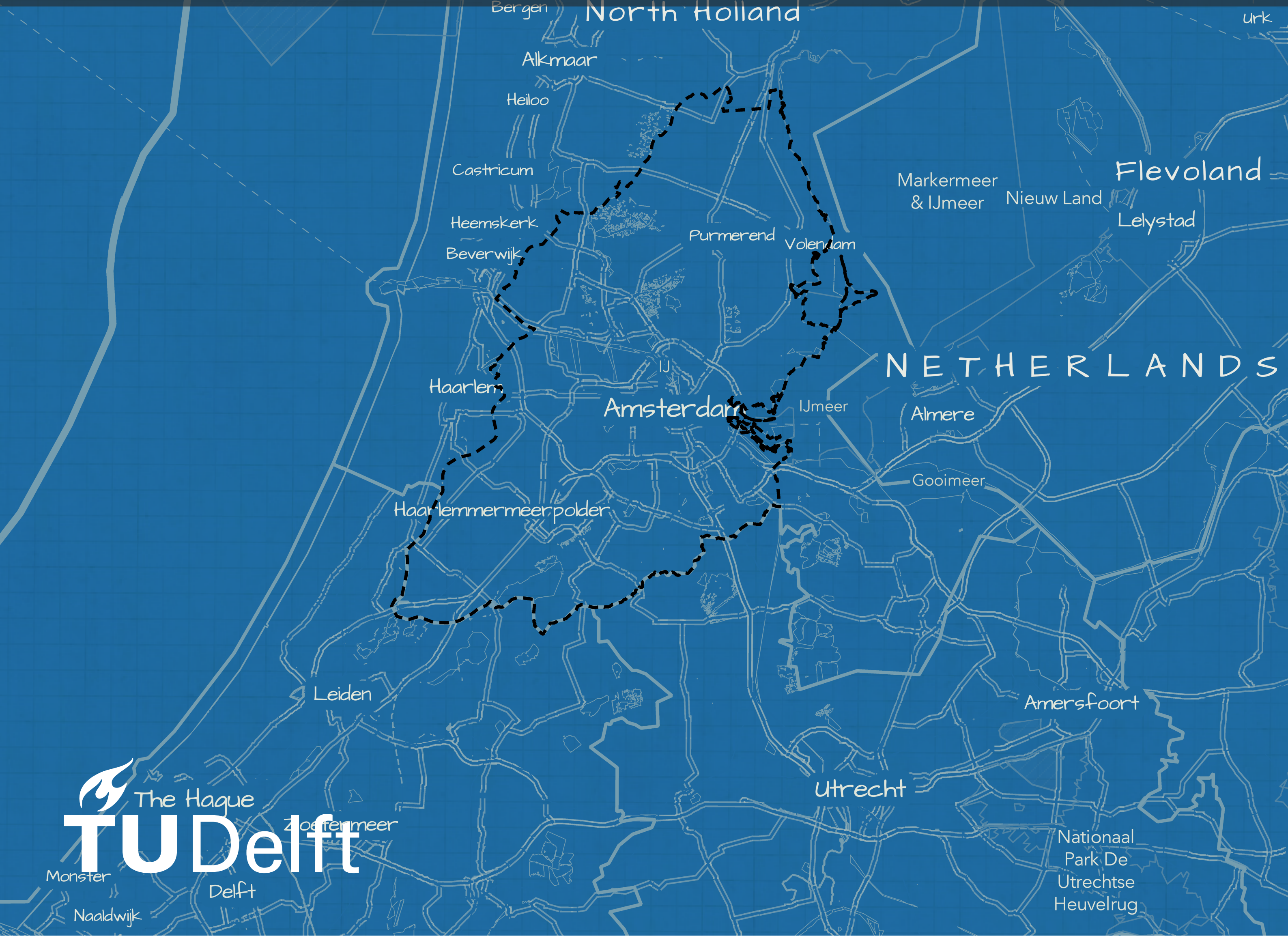
# Potential Impacts of Transit-Shared Bike Integration on Equity in Job Accessibility

## A Case Study in the Amsterdam Transport Region

CIE5060-09 MSc Thesis

Quanyi Wang



# Potential Impacts of Transit-Shared Bike Integration on Equity in Job Accessibility

## A Case Study in the Amsterdam Transport Region

by

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to obtain the degree of Master of Science
in Civil Engineering with Track Transport & Planning
at Delft University of Technology

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# Preface

As I draft these words, it means my master's journey has finally come to an end. You may feel my strong desire for graduation; indeed, even though the future is filled with uncertainty, I always feel excited about life beyond the academic chapter. Despite specialising in road traffic systems for my master's program, I decided to explore a topic that truly intrigued me, steering my academic exploration in a new direction.

Reflecting on the past year's experiences, I cherished the process of starting from initial awareness to eventual comprehension of knowledge. I have learned that without the accumulation of knowledge, many problems are beyond the scope of my abilities. Similarly, without the experience of the TU Delft master's program, I would not have understood myself better. Although life as an international student can be challenging, I will undoubtedly miss this experience in the future.

I would like to take this opportunity to express my gratitude to those who have supported me during this period.

Firstly, I want to thank my thesis committee. My chairperson, Niels van Oort, thank you for consistently promoting my graduation progress forward. Each meeting with you is encouraging because I can have a clear direction for the following path. My daily supervisor, Matthew Bruno, I appreciate the regular meetings and the post-meeting deadlines, significantly making me more productive. Additionally, thank you for your feedback on every report I submitted. My second supervisor, Adam Pel, thank you for your advice and guidance in enhancing the academic and logical aspects. Every time I digest the notes you give, I realise they are crucial in shaping my thesis. My external supervisor, Hans Voerknecht, thank you for helping me to learn the IKOB model and offering practical insights that add real-world significance to my thesis. Without your collective help, I could not have successfully completed this thesis.

