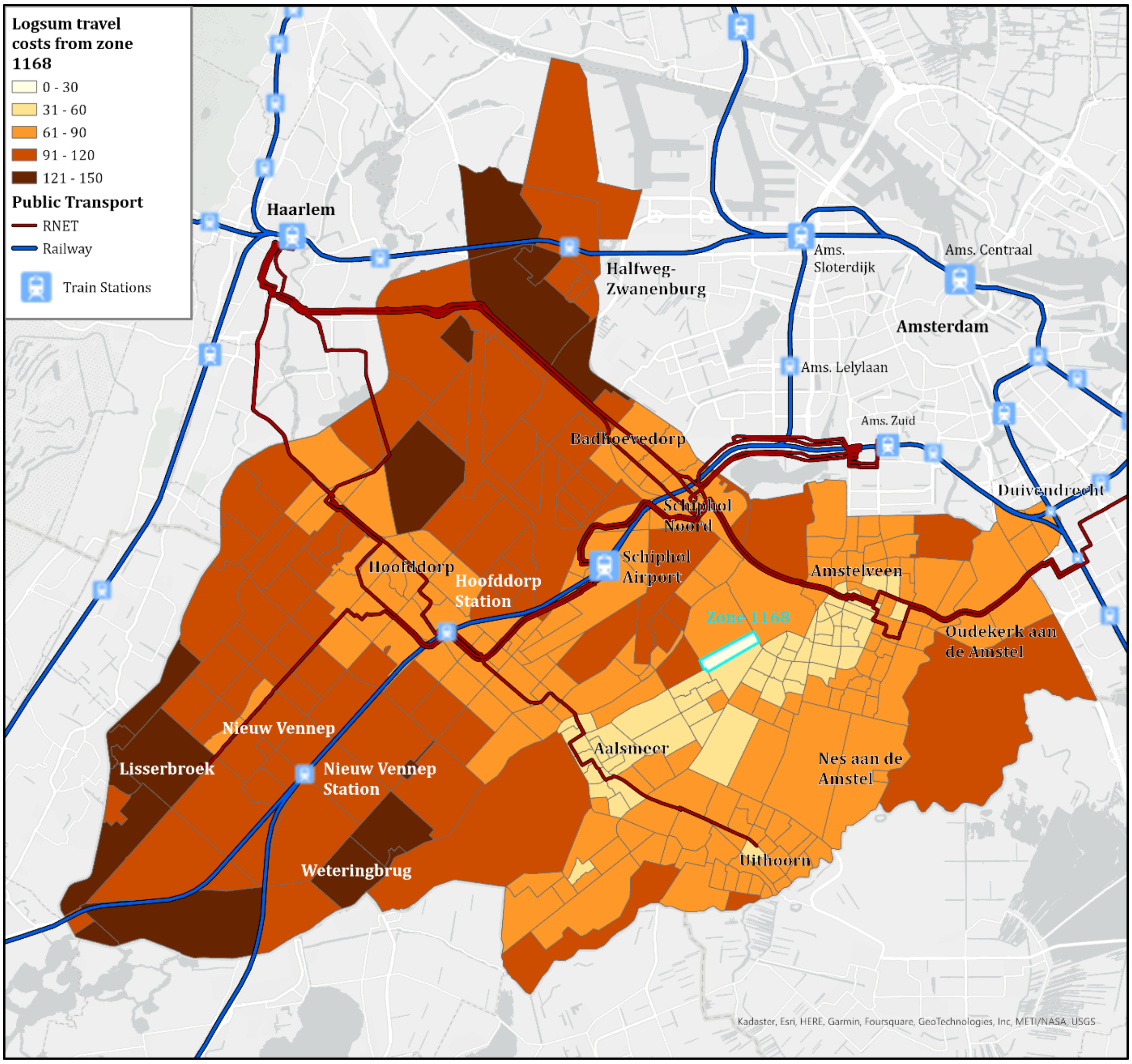


Figure 36: PT logsum travel costs from zone 1168 for original PT network

From the figure above, the effect of the use of the logsum travel cost as the accessibility measure can be seen. Generally, the use of this measure leads to zones closer to the target zone having low travel costs, while zones further away have a higher travel cost simply due to the larger distance that must be traversed to access them. Travel cost information displayed in this manner could be used to help identify areas physically close to the target zone but with high travel costs, as these are areas where network improvements could have a larger impact on the VF value. Zones with high travel costs that are far away may not be worth prioritizing for improvements, as these travel costs will be higher anyways due to the large physical distance between these zones and the target zone. The routes modified in Table 6 were located north adjacent to zone 1168, which partially explains why frequency adjustments to these routes were so effective at reducing the VF value. A new spatial distribution of travel costs according to iteration 2 in Table 6 is shown in Figure 37 below.

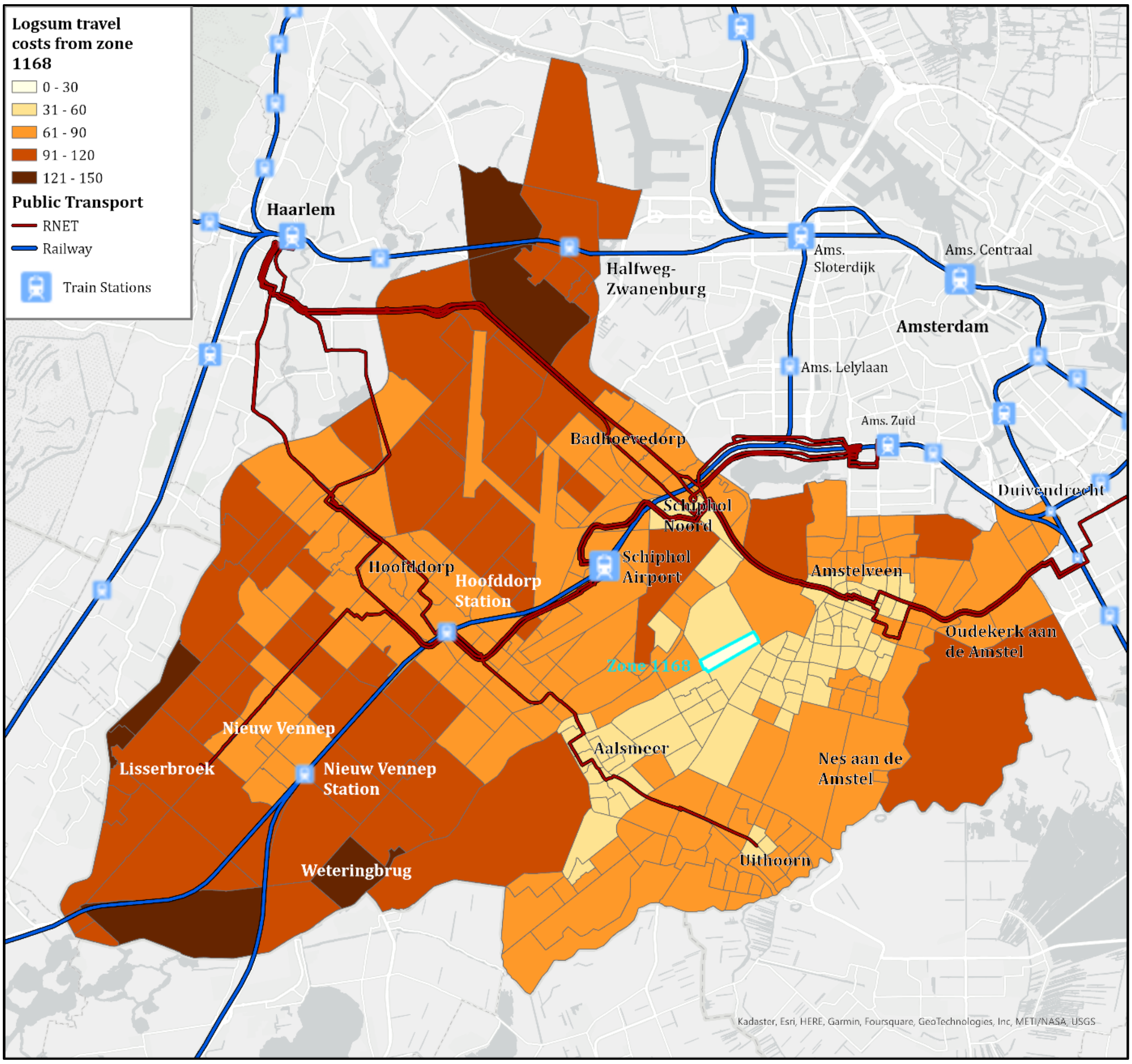


Figure 37: PT logsum travel costs from zone 1168 for modified PT network

When comparing Figure 36 above with Figure 37, it can be seen that the logsum travel costs for areas close to zone 1168 have decreased. However, it is not necessarily efficient or practical to increase frequencies to the extent shown in the later iterations in Table 6, depending on the ridership on these routes.

Additionally, not all zones will have VF values that can be improved solely through frequency increases. Even large frequency increases in some zones have only a minimal impact on the VF value. This could mean that other components of network design, for example the stop locations or routing, could be the primary reasons for the low VF value. However, this theory would require additional research for confirmation. This shows the limitations of frequency adjustments in and near the target zone on accessibility improvements.

5.8.2 Frequency decreases

For frequency modifications in VENOM to be cost-neutral, it is necessary to reduce frequencies on other routes. Without knowledge of demand patterns, this can be done in areas with VF values significantly lower than the minimum. It should be noted that this could also increase the VF values in the target zone if the frequency-reduced routes are used for travel from the target zone.

One problem with this approach of decreasing frequencies in zones with low VF values is that there are no additional criteria that can be used to select which destination zones to select for frequency decreases. This is especially problematic in the case that there are a high proportion of zones with low VF values. This could potentially make the route selection for frequency reduction somewhat arbitrary, leading to a conflict with other PT objectives. For example, even if the strategy was to reduce frequency first in areas with the lowest VF values, this could also be contrary to other PT goals such as balancing existing ridership with seating capacity. It could be recommended to use another factor, such as the total number of passengers per hour on a route, as the additional criteria for selecting where to reduce frequency to compensate for frequency increases in other areas. However, this is not done in this thesis as the goal is to demonstrate the application of equity evaluation in network planning in a way that is agnostic to existing demand.

Another issue is the temptation to reduce frequencies on routes at the edge of the study area where much of the route is outside of the AML boundary. This can decrease in-service time without significantly increasing travel time within the concession. This could lead to the target VF values and cost neutrality being achieved, but at the expense of accessibility in the areas outside of the concession area.

An example is shown below, where the frequency was decreased on some routes to compensate for frequency increases to improve the accessibility of zone 1168. The frequency increases that will be kept in the model are those from iteration 2 in Table 6, as the frequency increases in iterations 3 and 4 did not have a significant enough VF value decrease to justify the large increase in operating resources. These frequency increases require an additional ~28 hours of in-service time; therefore, the goal was to decrease in-service time an equivalent amount with frequency reductions. This was done by decreasing frequencies on routes in zones with low VF values, listed below:

- Route 310: decreased mainline frequency from 3.5-4x/hr to 2x/hr; decreased shortline frequency from 5.5x/hr to 3x/hr
- Route 170: decreased frequency from 3.5-5.5x/hr to 2-3x/hr
- Route 142: decreased frequency from 2.5-4x/hr to 2x/hr
- Route 168: decreased frequency from 3.5-4x/hr to 2x/hr
- Route 300: decreased frequency from 10x/hr to 7.5x/hr
- Route 268: decreased frequency from 4x/hr to 2x/hr
- Route 365: decreased frequency from 5.5-7.5x/hr to 4-5x/hr
- Route 146: decreased frequency from 2.5-3.5x/hr to 2x/hr

The routes where frequency was increased and decreased are shown in Figure 38.

