EVALUATING AND MODIFYING A PUBLIC TRANSPORT NETWORK TO ACHIEVE AN EQUITABLE DISTRIBUTION OF ACCESSIBILITY

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Good public transport (PT) accessibility is an important element of a well-functioning transport system, providing people with access to employment, education, healthcare, and other important services. It is therefore important to understand if public transport accessibility is distributed in an equitable, or fair, manner. For this to happen, equity must be clearly defined and quantified in public transport planning. In this research, we evaluate the equity of a public transport network according to three distinct distribution principles: egalitarianism, proportionality, and sufficientarianism. We do this by evaluating the distribution of public transport accessibility, which is measured using the logsum travel cost. We present different evaluation methodologies to evaluate the accessibility distribution for each principle and apply them to the Amstelland-Meerlanden (AML) concession area of the Netherlands. This results in the identification of zones of surplus and deficit accessibility, and their magnitudes, according to the definition of each principle. Here we find that the distribution of logsum travel costs within the AML concession area most closely resembles an egalitarian PT network. We then use the results of each equity evaluation to make frequency modifications to achieve a more equitable public transport network according to each distribution principle. We find that there is almost no overlap between areas of significant surplus and deficit between the three principles, meaning that there are significant planning implications for the selection of one principle over another. We identify sufficientarianism as the most methodologically suitable of the distribution principles in this study to use in active network planning, however it is challenging to define a minimum accessibility threshold.

1. INTRODUCTION

An efficient and effective public transport (PT) system is a necessary component of a well-functioning society. However, efficiency and effectiveness do not guarantee that the costs and benefits of the PT system are equitably distributed (Kim et al., 2019). The PT system can have a significant impact on one's ability to access economic opportunities, education, healthcare, and other services (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 et al., 2019). Given these outcomes, it is important to understand if transport accessibility and its benefits are distributed in a fair, or equitable, way. It is not a straightforward task to determine the "appropriate" or "fair" distribution of PT accessibility, as this is a debate that has to do with the goals and ideals of society and policymakers (Rubensson et al., 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 et al., 2019).

The goal of this research 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 research therefore aims to answer the following 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?*

2. WHAT IS EQUITY?

The following sections clarify the definition of equity in the context of this study and its components.

2.1 Equity vs. equality

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 accessibility. 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).

2.2 Components of equity

Martens et al. (2019) define 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 et al., 2019).

2.2.1 Benefits and costs

Martens et al. (2019) identify four dimensions of benefits and burdens in transport: mobility/accessibility, traffic-related pollution, traffic safety, and health (Martens et al., 2019). In this research, PT accessibility is selected as the resource whose distribution is being evaluated, which must be measured using a defined accessibility metric. Geurs and van Wee (2004) identify four types of accessibility measures: infrastructure-based, location-based, person-based, and utility-based (Geurs & van Wee, 2004):

- Infrastructure-based: measures the performance of the transport network without considering the land use component of accessibility, for example average speeds or hours lost in congestion.
- Location-based: measures the number of opportunities reachable within a given time or distance. Interaction between transport and land use can be considered using a gravity-based measure, which uses an impedance function to assign further or smaller destinations diminishing attractiveness.
- Person-based: opportunities reachable on an individual level, taking into account space and time restrictions. This disaggregate approach has the benefit of a stronger theoretical basis, but more data requirements and complexity.
- Utility-based: sum of the utilities for all choices available to the traveler (the logsum). Although this measure may be complex, it is based on theories of travel behavior and can be calculated from a standard 4-step transport model (Rubensson, Susilo, & Cats, 2020).

2.2.2 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 can be divided into two relevant categories (Carleton & Porter, 2018; Aman & Smith-Colin, 2020; Ricciardi et al., 2015):

- Income and social class: socioeconomic variables related to income, race/ethnicity, employment status, gender, local language fluency, immigrant status, single parent status, housing rent, illiteracy, job level, and education.

- Mobility need and ability: socioeconomic variables related to 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.