I extend my deepest appreciation to my family, my parents and elder sister, for their unwavering encouragement and support, and to friends who have been constant companions on this journey.

Lastly, I want to remind myself that this is not just an endpoint but also the beginning of a new chapter in my life. I hope I can always follow my heart in future decisions.

”Everything happens for a reason”.

*Quanyi Wang*
*The Hague, January 2024*

# Summary


## Introduction

Travelling to work is one of the essential activities in individuals' daily lives, but the options available for employment locations are often limited. Therefore, transportation systems are crucial in determining individuals' ability to reach their workplace. Although car ownership is often considered the most effective means of improving accessibility and providing superior access compared to other transport modes in most circumstances (Martens et al., 2022; Pritchard, Stępniak, et al., 2019; Qin & Liao, 2022), it can be financially restrictive for low-income groups, and the promotion of car use is not in line with sustainability and livability goals.

Transit-dependent commuters face significant challenges in accessing job opportunities since the public transport systems do not provide door-to-door accessibility (Kosmidis & Müller-Eie, 2023; Shelat et al., 2018). In recent years, shared mobility services have gained popularity for greater flexibility in first/last-mile segments of multimodal trips (Rongen et al., 2022; Shaheen & Chan, 2016). These services could be a promising solution to improve accessibility for groups that rely on public transport, thereby addressing issues of accessibility inequity. Such intervention aligns well with the unique Dutch cycling culture, where cycling already accounted for a substantial portion of transit trips. However, due to the limited availability of bikes at the egress-end, the trips on the activity-end are less utilised compared to the home-end trips (Brand et al., 2017; Mathijs de Haas, 2020; Shelat et al., 2018). Therefore, integrating shared bikes with transit as an egress mode could be an effective intervention to enhance the accessibility for transit-dependent groups and promote social equity.

Despite the potential of shared bikes to enhance accessibility, the impacts of transit-shared bike integration on equity in job accessibility have not been comprehensively explored. In most studies, transfer between transit and bike is generally assumed to be possible in all locations (Boarnet et al., 2017; K. T. Geurs et al., 2016; Pritchard, Stępniak, et al., 2019; Pritchard, Tomasiello, et al., 2019; Qin & Liao, 2022; Wang et al., 2022; Zuo et al., 2020), which is not the case in reality. The locations that allow travellers to shift from transit to shared bikes, the operating system, and the cost of share-bike use all affect practical use. Addressing this research gap is essential for optimising transit-shared bike integration and realising their full potential in advance transport equity.

Ensuring an equitable distribution of accessibility remains a challenge due to inherent variations in land use, transport systems, individual circumstances, and temporal factors. However, existing research often uses a generalised measure. It overlooks the heterogeneity within population groups when calculating accessibility, resulting in ignorance of groups more likely to experience extremely low accessibility (Curl, 2018; Pot et al., 2023; Ryan & Pereira, 2021). Furthermore, accessibility that is traditionally calculated may fail to capture the real-life acces-

sibility experienced by individuals. To address this issue, the concept of perceived accessibility has been introduced to incorporate individuals' subjective factors, reflecting how the provided job opportunities can be valued as accessible for a person (Pot et al., 2023).

An analysis of accessibility inequality provides valuable insights for guiding transport policy decisions. However, the traditional utilitarian approach assigns equal weight to all individuals and does not consider the distribution effects (Di Ciommo & Shiftan, 2017; Pereira et al., 2017; van Wee & Mouter, 2021). In addition, studies that focus on disparity analysis from an egalitarian standpoint only reflect the level of equity and fail to adequately answer whether people have sufficient accessibility to participate fully in society (Lucas et al., 2016). Consequently, there has been a call for a shift towards sufficiency analysis (Martens et al., 2022). Applying the sufficientarianism theory allows for identifying groups that suffer from insufficient accessibility, which is beneficial for proposing targeted policies to alleviate their situations. However, there is still a lack of research regarding the impacts of shared bike-transit integration on equity through the lens of the sufficientarianism principle.

This study aims to address the identified research gaps by conducting a "what-if analysis" in the Amsterdam Transport Region. The analysis will investigate the potential impacts on job accessibility for commuters without car access and the overall equity of the transportation system if shared bikes are provided at transit stations as the egress mode. In order to achieve the objective, this thesis will answer the following main research question:

**What would be the impacts on job accessibility for commuters without car access and the equity of the whole transportation system in the Amsterdam Transport Region if shared bikes were provided at transit stations as an egress mode?**

The sub-research questions derived from this main research question are as follows:

1. What is the most suitable principle to define an equitable distribution in the context of job accessibility?

2. What influencing factors are relevant in individuals' perceptions of job accessibility?

3. Which accessibility measure will be applied to incorporate individuals' perceptions, ensuring a more realistic estimate of equity in job accessibility?

4. How can the impacts of providing shared bikes as an egress mode at transit stations on equity in job accessibility be evaluated based on the selected accessibility measure and equity principle?

5. What are the potential implications of the outcomes of creating a more equitable transportation system in the Amsterdam Transport Region?