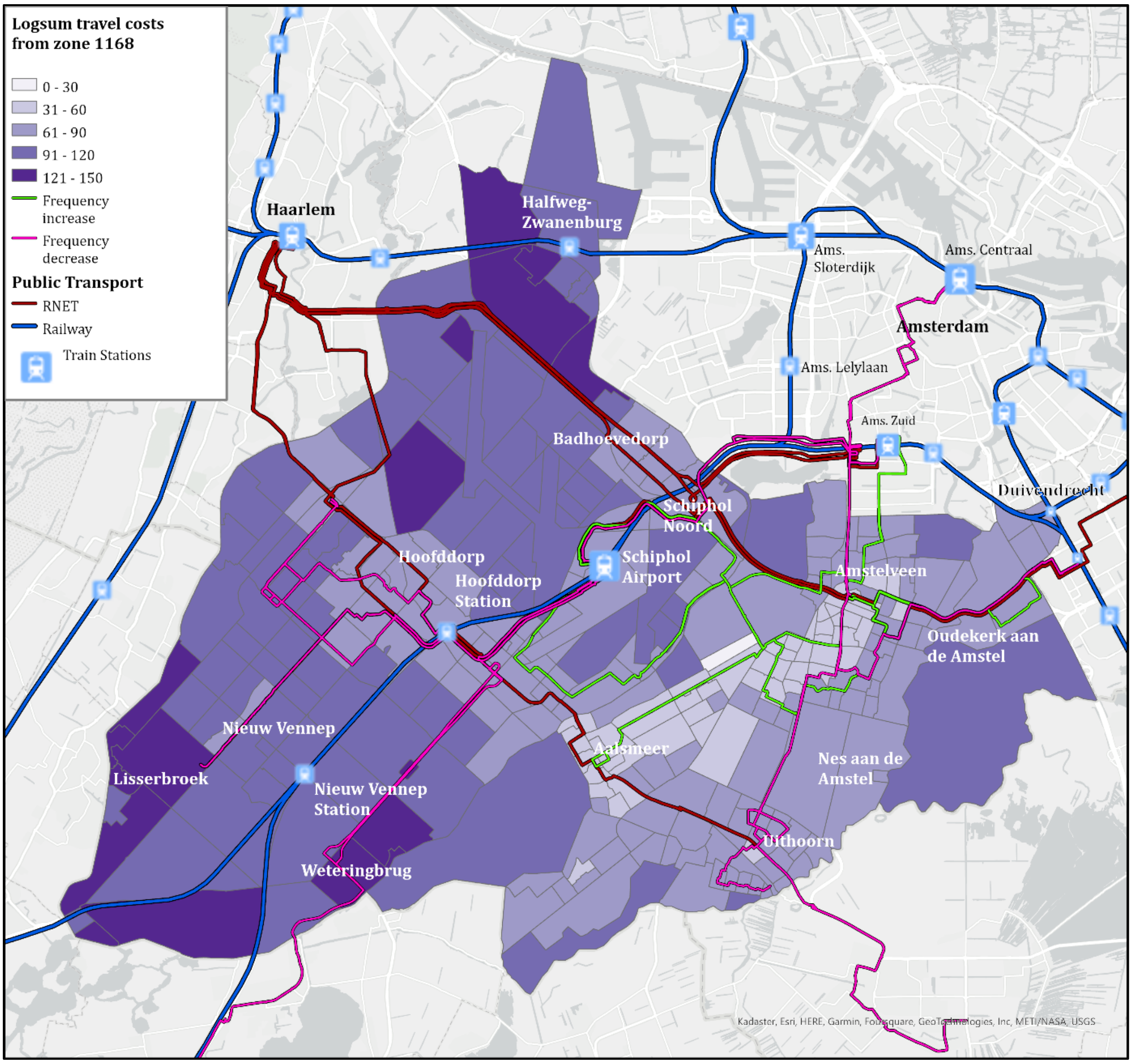


Figure 38: Routes with frequency modifications

Due to the large frequency increases required to significantly reduce the VF value for zone 1168, frequency decreases on many routes were required to achieve a reduction in a comparable number of service hours (27.6). The VF value for zone 1168 with the frequency increases from iteration 2 alone was 2.22, and the VF value for zone 1168 with both increase and decreases is 2.24. This demonstrates that it is possible to implement cost-neutral frequency changes to improve the VF value for an area. However, it should be kept in mind that these changes were made without regard for any additional factors, namely ridership. Additionally, it was very difficult to find a combination of frequency adjustments that could decrease the VF value to below the sufficiency level, as zone 1168 had the worst VF value in the study area that was significantly larger than the sufficiency threshold of 2.11.

It is also important to look at how other zones in the study area were affected, as their VF values may have changed as a result of the frequency adjustments. Figure 39 below shows the distribution of VF values with the previously mentioned frequency adjustments. In order to avoid the issue of the new VF value distribution shifting the target VF value (which was based on the original distribution), the average and standard distribution from the original network were used.

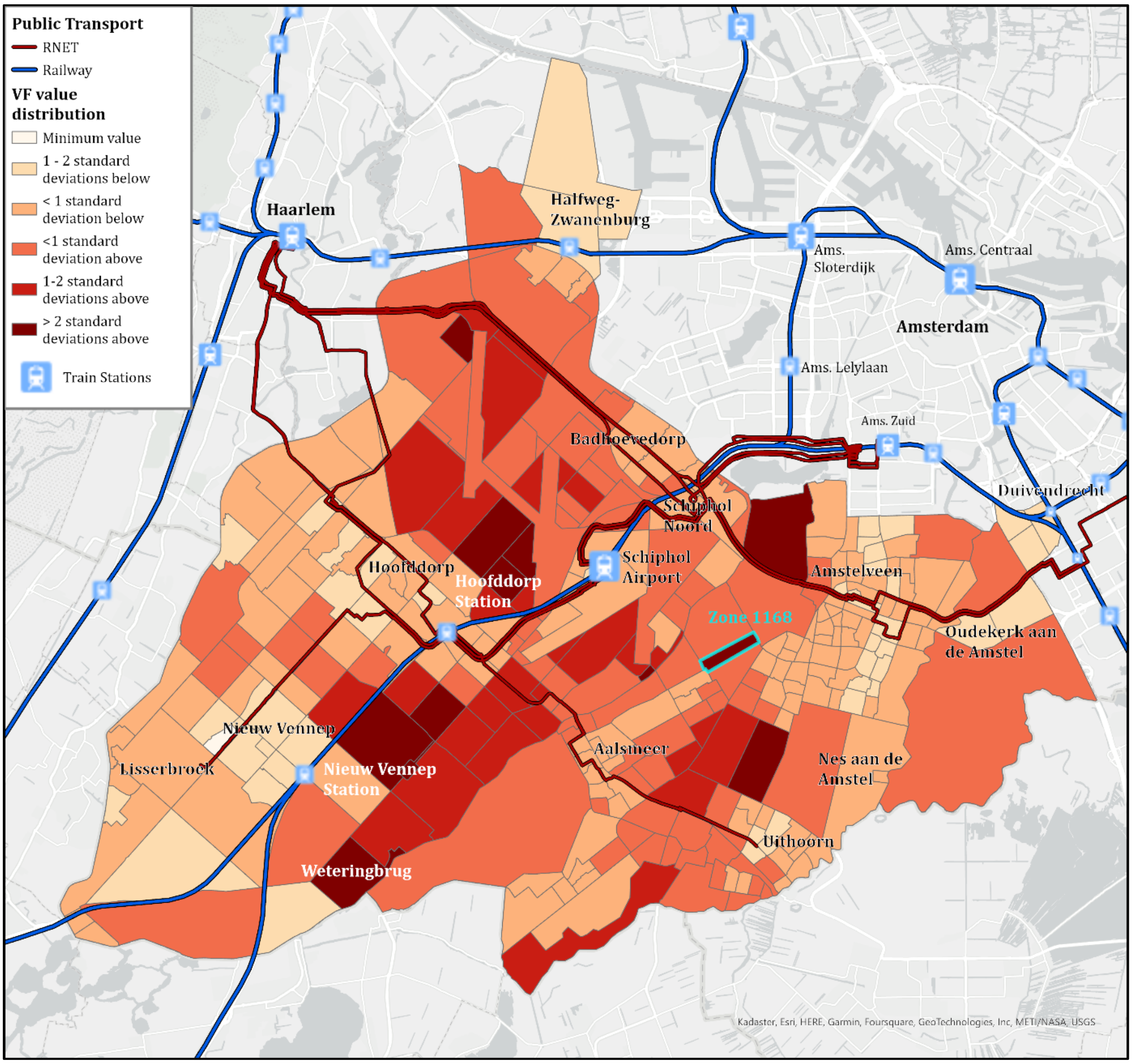


Figure 39: Distribution of VF values after PT frequency modification

In Figure 39 above, the original VF value of 2.11 was kept as the sufficiency threshold. When compared to the original distribution in Figure 36, it appears that for the most part, the distribution of VF values remains the same. The most noticeable difference is that some of the lowest VF values have increased, hence there are no more VF values more than 2 standard deviations below the average VF value. Overall improvements in the accessibility distribution can be seen when comparing the previously identified insufficient zones for the original and updated networks, as seen in Table 7 below.

Table 7: VF values of insufficient zones before and after PT frequency modifications

Zone Number	Original VF value	New VF value	Difference	Accessibility Increase or Decrease?
944	2.248	2.238	-0.01	Increase
951	2.358	2.359	+.001	Decrease
966	2.13	2.11	-0.02	Increase
970	2.127	2.10	-0.027	Increase

973	2.158	2.17	-0.012	Increase
974	2.357	2.362	+0.005	Decrease
1025	2.294	2.297	+0.003	Decrease
1027	2.168	2.154	-0.014	Increase
1031	2.163	1.148	-0.015	Increase
1033	2.126	2.03	-0.096	Increase
1034	2.182	1.916	-0.267	Increase
1035	2.211	2.031	-0.181	Increase
1036	2.335	2.147	-0.188	Increase
1042	2.313	2.298	-0.015	Increase
1057	2.175	2.116	-0.059	Increase
1072	2.226	2.205	-0.021	Increase
1168	2.402	2.236	-0.166	Increase

As seen in Table 7 above, three of the seventeen zones with insufficient accessibility have had small accessibility decreases. Fourteen of the seventeen insufficient zones experienced accessibility improvements, with five zones improving to a sufficient VF value. Additionally, no previously sufficient zones had VF values that decreased to an insufficient level. Therefore, the modifications made to improve accessibility in zone 1168 had overall positive impacts on other zones and on the overall accessibility distribution according to sufficientarianism.

The changes in VF values in the AML area can be seen in Figure 40 below.