2.2.3 Distribution principles

Distribution principles provide alternative ideas of what resource distribution is accepted as fair. Utilitarianism is currently the dominant principle used in transport planning, stating that a distribution is fair if it maximizes the total benefits for society. This means that the total accessibility should be maximized, and that it is acceptable for some people to have poor accessibility if society overall experiences a high accessibility (Bills & Walker, 2017).

2.3 Selection of equity components

The selection for each of the three components of equity evaluation in this research is listed below:

- *Benefits and costs:* Accessibility is the resource whose distribution is being evaluated, and the accessibility measure selected is a utility-based measure, known as the logsum accessibility. This is measured for each zone as the perceived travel cost to all other zones, and can be interpreted as a potential cost of travel within the study area.
- *Socioeconomic groups:* This research mainly focuses on inequity of accessibility between areas, with one of the selected distribution principles additionally considering inequity between income groups.
- *Distribution principles* (Litman, 2022):
    - *Egalitarianism*: A distribution is fair if all people are treated equally, therefore all people should receive the same level of PT accessibility.
    - *Proportionality*: Resources should be distributed among groups in rough proportion to the groups' share of population, with an acceptable range in deviations. This means that PT should be allocated based on the distribution of the population.
    - *Sufficientarianism*: A distribution is fair if it meets the basic needs of everyone and guarantees their continued well-being. Therefore, 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.

3. METHODOLOGY

For each of the three distribution principles, we determined the appropriate equity evaluation methodology and applied it to evaluate the equity of a case study area. We then attempt to use the results of each equity evaluation as an input to inform PT network modifications, which in this study are limited to frequency changes, to design a more equitable PT network according to each principle. A more detailed explanation of the methodology can be found in the complete version of the thesis (van Luven, 2022).

3.1 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. 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 within the study area. In this research, we refer to the logsum accessibility measurement as the logsum travel cost, which can be interpreted as a potential perceived cost of travel. 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.

This research uses the Northern-wing Traffic Engineering Model (VENOM), a regional transport model that includes Haarlem, Zaanstad, Amsterdam, and Utrecht. VENOM connects as much as possible to the National Regional Model West of the Netherlands and uses OmniTRANS traffic modelling software. Public transport is separated from other modes as a separate OmniTRANS project; this part of the model is used in this analysis. BTM (Bus Tram Metro), train, and HSL (high-speed line) are the three categories of PT modes available in VENOM (Willigers, 2020). The most current base year at the time of this research is 2014, and the selected time period for this analysis is the morning peak period (7:00 – 9:00). The spatial unit 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.

We use data from the generalized travel cost skim matrix, which contains the shortest travel cost between all OD pairs, to calculate the logsum travel cost in this research. 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. We also consider weights for different travel time components indicating the perception of time and cost in the generalized travel cost calculation. These travel time components have different weights per mode, and include in-vehicle time (weight 1,15 for bus, 1 for other PT modes), waiting time (weight 1,725 for bus, 1,5 for other PT modes), transfer penalty (weight 5 per transfer), transfer walking time (weight 1), and fare (weight 1) (Willigers, 2020).

The final generalized travel costs between all zones in VENOM are provided in the form of an origin-destination skim matrix. We use the costs from this matrix to calculate the logsum accessibility, which adds the generalized travel costs from one zone to all other zones in the study area, for every origin zone. This represents a cost for all potential, not actual, travel within the area. It should also be noted that we do not weight travel cost based on travel demand in this analysis because it could introduce bias from existing spatial disparities.

3.2 Egalitarianism equity evaluation

Equity evaluation according to egalitarianism is done using the Lorenz curve and the Gini coefficient as explained in the sections below.