## Methodology and Data

Considering varied renting costs of shared bikes due to different operating systems and price strategies of different companies, the impacts of transit-shared bike integration on equity in job accessibility are investigated by comparing four scenarios, including a base scenario and three intervention scenarios with varying renting prices (0, 1 and 2 euro per trip). The methodology for this study is structured into three main steps:

**1. Impacts Modelling:**
Firstly, the impacts of locations where commuters can shift from transit to shared bikes are modelled in the IKOB model Voerknecht (2021). A total of 103 locations for transit-shared bike integration are considered in this thesis, combined from several sources, including the NS train stations and P+R facilities in the Amsterdam Metropolitan Area and service points for shared bikes in the municipality of Amsterdam.

In order to incorporate the impacts of transit-shared bike integration, this step involves several assumptions. The first assumption is that the travel decay curve of groups using transit-shared bike integration is assumed to be equal to the transit curve as the transit is the main trip due to calibration and validation difficulties without empirical data. The second assumption is that all commuters will choose the transit stations that provide minimum travel time between each origin and destination. The third assumption is that commuters take the mode that provides maximum weight across their available mode options.

**2. Accessibility Calculation:**
Secondly, as the IKOB model distinguishes 60 subgroups based on preferences, car ownership and income class, the accessibility for each subgroup is calculated first. Afterwards, population-weighted average accessibility for four groups of commuters (low/high-income groups with/without car access) is calculated in four scenarios. In addition, the population-weighted average accessibility for each neighbourhood and the whole Amsterdam Transport Region is also calculated.

**3. Equity Evaluation:**
Thirdly, a coordinate system integrating the "Potential Mobility Index" (PMI) and accessibility, along with "Accessibility Fairness Index" (AFI) in sufficientarian approach (Martens, 2016) will be applied for equity evaluation in all scenarios. The PMI for each subgroup is assumed to be the arithmetic average of their available mode options. The coordinate system will visualise the commuters experiencing accessibility deficiency in neighbourhoods. AFI will represent the severity of deficiency for different commuters or neighbourhoods. Additionally, the contribution to the overall level of accessibility deficiency for different commuters/neighbourhoods will be determined.

Finally, results in the distribution of job accessibility and level of equity within the four scenarios will be compared and analysed visually and statistically.

## Potential Accessibility and Potential Mobility Index

The thresholds of job accessibility (126517 jobs) and PMI (16.45 $km/h$) are determined based on the population-weighted average values for all groups in the whole Amsterdam Transport Region during peak hours. Ideally, the threshold values of PMI and accessibility are determined through a democratic process, but descriptive statistics would be more practical (Martens, 2016). Although different thresholds will make the results different, there is no good or bad between these thresholds. The determined thresholds are primarily used to define the rule for whether people can access sufficient jobs or not.

After determining the thresholds of PMI and job accessibility, the coordinate system, including four different subgroups, is visualised in Figure 1. Notably, Low-income groups without car access suffer from accessibility deficiency in all neighbourhoods. Only a few neighbourhoods can offer sufficient job accessibility for high-income groups without car access. Furthermore, groups with car access are generally expected to have higher job accessibility. However, this is not true for low-income groups, who still face limited accessibility in most neighbourhoods. Nevertheless, it is essential to note that only groups falling below both accessibility and PMI thresholds contribute to the AFI value. Therefore, groups to the right of the PMI threshold line are excluded, as the predominant impacts in this context are more related to land use rather than transportation-related factors.