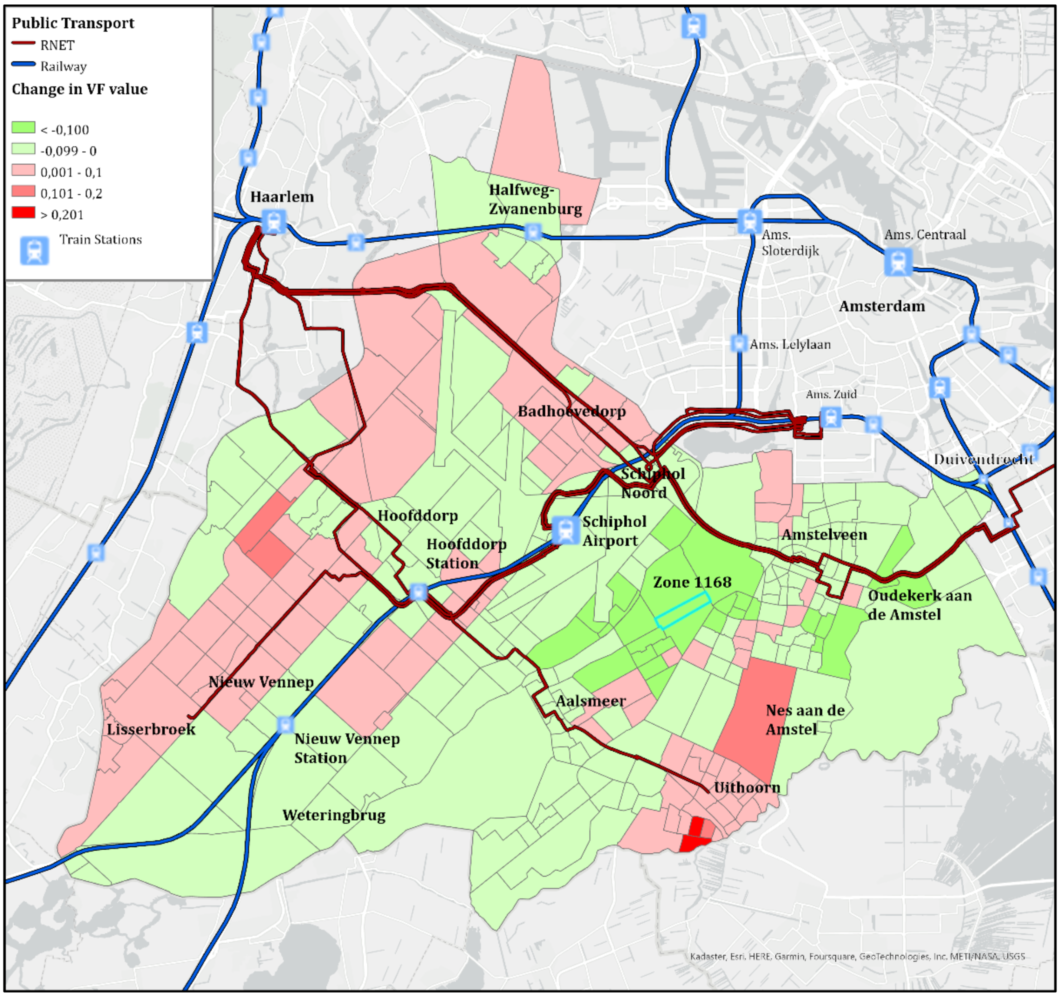


Figure 40: Changes in VF value distribution from PT frequency modifications

As expected, the largest decreases in VF values are around zone 1168. The largest decreases occurred in Uithoorn, Hoofddorp, Nieuw-Vennep, and the northern areas of the concession. These changes make sense as these areas contained the routes targeted for frequency decreases.

Unlike the equity evaluation methods for egalitarianism and proportionality, it is easier to use the equity evaluation for sufficientarianism in the frequency adjustment process, as the target VF value for each zone can be kept constant for each iteration. However, because the accessibility measure used in this study is the logsum travel cost, changes to frequency in a zone affect more zones than just the target zone. This means that accessibility improvements from frequency increases in target zones can be undone by frequency decreases in other zones. Additionally, without other criteria for frequency modifications other than the VF value, the frequency modification process can potentially become arbitrary when there are many possibilities for where to change frequencies. It can also lead to routes on the periphery of the study area with large parts of the route outside the concession boundary being targeted for frequency decreases. This is the easiest way to reduce operating costs without increasing VF values, but this incentive misalignment can negatively impact accessibility in areas adjacent to or on the periphery of the study area. Finally, this method was only applied to increase accessibility for the zone with the lowest VF value, when in actuality there were several other zones with insufficient accessibility. It is more challenging to improve accessibility for several areas at a time than for just one, especially when every frequency increase must be compensated for by a frequency decrease to maintain cost neutrality. Therefore, while it is more feasible to use the principle of sufficientarianism in the network planning process than for the other principles, there are still limitations and challenges that limit the practicality of the applied method.

5.9 Comparison and Synthesis

The following section will demonstrate how the results of the equity evaluation of the existing network compare for each principle in terms of their spatial distribution. An additional equity analysis for sufficientarianism was carried out at the PC4 level in order to compare egalitarianism and proportionality with the same level of spatial detail. The results of this individual analysis can be found in Appendix B.

5.9.1 Spatial distribution of inequity

Figure 41 below shows how the zones with accessibility surpluses compare between the distribution principles of egalitarianism and proportionality. Sufficientarianism is not considered here, because as was previously mentioned, this distribution principle is only concerned with achieving a minimum level of accessibility and a surplus is therefore not possible.

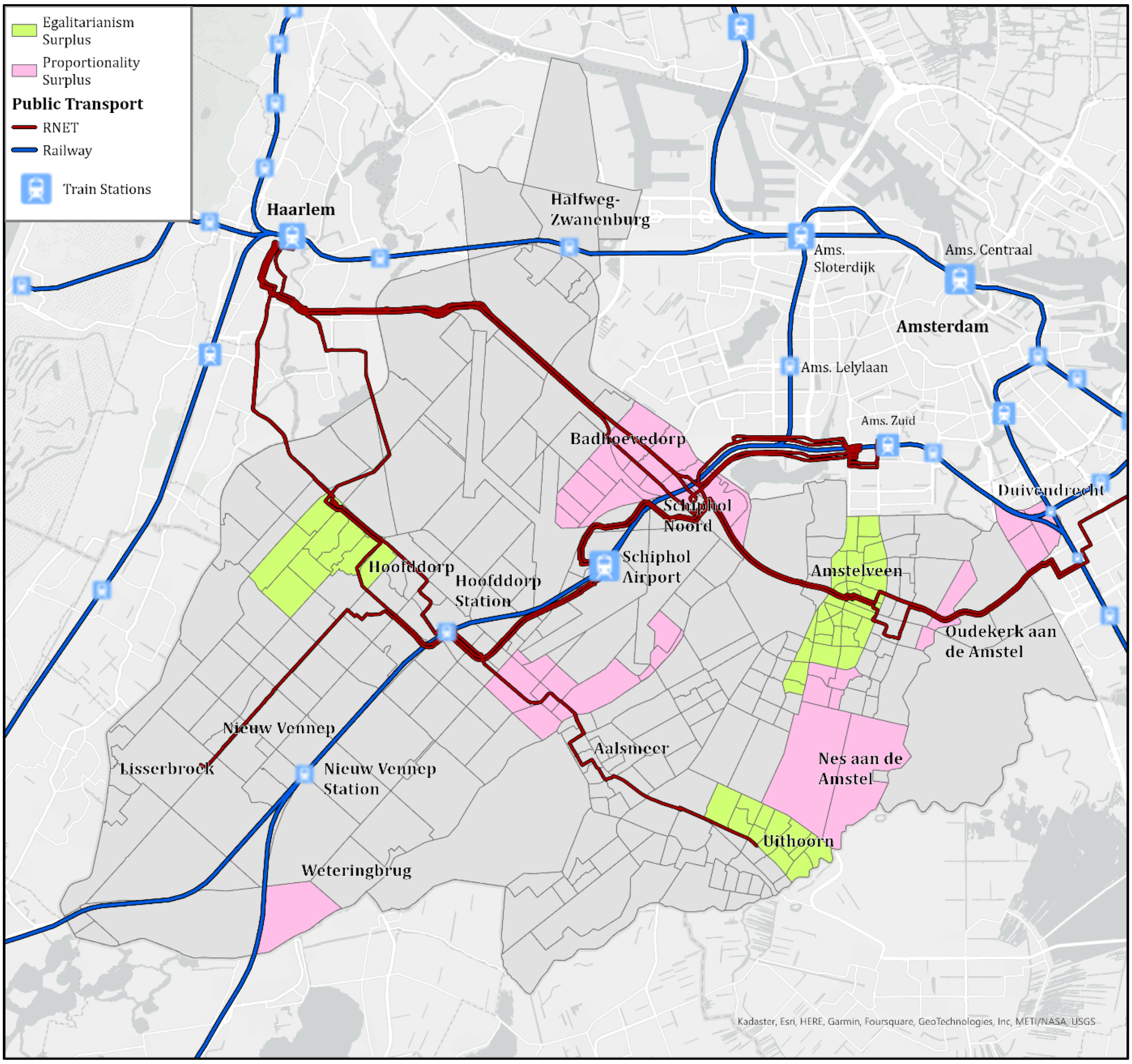


Figure 41: Comparison of areas of surplus accessibility within Amstelland-Meerlanden

In the figure above, an egalitarian surplus is considered as an area where the accessibility surplus is more than 0.5% due to the high level of equality already present in the accessibility distribution. A proportionality surplus is considered as an area where the target logsum travel costs exceed the actual costs by more than 3,248 perceived minutes, as this is one standard deviation above the average logsum travel cost. This threshold was selected instead of a threshold of 0 due to the large proportion of zones with excess accessibility according to this principle, and because of the difficulty of achieving a perfectly ideal PT accessibility distribution according to proportionality. With these thresholds, it is possible to see the geographical differences in the areas identified as having accessibility deficits according to each principle. The most noticeable aspect of the figure is that there are no overlapping zones between these two principles. This is summarized in Table 8 below.

Table 8: Number of zones per distribution principle with an accessibility surplus

Distribution Principle	Number of PC4 postcodes with Accessibility Surplus
Egalitarianism only	5
Proportionality only	10
No significant surplus	33

A notable finding is that according to egalitarianism, there are surpluses in denser zones, including residential areas of Hoofddorp, Uithoorn, and Amstelveen. These areas are some of the densest zones of the concession, classified primarily as central urban areas. These zones receive a higher level of PT supply compared to surrounding zones due to their density of human activity, therefore, it is expected that they have a higher level of accessibility relative to the equal level. Proportionality, on the other hand, shows surpluses primarily in lower density zones, such as near Schiphol airport, Nes aan de Amstel, Oudekerk aan de Amstel, and Weteringbrug. These areas are classified as rural living and recreation areas. The only exception is Badhoevedorp, which has an accessibility surplus, despite being classified as an urban living and working area. This means that if any service planning decisions were made that would reduce PT service in areas of accessibility surplus, higher density areas would be affected if egalitarianism was used as the distribution principle, while primarily lower density areas would be affected if proportionality was used. In practice, reducing PT service in high density areas could conflict with other PT objectives, potentially demonstrating one of the limits of an egalitarian approach.

Figure 42 below shows how the zones with accessibility deficits compare between the distribution principles of egalitarianism, proportionality and sufficientarianism.