3.2.1 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). The x-axis of a Lorenz curve is the cumulative proportion of the population ordered from lowest to highest income and is calculated using equation 1:

$$x_1 = \frac{pop_1}{\sum_1^n pop_n},\ x_2 = \frac{pop_1 + pop_2}{\sum_1^n pop_n},\ x_3 = \frac{pop_1 + pop_2 + pop_3}{\sum_1^n pop_n}, \text{ etc.} \qquad (1)$$

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

The y-axis data for a Lorenz curve is the cumulative proportion of the logsum travel costs, weighted by population and is calculated using equation 2:

$$y_1 = \frac{LTC_1 \times pop_1}{\sum_1^n LTC_n \times pop_n},\ y_2 = \frac{LTC_1 \times pop_1 + LTC_2 \times pop_2}{\sum_1^n LTC_n \times pop_n},\ y_3 = \frac{LTC_1 \times pop_1 + LTC_2 \times pop_2 + LTC_3 \times pop_3}{\sum_1^n LTC_n \times pop_n}, \text{ etc.} \qquad (2)$$

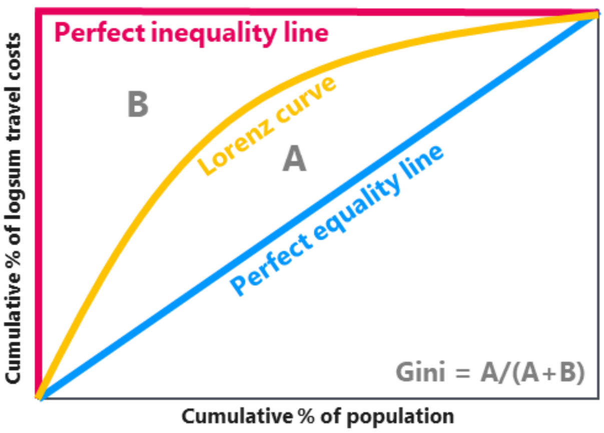

Figure 1: Example Lorenz curve (based on Rodrigue, 2020)

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 population and logsum travel cost data can then be plotted in the manner shown in figure 1. According to egalitarianism, postcodes with a higher proportion of the logsum travel costs relative to their proportion of the population have an accessibility deficit, while postcodes with a lower proportion of the logsum travel costs relative to proportion of population have a surplus.

3.2.2 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). The Gini coefficient can be calculated using equation 3 below (Gini, 1912):

$$G = \left|1 - \sum_{i=1}^{N} (\sigma X_{i-1} - \sigma X_i)(\sigma Y_{i-1} + \sigma Y_i)\right| \qquad (3)$$

Where:
σX = the cumulative proportion of the population 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).

3.3 Proportionality equity evaluation

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, we compare the actual accessibility of each zone to a calculated target accessibility. The target accessibility is the accessibility that is warranted based on factors that influence PT use, for example population density, employment density, and/or address density. In Figure 2, the blue line represents the target accessibility based on the selected legitimate factors, and points A-C represent actual accessibility levels in zones A-C. In this example, point A has higher than proportional travel costs, B has an appropriate level of travel costs, and point C has lower than proportional travel costs. In other words, zone A has an accessibility deficit and zone C has an accessibility excess.

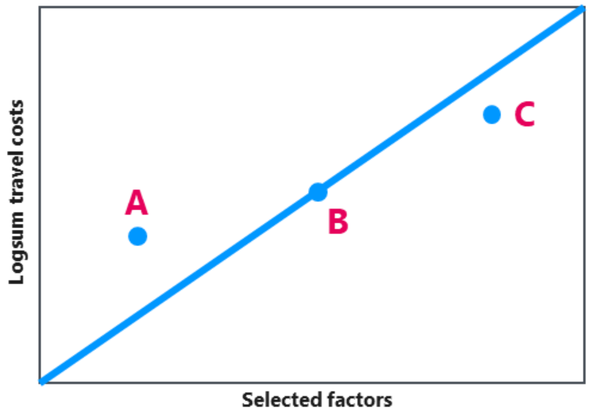

Figure 2: Target accessibility as a function of selected land use/demographic factors (Rubensson et al., 2020)

To determine what factors to use in the final regression model, we perform a separate linear regression analysis for each potential factor. Factors with higher R-square values and coefficients with p-values less than 0,05 should be considered for inclusion in the final regression. We then perform a multiple regression with the factors selected from the single regressions but this time including all the selected factors as independent variables. We then check the resulting R-square and p-values for goodness of fit and significance, respectively. It is important to note that this research uses linear regression and therefore implies an assumption of linearity in the data, which may not necessarily provide the best fit for the data.