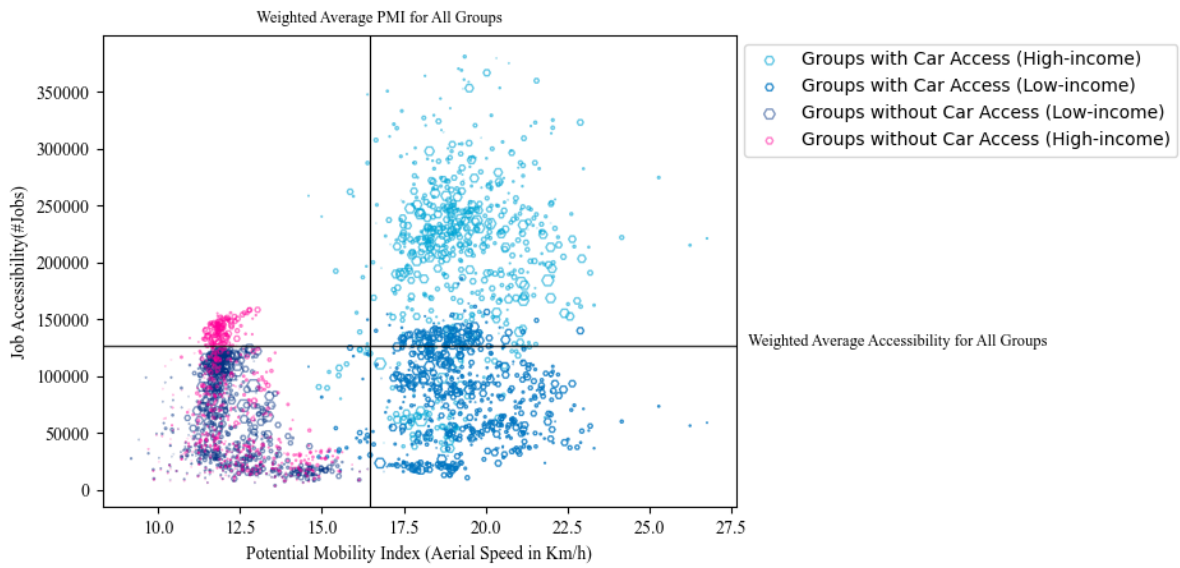



**Figure 1:** Coordinate System for Groups with/without Car Access from Low/high Income Class

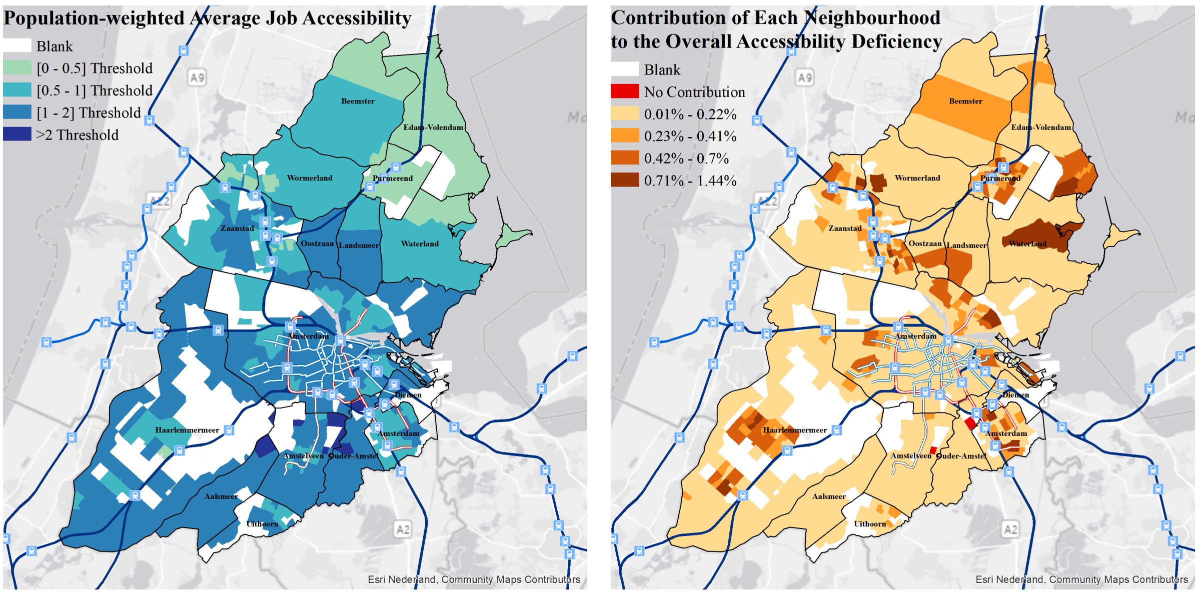
## Base Scenario: Without Transit-Shared Bike Integration

When evaluating the impacts of transit-shared bike integration on accessibility and equity, various disaggregate levels can be examined, ranging from the whole network to neighbourhoods and specific subgroups. This thesis presents three levels of disaggregation in the introduction of the base scenario: (1) Group level-1 (All groups); (2) Group level-2 (Groups with/without car access); (3) Group level-3 (Low/high-income Groups with/without car access).

Firstly, it is found that aggregated results tend to ignore the groups that are experiencing accessibility inequity, resulting in the inequity issue being overlooked. Therefore, the impacts of transit-shared integration will be analysed using group level-3 to understand better who is more likely to experience accessibility deficiency and the extent of severity they might experience.

Figure 2 illustrates the distribution of population-weighted average job accessibility and the contribution of each neighbourhood to the overall severity of accessibility deficiency, respectively. Contrary to expectations, Amsterdam is not the municipality with the highest average job accessibility. This unexpected outcome can be explained by the fact that low-income people and those without cars account for most of Amsterdam. Meanwhile, although jobs are concentrated in Amsterdam, most jobs cannot be matched by low-income groups. Nevertheless, Amsterdam has a well-developed public transportation system that enables low-income groups without cars to access jobs beyond the accessibility threshold.

Conversely, most commuters living outside Amsterdam, particularly those living near train stations, are unable to access sufficient job opportunities (Figure 2a) and significantly contribute to the overall severity of accessibility deficiency (Figure 2b). This is primarily due to the high share of low-income groups and those without car access living in these neighbourhoods. Although it might be convenient for them in the first-mile segments, this suggests an important insight that merely facilitating the first-mile to transit stations may not fully address the broader issue of limited job accessibility for transit-dependent inhabitants. Therefore, providing shared bikes at the transit stations as egress shows great potential to improve job opportunities for groups without car access and the overall fairness level of the transportation system.




(a) (b)

**Figure 2:** Weighted Average Accessibility in Each Neighbourhood (a); and the Contribution of Neighbourhood to the Overall Accessibility Deficiency (b)

## Impact of the Transit-Shared Bike Integration on Job Accessibility

Firstly, groups without car access can always benefit more than groups with car access in all scenarios, irrespective of the magnitude of increased job accessibility. For groups with car access, low-income groups can benefit slightly more than high-income groups when the price is set at 0 and 1 euro. However, there is a significant drop in the population benefiting from improved job accessibility for low-income groups when the price increases, from 90.62% (0 euro) to 81.78% (1 euro) and 44.91% (2 euro). In contrast, 89.86% low-income groups without car access can still improve job accessibility even at 2 euros. The greatest benefits of this intervention are assigned to high-income groups without car access, as their job accessibility can be improved for over 99% of them in all pricing scenarios.

Secondly, Figure 3 illustrates how the benefits are distributed among the four subgroups in all intervention scenarios. High-income groups without car access can experience the most substantial improvements in all scenarios. More importantly, they can still have 3.33% improvements in average job accessibility when the price is 2, while there are almost no improvements for other groups. For low-income groups with car access, improvements in job accessibility are higher than high-income groups with car access when shared bikes are free. It can be explained by the mathematical calculation of population-weighted average accessibility, where population size and magnitude of improvement collectively affect the improvement. Therefore, high-income groups with car access failed to overcome the effects of the smaller population size of low-income groups with car access through the more considerable magnitude of accessibility improvement when price = 0.