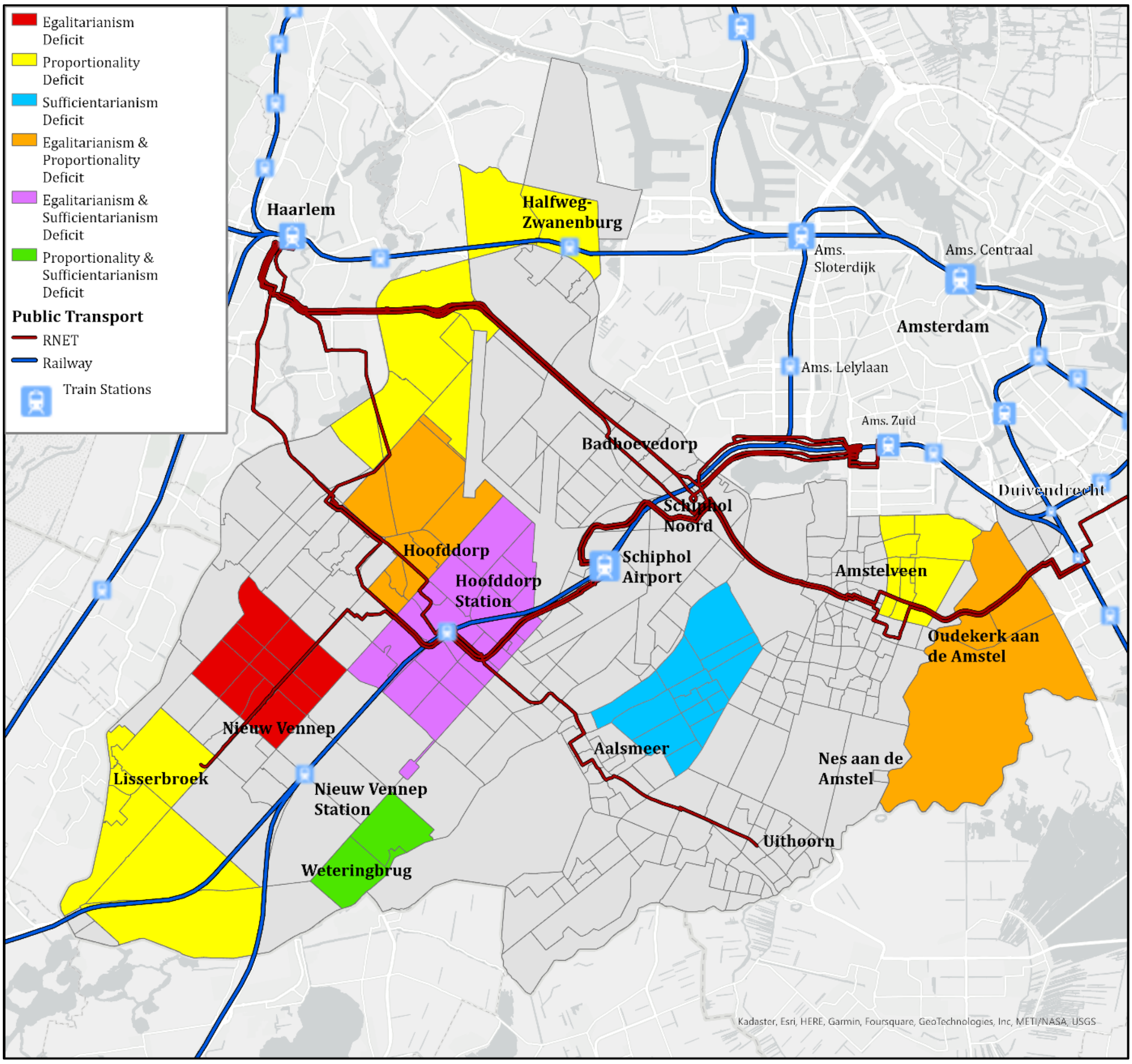


Figure 42: Comparison of areas of deficit accessibility within Amstelland-Meerlanden

For egalitarianism, a threshold of 0.5% excess travel costs is applied for an area to be considered to have an accessibility deficit. A threshold of more than -3,248 perceived minutes (average minus one the standard deviation) is applied for an area to have an accessibility deficit according to proportionality. Zones with a VF value below the 95th percentile of PC4-level VF values (2.13) are considered deficient in accessibility according to sufficientarianism. As can be seen in Table 9 below, there are only a few overlaps between two of the distribution principles when identifying PT accessibility deficits, and no overlaps between all three principles.

When the deficit areas according to each distribution principle are seen together on the same map in Figure 42, it is clear that the peripheral areas of the concession appear to be deficient according to at least one principle. This could indicate that the borders of the concessions receive a lower than justified level of PT service due to their location on the periphery of the area.

Table 9: Number of zones per distribution principle with an accessibility deficit

Distribution Principle	Number of postcodes with Accessibility Deficit
Egalitarianism only	1
Proportionality only	5
Sufficientarianism only	1
Egalitarianism and Proportionality	2
Egalitarianism and Sufficientarianism	1
Proportionality and Sufficientarianism	1
No deficit	37

As previously discussed, the zones classified as deficient according to each principle are generally low density, with some exceptions. These exception areas turn out to be the areas that the some of the different principles have in common. The common deficit zones for egalitarianism and proportionality are in northern Hoofddorp and Oudekerk aan de Amstel. This part of Hoofddorp has a low population density and a low-moderate employment density, while Oudekerk aan de Amstel has a low density in both aspects. For the common zone between egalitarianism and sufficientarianism located in central Hoofddorp, there is a low-moderate population density and a moderate employment density. The common zone between proportionality and sufficientarianism, located in Weteringbrug, has a low density of human activity.

This shows there is some common ground between zones identified as deficient according to different principles when the density of the zones is slightly higher, although overall, there are not many overlapping zones. The differences in geographical locations for each distribution principle demonstrates the impact and importance of the selected distribution principle used in equity evaluation, as each principle would recommend addressing different areas within the concession.

5.9.2 Degree of inequity

Due to the use of the same accessibility measure and spatial scale for each distribution principle while evaluating the AML area, it is also possible to compare the degree of inequity between the three principles. The comparison of excess and deficit logsum travel costs according to each principle is shown in Figure 43 below.

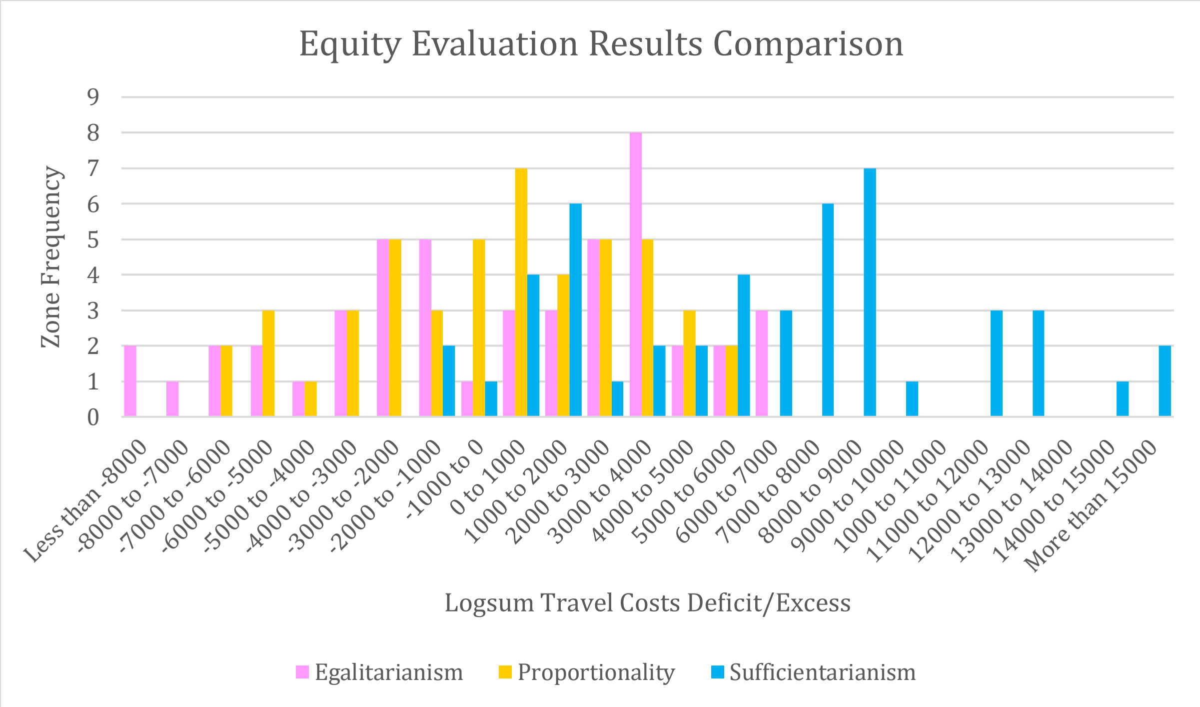


Figure 43: Comparison of accessibility surplus and deficit distribution in Amstelland-Meerlanden

In the figure above, negative values indicate an accessibility deficit, while positive values indicate a surplus. Based on Figure 43, egalitarianism and proportionality have similar accessibility deficit/excess distributions, while sufficientarianism is skewed with the most zones exceeding the minimum threshold. The similarity between egalitarianism and proportionality likely has to do with the fact that in this analysis, they consider population and population density, respectively. Therefore, there is more common ground between egalitarianism (when evaluated in absolute terms and not percentages) and proportionality than with either of these principles with sufficientarianism, which does not consider population. Table 10 below shows the number of surplus and deficit zones per distribution principle, as well as the sums of the deficits and surpluses.

Table 10: Number and sum of surplus and deficit zones per distribution principle

Distribution Principle	Number of Surplus Zones	Number of Deficit Zones	Sum of Deficits and Surplus
Egalitarianism	25	23	0
Proportionality	22	26	0
Sufficientarianism	3	45	301,094

Comparing the sums of the deficit and surplus logsum travel costs for each principle demonstrates that egalitarianism and proportionality suggest a redistribution of existing resources, while sufficientarianism shows a large degree of accessibility larger than the minimum level. However, it is important to note that the distribution of excess and deficit travel costs for sufficientarianism depends on the VF value defined as the sufficiency threshold, which could significantly impact the skew of this distribution. In this analysis, a sufficient VF value was defined as a one below the 95th percentile of VF values, leading to a distribution where 95% of postcodes have an accessibility surplus. According to a strict definition of sufficientarianism, it is not possible to have an accessibility surplus as this principle only states the existence of a minimum accessibility level, however the "excess" travel costs are shown in Figure 43 to illustrate the distribution of values below the maximum threshold.

Insight can also be gained by ranking the zones with the ten largest absolute deficits and surpluses per distribution principle. Nine out ten of the zones with the highest accessibility deficits are the same for egalitarianism and proportionality, when both are evaluated in absolute terms, one of which is also identified as deficient according to sufficientarianism. This is somewhat expected because the ideal accessibility for egalitarianism and proportionality is based on a linear relationship between a population factor and the actual accessibility. Therefore, similar gaps between the ideal and actual accessibilities will be identified, although the magnitude is smaller for proportionality than for egalitarianism.

The zone where all zones identify an accessibility deficit contains Leimuiderbrug and Rijsenhout in the southeastern part of the concession. This zone is classified as a rural and recreational area and has a very low population and employment density of 83 inhabitants and 49 jobs per square kilometer. There are no AML bus routes servicing this area or the directly adjacent zones, although there is some bus service from a neighboring concession. This could explain why the PT accessibility within AML, which is captured by the use of the logsum travel cost measure, for this zone is low.

Egalitarianism and proportionality share two out of ten surplus zones, egalitarianism and sufficientarianism have one zone in common, and proportionality and sufficientarianism share two out of ten zones. The common zones with significant surpluses and deficits between the three principles show that there are similarities in the equity evaluation results between egalitarianism and proportionality both in terms of geography and magnitude. However, sufficientarianism does not share these similarities to the same extent.