We use the resulting multiple regression equation 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, we compare them to the actual logsum travel cost per zone. 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.

3.4 Sufficientarianism equity evaluation

Sufficientarianism requires a judgement to be made to determine a single threshold for a sufficient level of accessibility (Litman, 2022). In this research we use the displacement time factor (DTF) to define minimum PT accessibility.

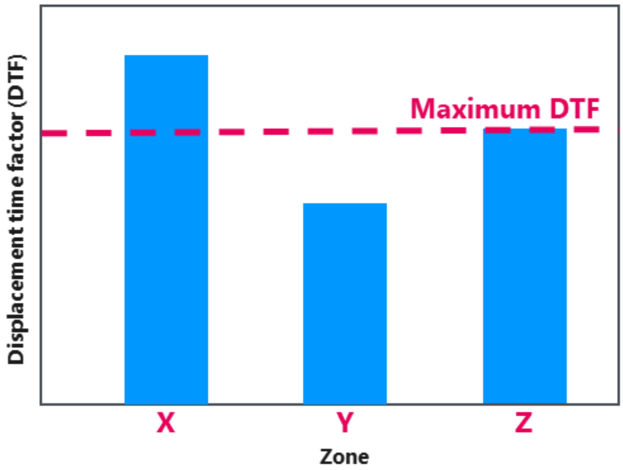

Figure 3: Example of maximum displacement time factor

In the Netherlands, a DTF is used to compare travel times between different modes, for example measuring the competitive position of PT relative to the car. The DTF value has been shown to consistently influence mode choice (Projectbureau Integrale Verkeers- en Vervoerstudie, 1995). The DTF value can be used as one way to define the level of sufficiency in PT accessibility, by comparing the ideal DTF value to the actual DTF value. The ideal DTF value can either be determined based on thresholds defined in previous research, or determined from the existing distribution of DTF values, for example by selecting a certain percentile DTF value as the threshold (van der Veen et al., 2020).

We calculate the DTF values from a 4-step transport model using the skim matrices for car and PT. The logsum travel costs can be calculated for each zone by summing the travel times from this zone to all other zones. For each zone, we divide the logsum travel cost for PT by the logsum travel cost for car to obtain the DTF value for that zone, as seen in equation 4 below for zone *i*.

$$DTF_i = logsum_{PT,i}/logsum_{car,i} \quad (4)$$

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

We then compare each DTF value to the selected threshold DTF value to determine if a sufficient level of accessibility is achieved. If a zone has a DTF value above the sufficiency threshold, then the zone has an accessibility deficit.

A DTF value below the sufficiency threshold is acceptable, as sufficientarianism does not allow for the possibility of an accessibility surplus.

4. CASE STUDY AREA

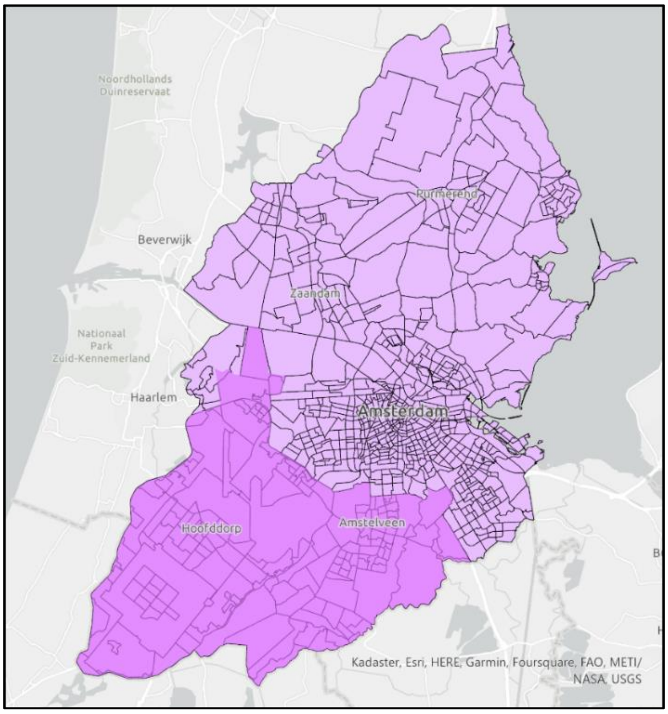

Figure 4: Location of the Amstelland-Meerlanden concession area (dark purple) within the Amsterdam Transport Region (entire area)