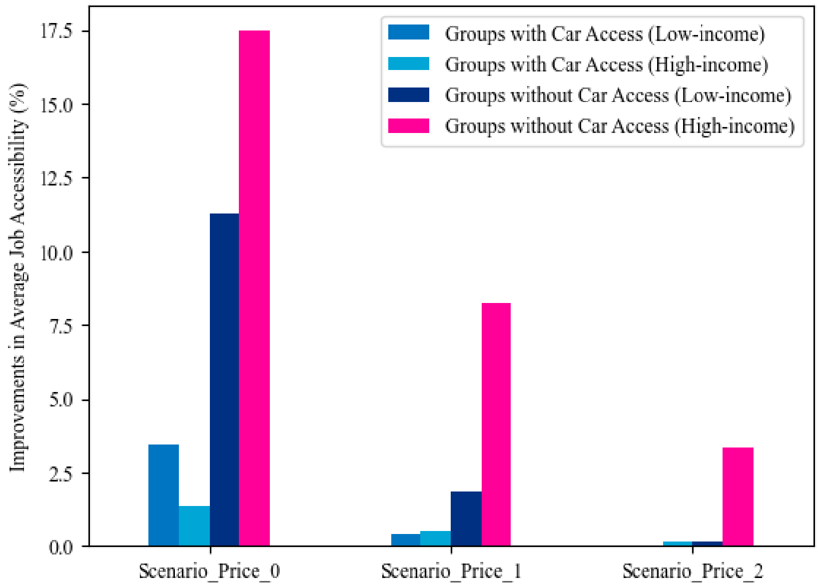



**Figure 3:** Improvements in Weighted Average Job Accessibility in the Three Different Pricing Scenarios: Group level 3

Thirdly, Figure 4 illustrates the geographical distribution of benefits of transit-shared bike integration in accessibility for groups without car access. It is observed that benefits are mainly concentrated in the municipality of Amsterdam and neighbourhoods near train stations. However, improvements significantly decrease with the increase in renting prices, which is attributed to the perception of higher travel resistance as travel costs increase. When the price =2 euros, high-income groups can still benefit in most neighbourhoods, except for several neighbourhoods on the border. In contrast, the number of neighbourhoods where low-income groups without cars can have improvements reduced significantly.

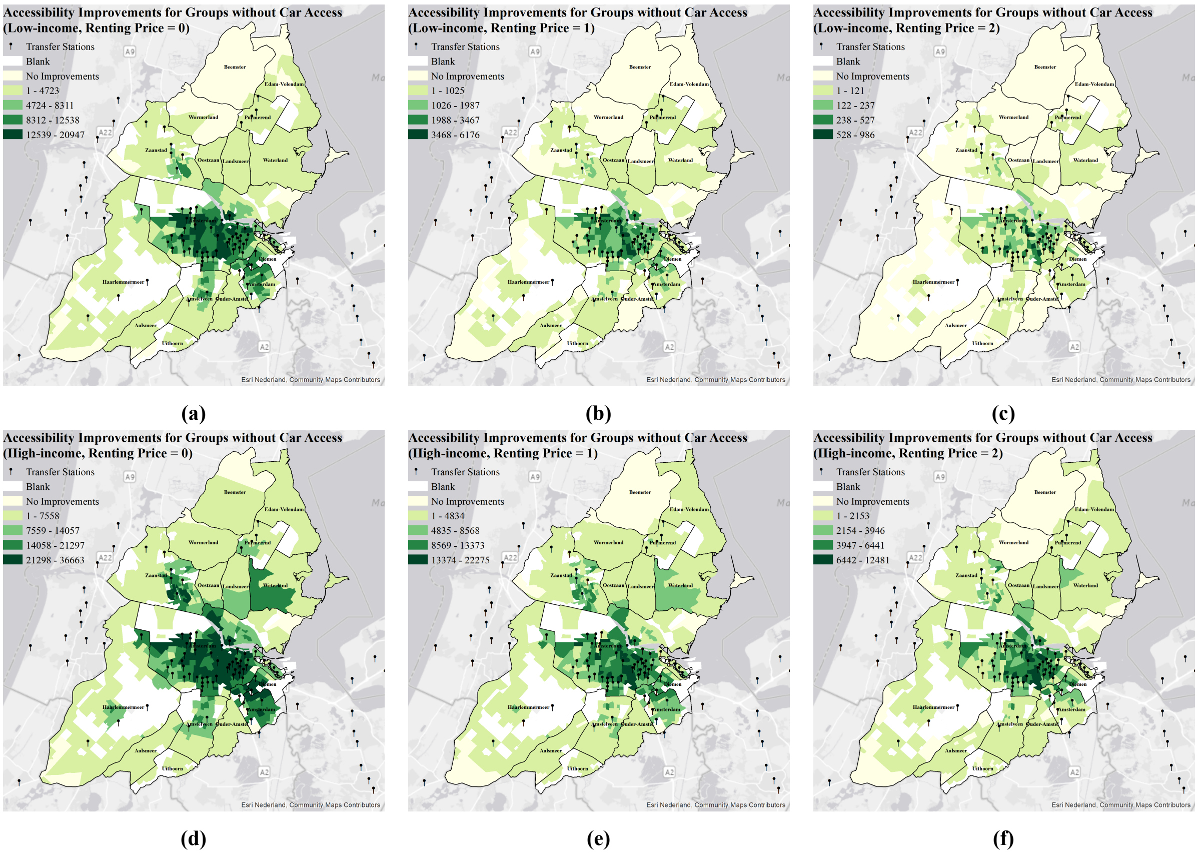



**Figure 4:** Improvements in Job accessibility for Groups without Car Access: Low-income, Renting Price = 0 (a); Low-income, Renting Price = 1 (b); Low-income, Renting Price = 2 (c); High-income, Renting Price = 0 (d); High-income, Renting Price = 1 (e); High-income, Renting Price = 2 (f)

## Impact of the Transit-Shared Bike Integration on Equity

Without introducing transit-shared bike integration, 100% low-income groups (31.39% in the total population) without car access contribute 85.85% to the overall accessibility deficiency. In contrast, for groups with car access from low income (26.11% in total population) and high income (34.76% in total population), each only contributes less than 5% to the overall deficiency severity. High-income groups without access account for the second highest contribution, 11.92%, but only 7.78% of the population in the case study area.