5.9.3 Synthesis

This chapter applied the equity evaluation methods from chapter 3 to the Amstelland-Meerlanden area and attempted to apply the results of these evaluations to the network planning process. It was found that the distribution of PT accessibility in the AML area most closely resembles that of an egalitarianism distribution, meaning that the logsum travel costs within the area are almost equally distributed. The geographical areas of inequity identified for each distribution principle were different for both accessibility surpluses and deficits, although this is influenced by the selected equity threshold per principle. Some similarities were identified between egalitarianism and proportionality when the ideal logsum travel cost per zone was compared with the actual travel cost. When the degree of accessibility inequities is compared, egalitarianism has the largest deficits while sufficientarianism has the largest excesses, although this is due to the selection of the sufficiency threshold.

When the equity evaluation results were used to inform frequency modifications in the AML area, it was found that the role of equity evaluation results in the network planning process according to each distribution principle is different. The main finding from the use of the three PT equity evaluation methods in network modification is that these methods are very difficult to apply for the principles of egalitarianism and proportionality. This is due to the circular calculations present in these methods, as each frequency modification changes the total accessibility in the area, which is used to calculate the target accessibility per zone. Therefore, equity evaluation according to these two principles is better suited for evaluation and comparison of PT networks. However, depending on the relevant factors selected to evaluate proportionality, the evaluation process can be useful for identifying PT accessibility gaps as a sort of latent demand indicator.

Sufficientarianism could be a more promising candidate for use in active PT network planning, as a stable accessibility target can be defined by the planner and does not have to be dependent on the existing accessibility distribution. However, this research identified several limitations that affect the use of equity evaluation results in planning according to this principle. Examination of other impacts of network changes made according to this method, especially those related to PT ridership, should be understood when adapting this method for use in network planning. Because this method is agnostic to demand, ridership impacts are not captured, so an equitable network where all zones achieve a minimum VF value may not be an efficient or effective one. Additionally, the same VF value threshold was used throughout the study area when there may be different PT goals for different types of areas. For example, in a city center, the goal could be to have PT accessibility be better than that for the car, whereas in a rural area this could be considered an unrealistic goal. This method could therefore be improved by defining a sufficient VF value per area type based on the desired modal share of PT (Gaaff, de Koning, Bonnier, van der Slot, & Mout, 2021).

The findings in this thesis link well with the report *Fair Mobility Policy* published by the Knowledge Institute for Mobility Policy (KiM), by demonstrating the outcomes of the selection of different distribution principles. The KiM report recommends a process for including justice in mobility policy and provides examples for three distribution principles: utilitarianism, egalitarianism, and sufficientarianism (Alonso González, Jonkeren, & Wortelboer-van Donselaar, 2022). According to this process, once it is decided that there is an equity goal for a policy, it should be decided which distribution principle is most suitable, which requires the balancing of conflicting interests by policymakers. The variables that can quantify the policy must be determined and then used to design indicators that can be evaluated to measure the effect of the policy on equity (Alonso González, Jonkeren, & Wortelboer-van Donselaar, 2022). The research in this thesis parallels the KiM framework and demonstrates its practical application, finding the quantification of variables and indicators to be a more challenging task than it seems. It is also important to consider the limitations of the chosen equity principles, variables, and indicators when interpreting the results of these evaluations, which will be discussed further in the following chapter.

6

Conclusion

This study compared the use of different accessibility distribution principles in public transport (PT) equity analysis and investigated how the evaluation methods and results could be used in PT network planning. The goal of this study was to understand the impacts of the use of different distribution principles in PT equity evaluation to inform future research and mobility policy. This was done by performing equity evaluations for the 2014 PT network of the concession area of Amstelland-Meerlanden (AML) in the service area of the Amsterdam Transport Region. Section 6.1 will summarize the main findings of this thesis by answering the main research question and sub-questions. Section 6.2 will present the main scientific contributions of the work in this thesis, and section 6.3 will discuss the practical implications. Section 6.4 will reflect on the limitations of this research, leading to future research recommendations in section 6.5 and policy recommendations in section 6.6.

6.1 Main findings

The following section highlights the main findings of this study by answering the sub-questions and main research question from section 1.4. Beginning with the sub-questions:

- *What distribution principles can be used to define an equitable distribution of PT accessibility, and how can their use in equity evaluation be quantified?*

This research sub-question was answered in section 2.3.3 of the literature review, which gave an overview of the many distribution principles that could be applied to PT equity evaluation. These are listed below (Pereira, Schwanen, & Banister, 2016; Litman, 2022; Rubensson, Susilo, & Cats, 2020):

- *Utilitarianism*: the dominant principle currently used in PT network planning, stating that the distribution of PT accessibility should maximize the total PT accessibility in the area of interest. It is acceptable for the distribution to be unequal if the aggregate PT accessibility is high. This can be problematic in the case where the total welfare of society comes at the expense of the least well-off, who are the most likely to depend on PT.
- *Sufficientarianism*: the distribution of PT accessibility should allow everyone to meet their basic needs using PT. These basic needs can include access to employment, education, healthcare, food, etc., although there is not one set definition. Therefore, the sufficiency level must be judged and set by the policymaker or other decisionmaker.
- *Egalitarianism*: states that everyone should receive the same level of PT accessibility. The evaluation of a distribution based on egalitarianism has been applied in many studies, in fields other than transport. In PT, this has generally been applied in regard to the supply of PT service, but this can be applied to the distribution of anything within a population, including PT accessibility, as was done in Rubensson et al. (2020).

- *Equal opportunity*: the distribution of PT accessibility is acceptable if everyone can reach the same number of specified opportunities. Any inequality that exists even after the same opportunities are afforded to all is considered a result of personal choice. Because this method is essentially an extension of egalitarianism, the accessibility distribution could be measured in the same way using a suitable accessibility metric.
- *Libertarianism*: the PT accessibility distribution should be determined by demand patterns and consumer choice. Priority is given to the rights of individuals, even if this comes at the expense of societal welfare. This is problematic in PT, as this principle does not consider power imbalances in society that the free market is not able to correct for that can affect how resources are distributed.
- *Rawl's Theory of Justice*: PT accessibility should be higher in areas with disadvantaged populations, although no applied examples were found in the literature specifying how much greater the accessibility for these populations should be.
- *Proportionality*: PT accessibility should be higher in areas with large populations, as density is a significant contributor to PT usage. A study by Rubensson et al. (2020) proposed a methodology for evaluating an accessibility distribution according to proportionality considering factors other than population density, therefore increasing the flexibility of this principle.
- *Maximum gap standard*: the distribution of PT accessibility does not have to be equal; if the accessibilities between different socioeconomic groups are not too large then the distribution is acceptable. However, this principle does not specify a minimum level of accessibility as a starting point, or a maximum gap size.

These many principles show the complexity of the answer to the question of what distribution is considered fair, as none can be judged as completely right or wrong. Ultimately, it was decided to select egalitarianism, proportionality, and sufficientarianism as the distribution principles to compare. This was because egalitarianism and proportionality do not require the selection of arbitrary thresholds, while sufficientarianism was chosen because of its relatively frequent applications in practice and previous research. Egalitarianism is the principle most used in previous research to evaluate the distribution of PT service supply, because the methods were easily transferrable from economics to other fields (Rubensson, Susilo, & Cats, 2020; Camporeale, Caggiani, & Ottomanelli, 2019; Wang, Liu, & Zhang, 2022). However, methods according to other distribution principles were also developed as the importance of equity, in contrast to equality, in PT became better understood. Needs-gap analysis is a type of proportionality evaluation that has been previously applied in several studies (Aman & Smith-Colin, 2020; Ricciardi, Xia, & Currie, 2015), with a method using linear regression that provides a more concrete target for the accessibility proposed more recently (Rubensson, Susilo, & Cats, 2020). Sufficientarianism is a measure that is mentioned in policy (Gaaff, de Koning, Bonnier, van der Slot, & Mout, 2021) with limited investigation in research when using the logsum travel measure, so it was decided to propose a method in this research (van der Veen, Annema, Martens, van Arem, & Homem de Almeida Correia, 2020). It was not possible to find quantifiable methods and applications for the other distribution principles, and these principles also require an arbitrary judgement to be made by the decisionmaker. For example, to apply Rawl's Theory of Justice, it would need to be determined how much better the accessibility should be for disadvantaged groups than the rest of the population.

The methods for evaluation according to these three distribution principles were presented in chapter 3. For egalitarianism, the Lorenz curve and Gini coefficient were calculated using zonal data on average income, population, and PT logsum travel cost. The Lorenz curve shows how the logsum travel costs are distributed throughout the population while the Gini coefficient indicates the overall equality of the accessibility distribution. For proportionality, multiple factors were tested to come up with a final multiple regression model based on population density and employment density. This model was used to calculate a target accessibility per zone, which was then compared with the actual accessibility per zone to determine if a zone experiences an accessibility surplus or deficit. Equity according to sufficientarianism was evaluated using the VF value for PT, which is the ratio of the logsum travel cost by PT to the logsum travel cost by car. The VF value for each zone was calculated and then a minimum VF value threshold was defined based on the original VF value distribution, as the average VF value plus two standard deviations. Any zones above this VF value threshold were then considered to be deficient in PT accessibility.

- *How does the spatial distribution and magnitude of PT accessibility deficits and excess identified in equity analysis differ based on the selected distribution principle?*

This sub-question was answered in chapter 5, when the equity evaluation methods from chapter 3 were applied to the case study area of Amstelland-Meerlanden (AML).

In terms of the locations of areas with a PT accessibility excess, only egalitarianism and proportionality can be compared since a surplus is not possible with sufficientarianism. Whether or not there are zones with an accessibility surplus according to both principles depends on if egalitarianism surpluses are evaluated based on the difference between the equal and actual travel cost value or based on the percentage logsum travel cost weighted by population. In this analysis, the latter method was used to compare the principles because these are the zones that would have the most impact on the equality of the accessibility distribution if their accessibility was changed. Based on this method, egalitarianism had five zones with a surplus while proportionality has nine, with no zones overlapping. The area types considered to have surplus accessibility also differ, with egalitarianism identifying moderate density zones and proportionality identifying zones of low density. If network planning decisions were to be made based on this criterion, then different area types would be affected based on the distribution principle used. Egalitarianism would recommend service reductions in denser zones, which could conflict with other objectives of PT.

There is more in common between the locations of accessibility deficits between the three principles. Egalitarianism and proportionality have two deficient zones in common, while the egalitarianism-sufficientarianism and proportionality-sufficientarianism combinations each have one deficient zone in common. There were no zones that were considered deficient in PT accessibility according to all three distribution principles. Most deficient zones according to each principle have a low density of human activity. A notable finding is that the few zones where the density is more moderate are the zones that overlap between different principles. This means that there is some common ground between the distribution principles when it comes to identifying areas of significant PT accessibility deficit. If network planning decisions were guided by these principles, then it is expected that some modifications would improve equity according to more than one principle. A notable pattern is that the locations of accessibility deficits in the AML area are primarily in the peripheral areas of the concession. This could indicate that peripheral areas are neglected according to one distribution principle or another due to their locations at the edge of the concession area. Additional attention should be given to these areas to ensure that they are not an afterthought in the planning process.