The study area selected for this research is the Amstelland-Meerlanden (AML) concession of the Amsterdam Transport Region in the province of North Holland, as shown in figure 4. At the time of this research, the most recent year where all required data is available is 2014 due to the update cycle of the transport model used. In 2014, this area had approximately 302.000 inhabitants and 191.000 jobs, with a lower population density and higher average income than the average for the Amsterdam Transport Region. This area is located southwest of Amsterdam and contains Schiphol airport, which is an important part of the Dutch economy. We study the AML concession that was active in 2014 during the 2008 – 2017 concession period. 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 6 BRT bus routes, 13 regional bus routes, 18 city and airport bus routes, and 16 other bus routes. There are also five train stations in the AML concession area, as well as metro services connecting Amstelveen and Amsterdam (Concessie Amstelland-Meerlanden (2008-2017), 2022).

5. APPLICATION AND RESULTS

In the following sections, we apply the methods presented in the methodology section to the AML concession area for each distribution principle.

5.1 Egalitarianism

When applying the principle of egalitarianism to an equity evaluation of the AML concession area, we obtain the Lorenz curve shown in Figure 5, which shows 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.

Overall, the distribution of accessibility in the AML concession area is quite equal, with most points following the equality line closely. However, as the population data is ordered by income, it is possible to see some small disparities between income groups. There is slightly better PT accessibility in the middle- and higher-income zones, where travel costs are below the "equal" level, relative to zones with low incomes, where travel costs are above the "equal" level.

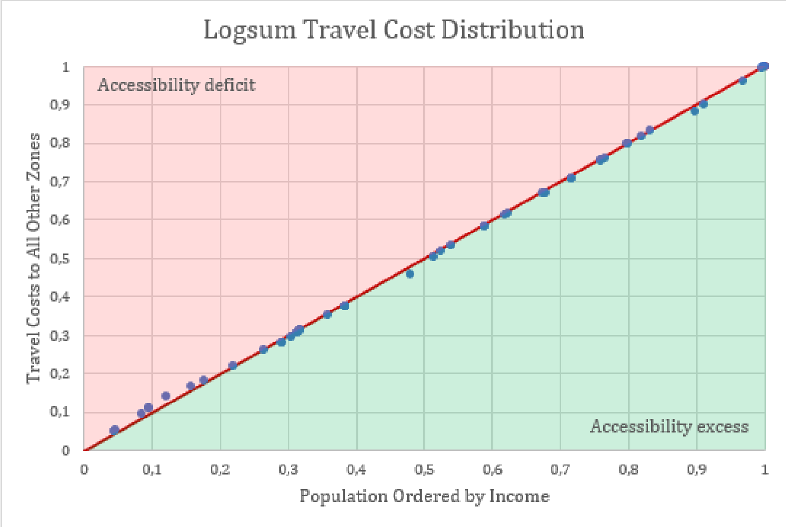

Figure 5: Lorenz curve showing distribution of logsum travel costs in Amstelland-Meerlanden

The overall equality in accessibility 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, as in-vehicle time is a major component of the generalized travel cost but is unaffected by the number and frequency of routes in VENOM. 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.

We then attempt 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.

5.2 Proportionality

Equity evaluation according to proportionality is done by comparing a calculated target accessibility and actual accessibility for each zone in the AML area. 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, we considered the factors population density, household density, employment density, and address density for inclusion in the final regression model. We perform regression analyses 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. Based on the results of the individual regression analyses, we selected jobs density and population density for inclusion in the final multiple regression analysis, as shown in equation 5 below. This leads to an R-square value of 0,397 with a p-value below 0,05.

$$Target\ Accessibility = 27111.5 - 1.343064 \times \text{Jobs density} - 1.037416 \times \text{Population density} \quad (5)$$

We use this equation to calculate the target accessibility, which we then compare to the actual accessibility to determine if a zone has an accessibility excess or deficit based on the selected factors, and the magnitude thereof. 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.