Overall, the equity improvements are mainly concentrated in the central area of Amsterdam, which can be observed in Figure 5. This figure illustrates the reduction in the severity of accessibility deficiency for groups without car access from different income classes within the three pricing scenarios. Neighbourhoods labelled in red represent groups previously regarded as deficient but can now access sufficient jobs with the intervention. For groups with car access, providing shared bikes at transit stations as an egress mode does not help low-income groups with car access shift from deficiency to sufficiency. Only when the renting price is set at 0 can high-income groups with car access and low-income groups without car access have sufficient jobs in an additional 3 and 47 neighbourhoods, respectively. However, high-income groups without car access can consistently benefit from this intervention in all scenarios. The improvements in job accessibility enable them to overcome the deficiency in an additional 25 and 11 neighbourhoods with prices set at 1 and 2 euros, respectively.

Even though the benefits of transit-shared bike integration are largely distributed to the groups without car access, high-income groups are more likely to be favoured. It can be explained by a trip's cost structure, including transit and shared bike costs. Transit cost dominates the overall expense for a journey, making the benefits of transit-shared bike integration less effective in alleviating the economic burden and potentially diminishing its attractiveness to commuters on longer trips. Therefore, high-income commuters are more likely to utilise the potential benefits of transit-shared bike integration than low-income commuters.

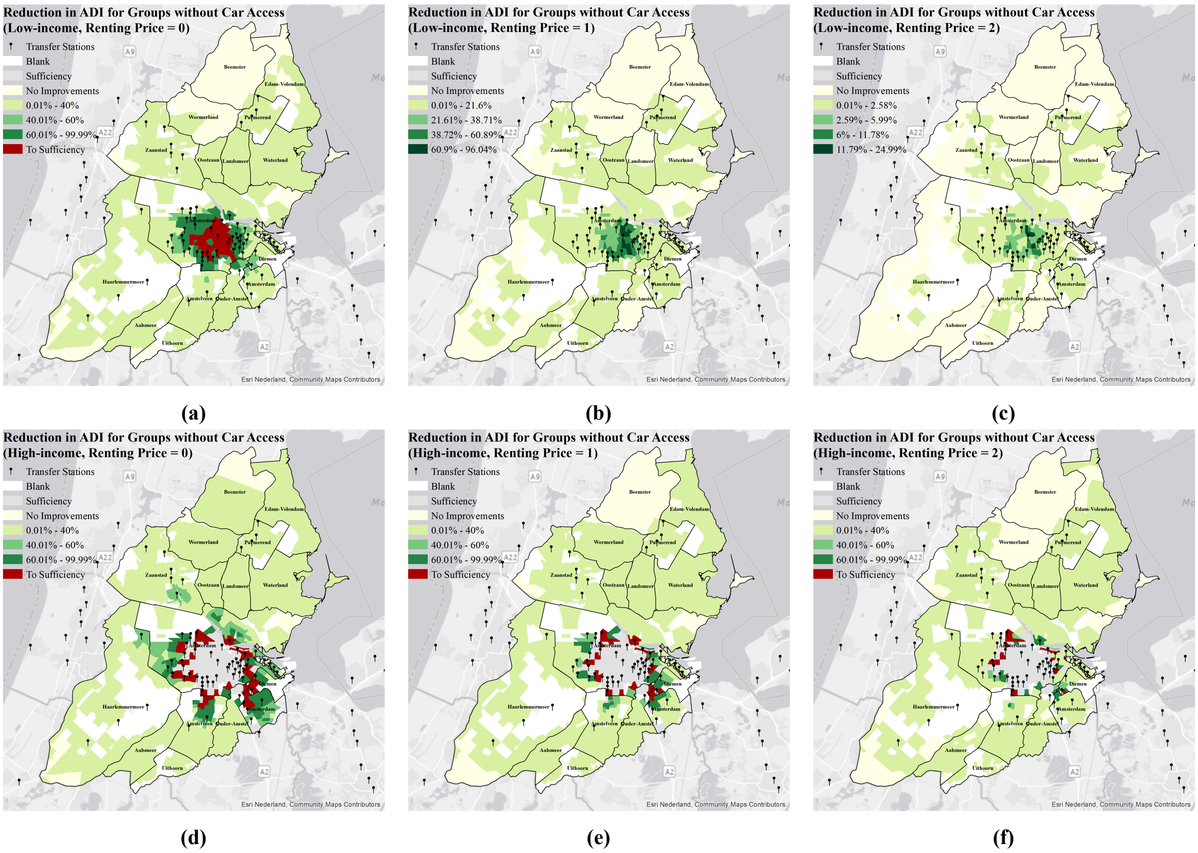



**Figure 5:** Reduction in ADI for Groups without Car Access: Low-income, Renting Price = 0 (a); Low-income, Renting Price = 1 (b); Low-income, Renting Price = 2 (c); High-income, Renting Price = 0 (d); High-income, Renting Price = 1 (e); High-income, Renting Price = 2 (f)

## Conclusion

In conclusion, this thesis addresses critical research gaps in transit-shared bike integration and its impact on equity in job accessibility. The results highlight the promising potential of this integration in improving accessibility for groups without car access, contributing to the equity of the transportation system. It can advance academic knowledge and offer practical insights for the transportation field.