- *How can the results from PT equity evaluation be used in PT network planning?*

In chapter 5, it was attempted to apply the evaluation results from each distribution principle to inform PT network modification in the AML concession area. Only frequency modifications were considered in the scope of this research, as this is a simple network modification with predictable impacts on travel costs, compared to rerouting and stop changes. The goal was for the frequency modifications to be cost-neutral, to evaluate the feasibility of making a PT network more equitable without increasing costs. However, frequency modifications to design a more equitable PT network turned out not to be feasible for the principles of egalitarianism and proportionality, due to the ideal accessibility level being dependent on the total accessibility in the area. This is because for egalitarianism, the ideal accessibility is the total accessibility divided by the number of zones, and for proportionality the ideal accessibility is calculated based on a regression where the actual accessibility is the dependent variable. Therefore, every time frequency modifications were made, the total accessibility changed, which altered the ideal accessibility per zone. This meant that the set of zones identified as having excessive or deficient accessibility could also change per iteration. This made it very difficult to understand where the next set of frequency changes should be targeted. Therefore, it is recommended that the results of equity evaluation according to egalitarianism and proportionality not be used as a planning tool to target network modifications when the logsum travel cost is the accessibility measure. However, these methods remain useful for the evaluation and comparison of different PT networks, as this could help inform decisions regarding which version of a network design to adopt. Proportionality, however, can be useful in drawing attention to areas that could have a good potential for PT services but have poor PT accessibility, as a sort of latent demand indicator based on the selected factors.

Sufficientarianism did not have this limitation of a shifting ideal accessibility since the sufficiency threshold can be defined and held constant by the planner or other decision-maker. After network modifications are made, it can then be checked to see if the zones with insufficient accessibility have reached the sufficiency threshold, and if any zones with sufficient accessibility have become insufficient. If the goal is to make cost neutral network modifications, however, this could present a problem. Cost neutral network modifications require service increases in some areas and service decreases in others. While the determination of insufficient zones for where to increase frequency was generally straightforward, it was not clear where it would be acceptable to reduce frequencies, as so many zones were considered to have more than sufficient accessibility. Without additional criteria, for example a factor such as ridership, it was not clear where frequency decreases would be most acceptable. Therefore, while it is possible to make cost neutral PT network changes to achieve an equitable PT accessibility distribution according to sufficientarianism, it is not recommended without the consideration of other criteria relevant to PT planning. Like with egalitarianism and proportionality, it is also possible to use equity analysis according to sufficientarianism to compare different PT network designs, by comparing the number of deficient zones and their magnitudes.

With these sub-questions answered, it is possible to address the main question of this research study, which is:

How do the outcomes of public transport equity evaluation vary for different accessibility distribution principles, and how can this inform the network planning process?

When individual equity evaluations were performed based on the three different distribution principles of egalitarianism, proportionality, and sufficientarianism, it was found that both the geographical location and magnitude of PT accessibility surpluses and deficits varied between each principle. A network with an equitable distribution of PT accessibility according to one distribution principle may therefore not be equitable according to another. However, some commonalities are found in the locations of accessibility deficits, many of which are found in the peripheral areas of the concession. Additionally, the classification of a zone as having excess, acceptable, or deficient accessibility depends heavily on the thresholds selected by the decisionmaker. Careful consideration is required in distribution principle selection and threshold determination, and should be be driven based on what is most valued in the societal context of the area.

While the results of equity evaluation can be used to inform network planning decisions, they should be used as one of the many inputs for PT network planning, and not as the deciding factor in planning decisions. All three distribution principles can be used to evaluate and compare different PT network designs. A PT network according to egalitarianism can be evaluated based on the Gini coefficient, which provides a single value on a scale from 0 to 1 that indicates the equality of the distribution. While the Gini coefficient on its own can be difficult to interpret, the Gini coefficients for two networks can be easily compared to determine which network has a more equal distribution of PT accessibility. PT networks according to proportionality can be compared based on the number of zones per network classified as having an excessive or deficient level of accessibility, as well as the magnitude of surpluses and deficits in these zones. However, the results of the evaluation methods for these principles cannot be used to suggest specific network changes due to the circular calculations present in these methods.

Sufficientarianism can be used to compare networks in a similar way, by comparing the number of zones below the sufficiency threshold, as well as their magnitudes. However, unlike egalitarianism and proportionality, sufficientarianism could also be used to inform network planning decisions, when used in combination with other information such as ridership. Zones with insufficient levels of accessibility according to the defined sufficiency threshold could be targeted for PT improvements. However, in the case of cost neutral network modifications where frequency decreases must be made to compensate for the increases in deficient areas, additional criteria should be used to determine where these decreases could occur without negatively affecting other PT objectives such a ridership.

6.2 Scientific implications

Previous research on public transport equity only used one distribution principle, or one combination of principles, to evaluate the equity of a PT accessibility distribution. It was previously unknown how the evaluation results for different distribution principles would compare to one another in the same study using the same accessibility measure. This research fills this gap and provides insight into the impacts of the selection of a distribution principle in equity analysis.

Previous studies in this research area did not attempt to apply the results of equity evaluation to PT networks; generally, it was only stated that this could be done later by practitioners. The lessons learned from applying methods and theories are also relevant for equity research, to demonstrate the feasibility of these methods in practice. This research attempted to use the evaluation results to make frequency modifications to the AML concession area PT network. It was found that this process can be more complicated than it seems, and that it is not feasible for all distribution principles. Understanding this could stimulate future research into the development of new methods for equitable planning according to these principles.

The methods presented for equity evaluation and comparison in this work could be transferred to other case study areas. The transferability of this research is dependent on the data availability at the appropriate spatial scale, but the data and 4-step transport model used in this study should be available from the transport authority. The methods used to evaluate a network based on egalitarianism and proportionality have already been applied in previous research to different case study areas, therefore they have already proven to be easily transferrable to other contexts (Rubensson, Susilo, & Cats, 2020; Deboosere & El-Geneidy, 2018). The evaluation method according to sufficientarianism was based on previous research using a different accessibility measure (Projectbureau Integrale Verkeers- en Vervoerstudie, 1995; van der Veen, Annema, Martens, van Arem, & Homem de Almeida Correia, 2020). While it would be preferrable to gain a better understanding of how sufficiency thresholds should be defined when the logsum travel cost is used as the accessibility measure, the method is still considered transferrable to other study contexts.

6.3 Practical implications

This research contributed to the understanding of how equity evaluation methods can be used to identify inequitable accessibility distribution. This is especially valuable in the identification of accessibility deficits, so that additional attention can be given to these areas in the planning process. As this research demonstrated, the location and size of the deficit depends on the distribution principle used in the evaluation. Understanding the distribution principles identified in this research could help to inform decisions in mobility policy. For equity to become a part of mobility policy, it is important to define what is meant by an equitable PT system. For example, should the system provide the same access to everyone, or should resources be allocated based on some specified criteria? In the latter case, should those criteria be related to demographics, land use, or socioeconomic characteristics of the population? How should accessibility be measured? This research addressed these questions and presented the differences in evaluation results between the three distribution principles, therefore demonstrating the careful consideration required when selecting which distribution principles should be used to guide mobility policy.

This research also gives insight to practitioners about the use of logsum travel costs as an accessibility measure. This measure is generally only applied in research as it can be difficult to interpret when compared to other metrics, for example location-based measures, which state how many opportunities an individual can reach within a predefined travel time or distance (Geurs & van Wee, 2004). There are benefits and drawbacks for each possible accessibility measure, mainly related to the tradeoff between simplicity and theoretical soundness. The more theoretically sound an accessibility measure is, the more complex and the less intelligible it becomes (Geurs & van Wee, 2004). This study used the logsum travel costs, which is considered more realistic but is not as simple to understand as infrastructure- or location-based measures. By using this accessibility measure in this research and discussing its limitations, it can be evaluated if this measure is suitable for use in mobility policy.

6.4 Limitations

Despite the valuable findings in this study, there are still some limitations that should be kept in mind when interpreting this research. There are limitations inherent to each of the three distribution principles, as well as limitations related to decisions made throughout the course of the research. These choices include the selection of the accessibility measure, the use of a 4-step transport model, and the limited scope and spatial scale of the study. These limitations are listed and described below.

Limitations of individual distribution principles

While the equity evaluation of the AML PT network showed that an egalitarian PT network is indeed achievable, there could still be challenges implementing this principle in other contexts. This is because in the face of limited resources, PT service is generally allocated to where it will be the most used. When the distribution of PT accessibility is equal, high accessibility in some zones will come at the expense of worse accessibility in other zones, given the same total accessibility. The ideal logsum travel costs per zone are 23,972 for egalitarianism, between 16,536 and 27,000 for proportionality, and between 18,922 and 43,876 for sufficientarianism. The zones with logsum travel costs lower for proportionality and sufficientarianism than for egalitarianism would receive worse accessibility in an egalitarian scenario, in order for other zones to receive better accessibility. Finally, it was not possible to use the results of the equity evaluation according to egalitarianism to make PT network modifications that would make the network more egalitarian. This was both because of the equality of the existing network, but also because of the circular nature of the calculations, the non-localized nature of frequency modifications, and the use of the logsum travel cost as the accessibility measure.

The evaluation methodology for proportionality also has some limitations in its application. In this research, linear regression was used for simplicity, despite some forms of non-linear regression having a higher R-square value. This could have affected the results by increasing the degree of accessibility surpluses and deficits. It is also possible that a zone could have a surplus according to linear regression but have a deficit according to non-linear regression, and vice versa. The model could therefore be improved by testing non-linear regression methods and selecting one with a better fit to the data. In terms of application, it was found that while proportionality is useful for identifying areas of accessibility deficit that could benefit from increased PT service, it is not suitable for locating areas of surplus where service could be reduced. This is because accessibility surplus is often the result of road network design or location between other zones with high level of PT service. This could make it more challenging to implement cost-neutral PT network changes. Finally, like egalitarianism, it is not possible to use the equity evaluation results according to proportionality for PT network modifications, because of the circular calculations, the scale of frequency changes, and use of the logsum travel cost.

The main weakness of the sufficientarianism evaluation methodology in this research is the use of the VF value relating PT accessibility to car accessibility. In practice, changes in car accessibility should not dictate parallel changes in PT accessibility, however this is inherent in this method. It may therefore be better to define a minimum accessibility threshold for PT that is independent of the accessibility of other modes. Additionally, this method used the same VF value for the whole study area, despite different areas having different mobility goals. This method could therefore be improved by assigning different minimum accessibility thresholds based on an area type classification, as is done in the Amsterdam Transport Region's Multimodal Network Framework (Gaaff, de Koning, Bonnier, van der Slot, & Mout, 2021). Finally, it may be questionable if the setting of a minimum is enough to achieve an equitable distribution of PT accessibility. It could therefore be recommended to combine sufficientarianism with another distribution principle to guide the distribution of PT accessibility beyond the minimum level.

Logsum travel cost as an accessibility measure

A major limitation of this research is the selection of the logsum travel cost as the accessibility measure. While all accessibility measures have their benefits and drawbacks, it is important to understand the impact that the selection of this measure has in this research.

The logsum travel cost of an area is highly influenced by its centrality. Zones towards the center of the study area will generally have better accessibility than zones on the periphery. This is because the distance from the target zone to all other zones in the study area will be less for a more central zone than for a peripheral zone. Depending on the distribution principle being used in the equity evaluation, this could mean that a central zone will appear to have a better accessibility than it really does, while a peripheral zone may appear to have worse accessibility.

This could lead to accessibility improvements being biased towards more peripheral zones over central zones.

Additionally, the same zone could have a high accessibility when it is the center of the selected area, but a lower accessibility with a different area selection when that zone is on the periphery. This also makes the results of equity evaluation partly dependent on the selection of the study area boundaries. The bias towards peripheral zones should therefore be kept in mind when interpreting the results of equity evaluation using the logsum measure.