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 of accessibility surplus 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 have been a bias towards more centrally located zones when the PT network was planned.

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.

5.3 Sufficientarianism

The equity of the AML area according to sufficientarianism 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 displacement time factor (DTF) value. The DTF 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 DTF value is defined as the average DTF value plus two standard deviations, in the absence of a previously defined standard for a sufficient DTF value when the logsum travel cost is used as the accessibility measure.

For the AML case study area, the average DTF value is 1,63 with a standard deviation of 0,24, leading to a maximum DTF 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 DTF value for each zone is then compared to this maximum DTF 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 DTF 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. On the other hand, 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.

We then used the evaluation results according to sufficientarianism to make frequency modifications, with the objective of improving the accessibility of the zone with the worst DTF value (2,4) without increasing operating resources. The objective of reducing the DTF value in this target zone below the maximum DTF value could not be achieved with frequency changes alone. This is because the impact of frequency modifications alone is limited as frequency only affects the waiting time component of travel cost, which is calculated as half the headway. Other PT network changes would be needed to alter the PT logsum travel costs enough to decrease the DTF factor past the maximum level. However, as a byproduct of the frequency modifications made for this zone, the

DTF 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.

5.4 Comparison of equity evaluation results

A 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 present.

5.4.1 Geographical locations of inequities

We compare the geographical locations of the zones with excess and deficient accessibility according to each distribution principle to understand if there is a difference in the spatial distribution of these zones between the three principles. Figure 6 shows the locations of zones with significant (more than 0,5%) 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.

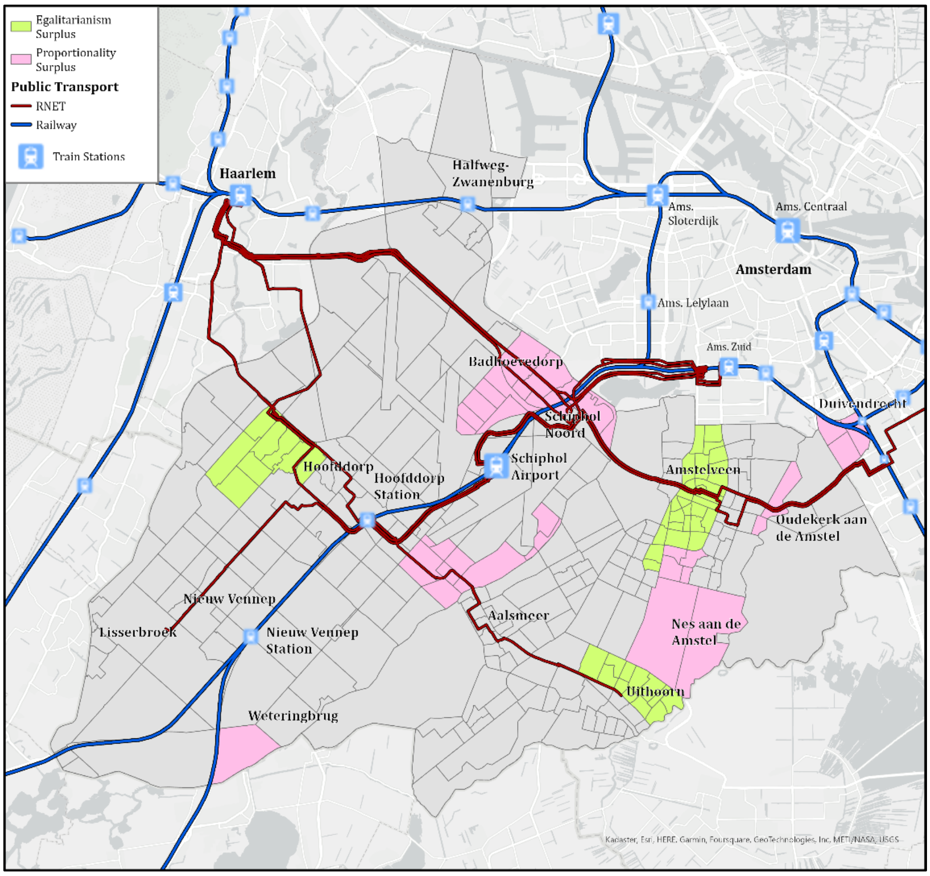

Figure 6: Comparison of zones of surplus accessibility within Amstelland-Meerlanden