Several generalised patterns can be summarised. Firstly, commuters living near transit stations are more likely to access an insufficient number of jobs and contribute significantly to the overall severity of accessibility deficiency even though they have convenient first-mile segments to transit stations. This is primarily due to the high share of disadvantaged groups living in these neighbourhoods and the low share of jobs matching their ability. Secondly, after introducing transit-shared bike integration, groups without car access can benefit more than groups with car access. However, equity-related benefits might favour high-income groups due to the cost structure of integration, including transit and shared bike costs. Thirdly, the accessibility improvements are mainly distributed to commuters living next to transit stations, while equity improvements are mainly distributed to areas with dense and developed public transport systems.

Nevertheless, it is essential to acknowledge certain limitations, such as deviation between assumed and actual travel behaviour for individuals, the omission of competition effects in job accessibility calculations, and the use of a rough assumption for the average potential mobility index for groups with multimodal options. Recommendations can be drawn for the methodology regarding the synergy of the IKOB model and sufficientarian approach and constructing updated parameters of the travel time decay curve. Additionally, policymakers from Amsterdam could perform equity analysis in a disaggregate manner to propose targeted policies for specific regions or groups. Future studies should prioritise a more accurate accessibility estimation by using advanced measures that reflect actual travel behaviour, considering competition effects in job accessibility calculations, and exploring the impacts of multimodal hubs, particularly with integrating electric mobilities. These recommendations aim to enrich our understanding further and guide the development of a more equitable transportation system.

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# 1
# Introduction

## 1.1. Research Background

Over the past several years, increasing attention has been made to improving accessibility to transport systems (Lucas et al., 2016; Van Wee & Geurs, 2011). The focus on transport policies has shifted from ”mobility” to ”accessibility” over the past two decades (Ryan & Pereira, 2021). Mobility measures the ease of movement through space, while accessibility measures the ability to reach desired destinations (Levinson & Wu, 2020). In the transport field, accessibility can be defined 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)” (K. T. Geurs & Van Wee, 2004). The interaction between land use, transport system, and individuals determines the level of accessibility (Pereira et al., 2017). However, accessibility is not always equally distributed due to the inherent differences in these three elements. Insufficient accessibility limits opportunities for essential activities, resulting in transport-related social exclusion risks (Di Ciommo & Shiftan, 2017; Fransen & Farber, 2019; Lucas et al., 2016; Unit et al., 2003; Van Wee & Geurs, 2011). As a result, accessibility has become a widely used indicator in equity assessment for a transport policy (Di Ciommo & Shiftan, 2017; Lucas et al., 2016).

Besides efficiency and effectiveness, a sustainable transport policy should also meet fairness (Young & Tilley, 2006). Equitable access to social and economic opportunities is becoming increasingly important as one of the primary goals of a transport system (Chinbat et al., 2023). Equity generally refers to the ”equitable distribution of benefits and burdens over members of society” (Di Ciommo & Shiftan, 2017; Litman, 2022; Martens et al., 2019). Unlike the similar term ”equality”, which treats everyone equally irrespective of differences, equity is a moral judgement (González et al., 2022). However, how equity should be defined, how to distinguish the groups for analysis, and which equity indicator and measure to be selected to evaluate the level of equity make the equity analysis highly complex (Van Wee & Geurs, 2011). Additionally, the current utilitarian appraisal method cost-benefit analysis (CBA), which aggregates the benefits and costs in monetary terms at the societal level, is unsuitable for evaluating transport policy that aims at improving equity since it does not consider the distribution effects (Di Ciommo & Shiftan, 2017; Lucas et al., 2016; Van Wee & Geurs, 2011). Furthermore, different equity principles have different standards for evaluating equity, which can result in conflicting outcomes because a policy may be regarded as equitable when evaluated one way but inequitable when evaluated another way (Camporeale et al., 2019; Van Wee & Geurs, 2011).

Recently, perceived accessibility emerged as a concept for incorporating the subjective factors of individuals to reflect how the provided opportunities can actually be valued as accessible for a person (Pot et al., 2023). It is suggested that accessibility measures should ideally consider land use, transportation, temporal and individual components (K. T. Geurs & Van Wee, 2004). However, most existing studies neglect the individual factors and predominantly measure accessibility based on a simple assumption of homogeneous characteristics among individuals living in the same location. Even though conventional accessibility measures can identify disadvantaged groups suffering from unfair accessibility, if the individual component is ignored, it might underestimate the inequalities and fail to achieve social justice goals. (Curl, 2018; Pot et al., 2023; Ryan & Pereira, 2021). Therefore, understanding what factors affect individuals' perception of accessibility and taking them into account as much as possible in accessibility calculation would be beneficial for a more realistic and accurate analysis of equity.