Another problem with the logsum measure of a predefined area is that only travel within the study area is investigated. This means that access to and from areas outside of the defined area boundaries is not considered, regardless of the importance of these destinations and corresponding demand patterns. Accessibility to zones outside of the study area can be impacted by any PT network modifications made within the study area, but this is not captured in this study. Excluding critical areas outside of the study area boundary therefore does not present the complete picture of the accessibility of an area.

In the selected method to calculate the logsum generalized travel costs, it was decided to not include weighting by PT travel demand. This is because one of the goals of this thesis is to compare accessibility distribution principles using a demand-agnostic method to avoid the influence of existing demand patterns on supply, as this could lead to propagation of existing inequities. However, not weighting the zones means that they are all weighted equally, which carries the limitation that in the network modification stage, zones with low PT demand may be recommended for a higher accessibility than makes sense according to the demand in that zone, and vice versa for zones with high importance.

Use of a 4-step transport model

In this research, a 4-step transport model was used to calculate the accessibility measure and make frequency modifications based on the equity evaluation results. These transport models contain simplifications and assumptions about traveler behavior that may not represent realistic traveler behavior or PT system operations. For example, in VENOM it is assumed that travelers are willing to walk up to 10km to access a PT stop. This does not represent realistic travel behavior and assuming this could inflate the PT logsum travel costs. Another assumption is that the PT services run exactly according to schedule and that crowding does not limit the choices of the traveler or travel time of the trip. This omission could make the logsum travel costs for PT appear less than they really are. Finally, the only access mode possible for PT is walking, which does not reflect the common use of bicycle as an access and egress mode in the Netherlands. This assumption could inflate the logsum travel cost calculation for PT. While it is currently not standard for a transport model to take all of these complexities into account, these simplifications should be kept in mind when interpreting the results and using them to inform network modifications decisions. This inflation and deflation of the travel costs could impact the evaluation results for sufficientarianism, which in this analysis uses the VF value to compare PT and car logsum travel costs, since the car travel costs are not affected by these assumptions. Use of an agent-based transport model would therefore be preferred and could provide a more complete picture of accessibility in an area.

Scope of the study

The scope of this study was limited in its application in several ways. Not all identified distribution principles, or any combinations of distribution principles, were evaluated in this research. Egalitarianism and proportionality are selected because their evaluation methods do not require thresholds to be selected, while sufficientarianism is chosen because it is the most mentioned in policy documents. Additionally, these principles were evaluated individually, and no combinations were evaluated. For policymakers to make an informed decision regarding the adoption of a distribution principle in equity evaluation, it would be useful to understand more of the options available.

The only network modification employed in this study was the changing of frequencies, and changes to stop locations or route alignments were not considered. However, this is relatively unimportant given the conclusion that the results of equity evaluation should not be used as the primary input for network modification decisions. Additionally, only the AM peak period was evaluated in this study, as the only time periods available in the model were the AM and PM peak. While the methods in this study can be easily reapplied to other time periods, the magnitude of temporal accessibility variations is not acknowledged, although it represents another dimension of accessibility inequity (Stępniak & Goliszek, 2017).

The case study area was limited to the 2014 PT network, as this was the most recent year for which all the required data was available due to the update cycle of VENOM. In practice, service planning decisions should be made based on current data. The applicability of the methodology in practice may therefore be limited if more current data is not available.

Spatial scale

The highest level of spatial resolution possible for each of the equity evaluations was the PC4 level for egalitarianism and proportionality, and the finer resolution PC5 level for sufficientarianism. When changing frequencies for each of the three principles, it was found that the spatial scale can make it difficult to determine where to target a frequency modification if there is a high density of routes in an area. For example, if a PC4 zone has an accessibility deficit and contains two or more routes, it is not clear which of the routes would benefit most from a frequency increase. While this can be tested through iterations, this becomes significantly more complicated as the number of routes in a zone increases, which can become impractical depending on the computation times in the transport model. This is still a problem at the PC5 level in several zones, although to a lesser degree.

Another challenge with working at both spatial scales is the non-localized nature of frequency modifications. If the frequency on a route is modified, all zones adjacent to the route experience a change in accessibility, as well as any zones with OD pairs that use that route. While this is not as much of a concern for sufficientarianism, it is problematic for egalitarianism and proportionality, as adherence to these principles depends on the total accessibility in the area. There is therefore a mismatch between the spatial scale of the results of equity evaluation, and the scale of PT network modification impacts.

6.5 Recommendations for future research

Further research should be conducted to finetune the components and process of the PT equity evaluation methods presented in this research. This could involve studying the impact of the use of different accessibility measures, consideration of demand in the evaluation or modification process, study of other distribution principles and combinations of principles, and analyzing the impact of improved equity on other service metrics.

Accessibility measure

Due to the limitations of the logsum travel cost measure, it would be interesting to investigate how the accessibility measure impacts the equity evaluation results. The same evaluation method could be performed using several different accessibility metrics and comparing the zones that are classified as having excess or deficit accessibility. Equity analysis is less concerned with the actual value of the accessibility measure, but with the distribution of accessibility within an area (Rubensson, Susilo, & Cats, 2020). Therefore, it would not be the actual accessibility values that must be studied, but how the accessibility distribution between zones changes. It may not be necessary to use more complex accessibility measures such as the logsum if the accessibility distribution between zones is similar. Measures that are simpler to articulate in policy, for example location-based measures that define accessibility as the number of opportunities reachable within a specific time threshold (Geurs & van Wee, 2004), could be used. Understanding the impact of the selection of the accessibility measure could make it easier to include equity in mobility policy.

Incorporation of existing demand

As mentioned in the discussion of limitations, this method did not weight accessibility according to demand. While this was done intentionally to avoid existing demand patterns influencing the recommended accessibility distribution, it also fails to consider that PT is a service dependent on demand. Even if improved equity is a goal of PT, it is generally considered secondary to accommodating ridership demand. Therefore, future research could focus on developing an equity evaluation method that incorporates consideration of existing demand and balances it with equity. Whether this demand would be for only PT or for all travel could be another dimension of study. Inclusion of demand could take the form of weighting the accessibility measure according to demand, or possibly another method. For distribution principles such as sufficientarianism where it is possible to use the evaluation results in PT network planning, this consideration of demand could also be incorporated as a step of the network modification process.

Other distribution principles

Future research could examine the quantification of other distribution principles, so that more types of equity evaluation can be quantified and applied. These could include the maximum gap standard and Rawl's Theory of Justice. This could provide insights into the benefits and challenges of adopting each principle, in the same way that performing equity analysis according to the three distribution principles in this study provided similar insights. Additionally, there are some distribution principles that could be logical to combine, and these combinations could be tested and evaluated. For example, a criticism of sufficientarianism is that it is only concerned with defining a minimum accessibility threshold but does not address the distribution of accessibility below that threshold. Therefore, the distribution of accessibility below the threshold could be addressed with another principle, for example proportionality. The definition of what principles to combine would be determined by the researcher based on the study context, and the feasibility of evaluation according to these combinations could be tested. This would be useful for practitioners considering which (combination of) distribution principles to adopt into PT equity policy.

Impacts of improved equity on other service indicators

Another unknown that remains regarding equity analysis is the impact that improved equity has on ridership, operating cost, and service effectiveness. These impacts could also vary per distribution principle. It is frequently mentioned in the literature that resources for PT improvements are limited and that improved social equity costs more (Camporeale, Caggiani, & Ottomanelli, 2019), but this has rarely been quantified, although there has been consideration of operating costs in literature. In the optimization literature, the objective function is the societal cost, which is a combination of user and operator costs (Camporeale, Caggiani, & Ottomanelli, 2019; Kim, Kho, & Kim, 2019). In the solutions, the decrease in user costs offsets the increase in operator costs for an overall societal cost reduction (Camporeale, Caggiani, & Ottomanelli, 2019; Kim, Kho, & Kim, 2019), but in practice the constraint on operator resources cannot be offset by user costs. Therefore, there is a practical benefit of a separate evaluation of operator costs.

Additionally, the impacts of improved social equity on service effectiveness have yet to be evaluated. It is commonly said that in PT, there is a tradeoff between ridership and coverage, so if resources are diverted in a less utilitarian way, then ridership will decline (Giuffrida, Pira, Inturri, & Ignaccolo, 2021). Wang et al. (2022) added service effectiveness as an additional dimension of needs-gap analysis to identify areas with low service effectiveness that would benefit from investment in transport infrastructure. Then, areas can be prioritized for improved service effectiveness based on the presence of vulnerable population groups (Wang, Liu, & Zhang, 2022). However, this study did not evaluate how service effectiveness was affected after the implementation of changes to the PT system to improve social equity. The quantification of operator cost and service effectiveness impacts could provide some helpful insights for practitioners as to the potential effects of the adoption of different distribution principles to improve the equity of their PT systems.

6.6 Recommendations for future policymaking

With additional research, the Amsterdam Transport Region and other transport authorities could more directly consider equity in PT service planning. This requires some choices to be made, including selection of a distribution principle or combination of principles, and defining how equity can be included in the planning process.

Selection of distribution principle(s)

While this research provided valuable findings regarding the selection of distribution principles in equity analysis, it cannot provide a value judgement regarding which principle is most suitable for use in public transport policy. This decision lies with practitioners and policymakers who understand what is considered the fairest according to the populations that they serve (Rubensson, Susilo, & Cats, 2020). To facilitate these discussions, it could be recommended to invest in additional research to address some of the remaining research gaps such as those mentioned in section 6.5. While this study was a useful first step in understanding the importance of distribution principle selection, it does not address all facets of equity evaluation and its use in network planning. Further research would allow more informed decisions to be made regarding the adoption of these principles into mobility policy.

From the three distribution principles examined in this research, sufficientarianism is recommended as the best candidate for use in PT policy based on the static nature of its minimum PT accessibility thresholds. However, it is not recommended to use the exact method described in section 3 due to the limitations of the logsum accessibility measure and the VF value. The logsum accessibility measure only captures the accessibility within the study area, so a better option could be to use a location-based accessibility measure that specifies a minimum number of opportunities that should be accessible with PT within a given time frame. Additionally, this method applies a single threshold to the whole study area, although areas with different land use types and population densities have varying mobility goals and therefore should have different thresholds. By refining the sufficiency thresholds according to the local context of each area, sufficiency thresholds can be set in a way that advances the equity goals of each area while remaining in balance with other goals of PT.

One noted weakness of sufficientarianism is that it is not concerned with the distribution of PT accessibility above the minimum level. Sufficientarianism could be combined with another distribution principle to guide the distribution of PT accessibility beyond this minimum, for example proportionality. This would mean that a minimum level of PT accessibility must be achieved, and then anything above this level should be proportional to the selected land use and demographic characteristics of the area. However, the previously mentioned weaknesses of equity evaluation and network planning according to proportionality should be kept in mind.

Incorporation of equity in service planning at the Amsterdam Transport Region

It should also be determined where equity evaluation fits into the network planning process at the Amsterdam Transport Region. Public transport services in the Amsterdam Transport Region service area are operated by several PT operators, some of which are part of a competitive bidding process and others that are part of in-house operation.