As shown in figure 6, 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 rebalancing was recommended based on the locations of these surpluses. This also shows a limit of egalitarianism, as this principle could conflict with other PT objectives such as ridership.

Figure 6 compares the zones with significant (more than 0,5%) accessibility deficits for the three distribution 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. No zones are considered significantly 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.

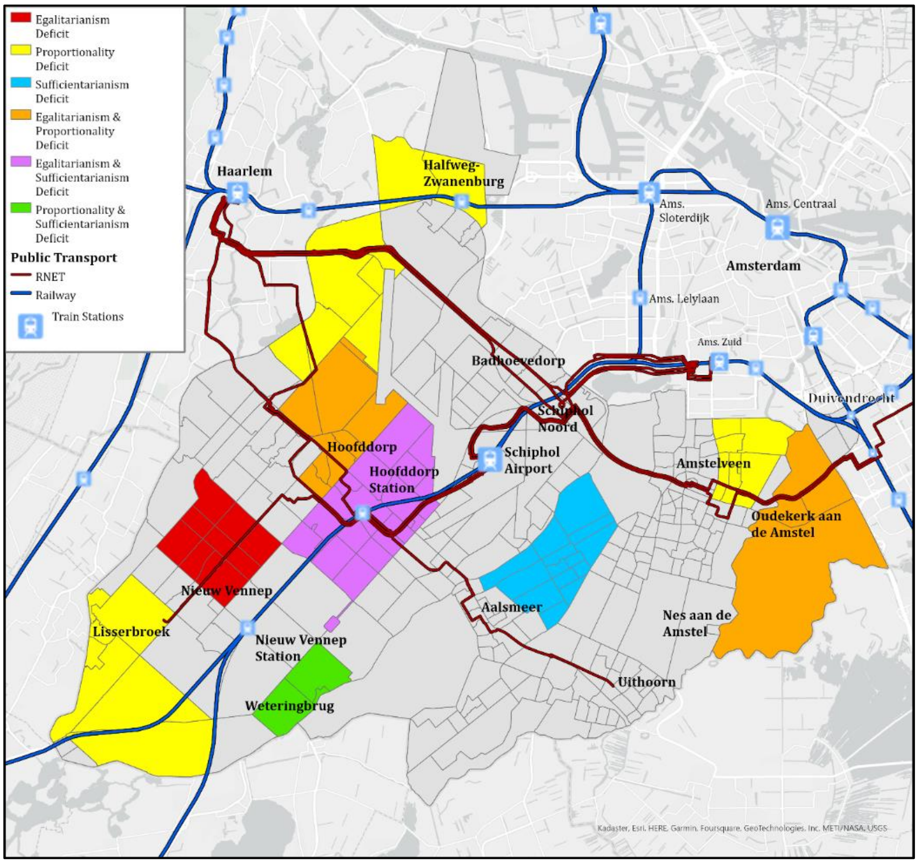

Figure 7: Comparison of zones of deficit accessibility within Amstelland-Meerlanden

5.4.2 Magnitudes of inequities

The degree of inequity also differs for the three distribution principles, as shown in figure 8. In Figure 8, 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.

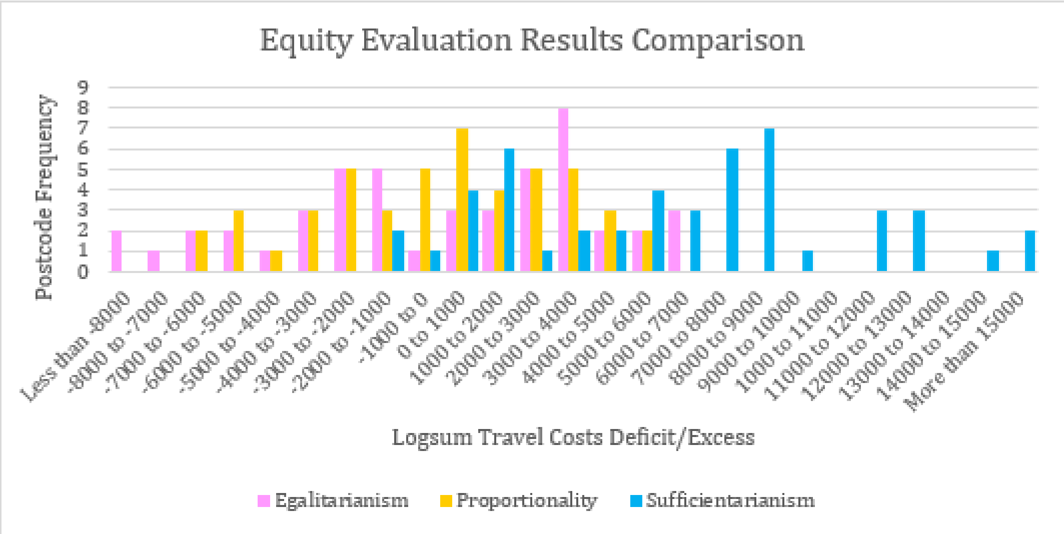

Figure 8: Comparison of accessibility surplus and deficit distribution in Amstelland-Meerlanden

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, we do not recommend to use the evaluation results in the network planning process independent of other inputs such as ridership data.

6. CONCLUSION

This research represents an early step towards assessing the extent to which public transport is equitable, with an application to a concession area in the Netherlands. However, there is still more work to be done before equity can be meaningfully included in mobility policy. We recommend transport authorities to invest in further research to address the limitations of this research 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. While this research provided valuable findings regarding the consequences of 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 et al., 2020).

We presented three different evaluation methodologies that can be used to evaluate the equity of an accessibility distribution according to the distribution principles of egalitarianism, proportionality, and sufficientarianism. We found that the distribution of logsum travel costs in the AML concession area most closely resembles an egalitarian distribution.

From the three distribution principles examined in this research, we found sufficientarianism to be 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 this research due to the limitations of the logsum accessibility measure and the DTF value. The logsum accessibility of a zone is highly influenced by its centrality, where more central zones appear to have a better accessibility than peripheral zones simply as a byproduct of their location. This is because the distance from a given zone to all other zones in the study area will be less for a more central zone than for a peripheral zone. Additionally, the logsum accessibility measure only captures the accessibility within the study area, so a better option would 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.

Regarding the use of the DTF factor to define the sufficiency threshold, the method in this research applies a single threshold to the whole study area. However, areas with different land use types and population densities have varying mobility goals and therefore should have different thresholds. For example, it may be desirable that PT accessibility in a high density city center is better than car accessibility, while for a rural area this would not be realistic. It is also important to consider target groups and their crucial destinations. For example, for students accessibility to education and recreational opportunities is crucial, while for the elderly access to healthcare and social contacts is more important. By refining the sufficiency thresholds according to the local context of each area and specific target groups, 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.

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.

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 concession documents by the Amsterdam Transport Region by specifying that PT provision is required in areas with certain populations, which is a form of proportionality and sufficientarianism. This could be extended by specifying a certain level of PT accessibility that must be achieved for every area type and/or target group. 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 and/or target group must be able to reach a minimum number of employment opportunities, educational opportunities, etc. within a specified travel time.

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.

Future research could examine the suitability of various accessibility measures for equity evaluation, for example how an equity evaluation using the logsum measure compares to one using a gravity-based location measure. This would assist decision-makers in defining an appropriate accessibility measure. There is also an opportunity for future research to study the extent to which existing demand patterns can be included in equity evaluation to better understand the relationship between and balance the sometimes competing goals of efficiency and equity. Finally, it is recommended to further study other distribution principles and combinations thereof. This could involve presenting alternative equity evaluation methodologies and their applicability in the network planning process.

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