Equity evaluation according to the selected distribution principle(s) could become part of the requirements for bidding, both in terms of submitting a bid and for service changes throughout the duration of the contract. Equity is currently considered in network planning by the Amsterdam Transport Region in concession documents by dictating that some form of PT must be provided in certain area types. This could be taken a step further by specifying a specific level of PT accessibility that must be achieved per area type. Depending on the accessibility metric used, there could be multiple equity requirements. For example, if a location-based measure is used, the requirement could state that residents of a zone of a certain area type must be able to reach a defined number of jobs, educational opportunities, grocery stores, etc. within a specified travel time, for various area types. It is possible that different concession areas may have different goals for PT accessibility, therefore it is important to consider the local context when setting sufficiency thresholds. Network designs proposed by different operators could be compared and the degree to which equity is considered could be used as an additional scoring criterion. This would allow for the comparison of different network designs proposed by operators during the bidding process. However, adding this criterion requires careful development, and it is important that consistent socioeconomic and accessibility data are used.

In addition to the inclusion of equity in the bidding process, equity can be considered throughout the operation of the concession agreement, as well as for in-house operations. It could be required that in the case of a significant service change, for example route realignment or frequency changes of a certain magnitude, an equity evaluation must be performed to determine what the impact on equity according to the selected distribution principle(s) will be. In the case that the network changes negatively impact the equity of the PT network, then it can be required to investigate alternatives with more favorable equity impacts prior to implementation. This would have the added benefit of balancing equity with other PT objectives, such as increased ridership and modal shift from cars, as equity would be significantly considered without being the primary motivator for network modifications. Considering equity both in the initial design of the network and in subsequent network changes would help ensure that PT accessibility is distributed in a fair way. By defining where equity evaluation fits into the PT system design process, equity will become more meaningfully included in future mobility policy.

Appendices

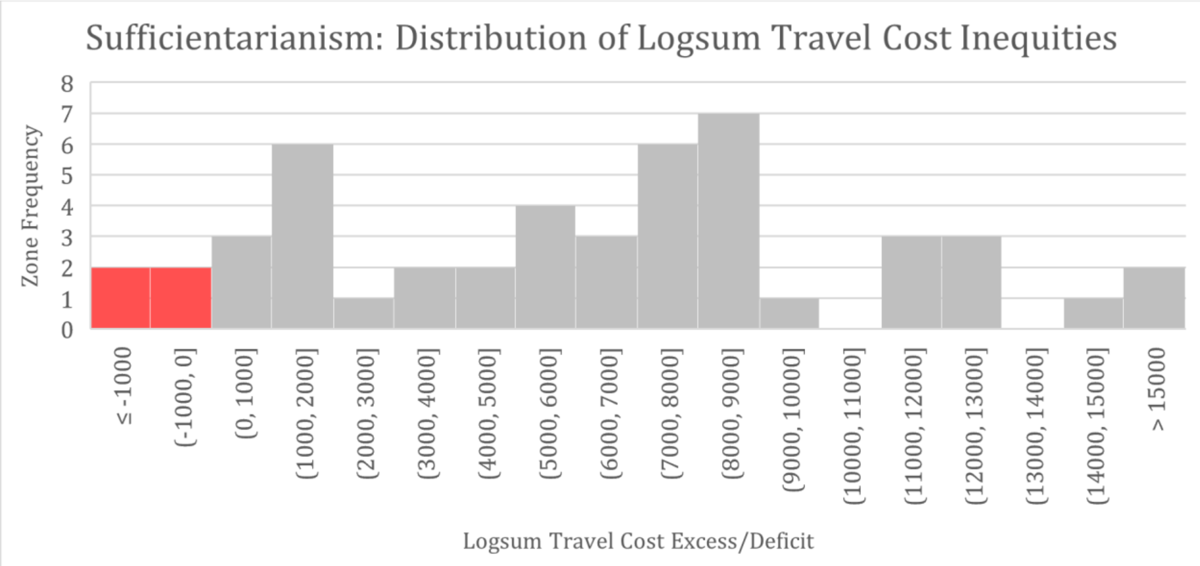
Appendix A: Fares per public transport mode in VENOM

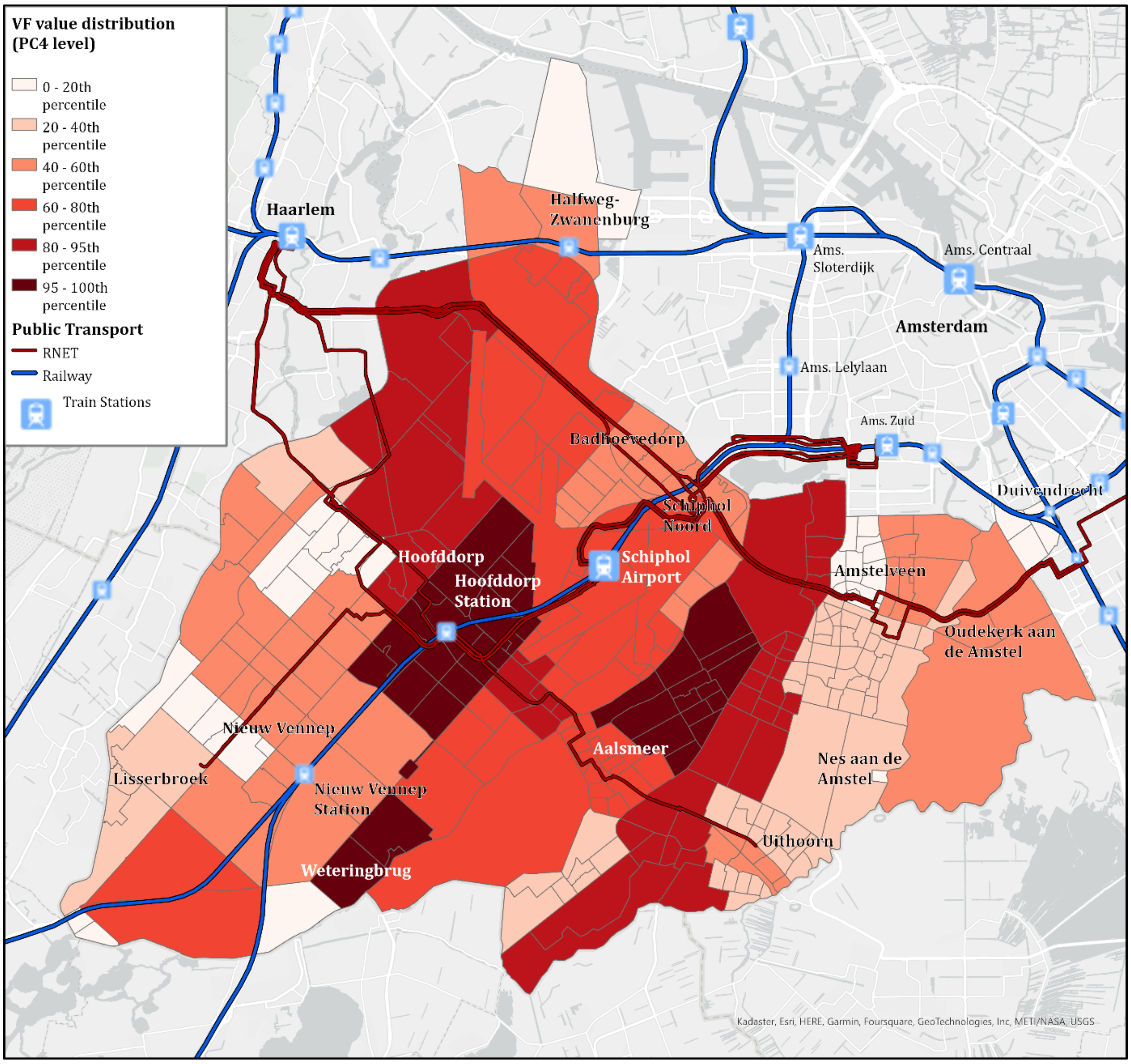
Distance	Train fare	HSL fare	Distance	Train fare	HSL fare
0	2,2	3,3	125	17,9	26,85
5	2,2	3,3	130	18,3	27,45
9	2,3	3,45	135	18,8	28,2
10	2,4	3,6	140	19,9	29,85
15	3,2	4,8	145	19,7	29,55
20	3,9	5,85	150	20,2	30,3
25	4,8	7,2	155	20,6	30,9
30	5,4	8,1	160	20,9	31,35
35	6,1	9,15	165	21,3	31,95
40	6,8	10,2	170	21,7	32,55
45	7,5	11,25	175	22,1	33,15
50	8,3	12,45	180	22,4	33,6
55	9	13,5	185	22,7	34,05
60	9,7	14,55	190	23,1	34,65
65	10,4	15,6	195	23,5	35,25
70	11,1	16,65	200	23,8	35,7
75	11,9	17,85	205	24,1	36,15
80	12,6	18,9	210	24,3	36,45
85	13,2	19,8	215	24,5	36,75
90	12,8	19,2	220	24,8	37,2
95	14,5	21,75	225	25,1	37,65
100	15,1	22,65	230	25,3	37,95
105	15,6	23,4	235	25,5	38,25
110	16,2	24,3	240	25,8	38,7
115	16,8	25,2	245	26	39
120	17,4	26,1	250	26,2	39,3
			500	99,99	149,99

Distance	Bus/Tram/ Metro Fare	Distance	Bus/Tram/ Metro Fare	Distance	Bus/Tram/ Metro Fare
0	0,87	51	8,01	102	15,15
1	1,01	52	8,15	103	15,29
2	1,15	53	8,29	104	15,43
3	1,29	54	8,43	105	15,57
4	1,43	55	8,57	106	15,71
5	1,57	56	8,71	107	15,85
6	1,71	57	8,85	108	15,99
7	1,85	58	8,99	109	16,13
8	1,99	59	9,13	110	16,27
9	2,13	60	9,27	111	16,41
10	2,27	61	9,41	112	16,55
11	2,41	62	9,55	113	16,69
12	2,55	63	9,69	114	16,83
13	2,69	64	9,83	115	16,97
14	2,83	65	9,97	116	17,11
15	2,97	66	10,11	117	17,25
16	3,11	67	10,25	118	17,39

17	3,25	68	10,39	119	17,53
18	3,39	69	10,53	120	17,67
19	3,53	70	10,67	121	17,81
20	3,67	71	10,81	122	17,95
21	3,81	72	10,95	123	18,09
22	3,95	73	11,09	124	18,23
23	4,09	74	11,23	125	18,37
24	4,23	75	11,37	126	18,51
25	4,37	76	11,51	127	18,65
26	4,51	77	11,65	128	18,79
27	4,65	78	11,79	129	18,93
28	4,79	79	11,93	130	19,07
29	4,93	80	12,07	131	19,21
30	5,07	81	12,21	132	19,35
31	5,21	82	12,35	133	19,49
32	5,35	83	12,49	134	19,63
33	5,49	84	12,63	135	19,77
34	5,63	85	12,77	136	19,91
35	5,77	86	12,91	137	20,05
36	5,91	87	13,05	138	20,19
37	6,05	88	13,19	139	20,33
38	6,19	89	13,33	140	20,47
39	6,33	90	13,47	141	20,61
40	6,47	91	13,61	142	20,75
41	6,61	92	13,75	143	20,89
42	6,75	93	13,89	144	21,03
43	6,89	94	14,03	145	21,17
44	7,03	95	14,17	146	21,31
45	7,17	96	14,31	147	21,45
46	7,31	97	14,45	148	21,59
47	7,45	98	14,59	149	21,73
48	7,59	99	14,73	150	21,87
49	7,73	100	14,87	500	99
50	7,87	101	15,01		

Appendix B: Sufficientarianism Analysis Results at PC4 Postcode Level





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