Unequal spatial distribution of opportunities and the transport system itself between different urbanised contexts, as well as the different socioeconomic characteristics, abilities, and preferences of individuals can often lead to unavoidable inequalities in accessibility across different transport modes, groups, and regions (Boarnet et al., 2017; Chinbat et al., 2023; Pritchard, Stępniak, et al., 2019; Qin & Liao, 2022; Tran & Draeger, 2021; van der Veen et al., 2020). Since the unequal distribution of benefits and costs is inevitable, Martens (2016) stated that "a fair transportation system provides all persons with a sufficient level of accessibility under most, but not all, circumstances". Car ownership has been identified as the most influential factor in improving access levels as cars provide superior accessibility than other transport modes in nearly all circumstances (Martens et al., 2022; Pritchard, Stępniak, et al., 2019; Qin & Liao, 2022). However, promoting car ownership does not align with environmental goals, and low-income and disadvantaged groups, who are often the most transit-dependent, have limited access to their desired activities because they cannot afford a car (Camporeale et al., 2019).

Travelling to work is one of the most important activities in individuals' daily lives, together with education and health care services. However, most people do not have the freedom to choose their employment locations, which means the transportation systems largely determine the ability to reach the workplace. For transit-dependent commuters, public transport does not offer the flexibility in door-to-door accessibility, which makes significant deterrence because of unavoidable access and egress time. In recent years, multimodal hubs have gained popularity as they can improve travellers' accessibility by seamlessly integrating different modes and potentially promote the transport system's equity (Arseneault, 2022; Frank et al., 2021; K. Geurs et al., 2022). Compared to the existing Park + Ride (P+R) facilities that mainly benefit people who already have car access, promoting the synergy between bikes and public transport could be an effective solution to this problem.

In the context of Dutch cycling culture, cycling already accounted for 43% of all train trips as first/last mile trips on the home side, while only 11% activity-end train trips are using bikes (Mathijs de Haas, 2020), which can be mainly explained by the limited availability of bikes at the egress-side of the trips (Brand et al., 2017; Shelat et al., 2018). Shared mobility services have been introduced to encourage the multimodal trips of travellers by providing flexibility in their first/last-mile segments (Rongen et al., 2022). Providing shared bikes at the egress side of public transport could be a promising intervention to enhance the accessibility for commuters without car access and promote equity in the transport system. However, some research has already investigated the impacts of the integration of bike and transit from the equity perspective. However, the benefits of equity in job accessibility if shared bikes are provided as the egress side of public transport have not been thoroughly explored. Furthermore, most research evaluated the equity in accessibility from the egalitarian perspective by identifying the disparities between different transport modes or regions. This approach has been criticised by Martens et al. (2022), who suggested that the equity assessment should shift from disparity analysis to sufficiency analysis. This shift is because disparity analysis fails to answer whether people are provided with a basic level of accessibility that allows them to participate fully in society. Additionally, it often overlooks the heterogeneity within the aggregated groups.

This research will conduct a ”what-if analysis” in a case study of Vervoerregio Amsterdam (Amsterdam Transport Region) to analyse the impacts of transit-shared bike integration on equity in job accessibility. It is expected to experience significant growth in population and employment, with 250,000 new homes and 230,000 jobs expected to be added in the Amsterdam Metropolitan Area by 2040 (van Frederikslust, 2021). This growth, coupled with the European climate goals, puts significant pressure on the mobility system. To ensure everyone can easily participate in social life to satisfy their needs, Amsterdam Transport Region is working towards creating an equitable transportation system. As the benefits and burdens of a transport policy are not evenly distributed, it is important to analyse accessibility inequity. This analysis will help urban planners or policymakers understand how interventions would impact the accessibility for different population groups and the overall equity level of the transport-land use systems. Based on the analysis results, transport policies can prioritise the groups experiencing unfair accessibility and help to create a more equitable transport system.

## 1.2. Research Gaps

Three research gaps were identified after reviewing literature about the assessment of equity and accessibility for transit-bike integration:

Firstly, most literature simply assumes homogeneous characteristics among different individuals (K. T. Geurs et al., 2016; Pritchard, Stępniak, et al., 2019; Pritchard, Tomasiello, et al., 2019; Qin & Liao, 2022; Wang et al., 2022). Only Zuo et al. (2020) considers the accessibility difference for different income classes and races, and Boarnet et al. (2017) takes into account the low-income groups and low-wage jobs, as well as the competition effects in the labour market. However, some other important factors of perceptions in land use, transport, temporal and individual components are not taken into account. For instance, the individuals' car ownership, preference of transport modes, the perceptions of monetary costs in travel resistance, the service quality of transport system or perceived safety. Incorporating these important factors could represent the opportunities that can actually be valued as accessible for individuals.

Secondly, the benefits of integrating transit and shared bikes on equity in job accessibility, particularly at the egress-side, have not been thoroughly explored. When calculating the travel time of transit-bike integration, bikes are often roughly modelled as the access or egress mode by replacing the travel distance of walking to cycling and are assumed to be possible for transferring in all zones, which is not the case in reality. For bike-sharing scenarios, the locations that allow travellers to shift from transit to bike and the characteristics of bike-sharing systems need to be modelled. Only Wang et al. (2022) examined the impacts of free-floating bike-sharing on job accessibility and equity. However, this study only uses travel time without consideration of monetary costs, which is a significant barrier to accessibility for disadvantaged groups. No scientific studies specifically look at the impacts of shared bikes as an egress mode at transit stations on equity in job accessibility.

Thirdly, the egalitarianism principle is applied in all relevant literature to investigate the impacts of transit-bike integration on equity in job accessibility. However, the egalitarian index only measures the level of equity and fails to identify the groups at risk of social exclusion (Lucas et al., 2016), as well as often neglects the heterogeneity within the aggregated groups (Martens et al., 2022). Therefore, this method is not suitable for equity analysis focusing on the group level. Sufficienatarianism would be a more suitable approach, but it has not been applied to investigate the impacts of transit-shared bike integration on equity.

## 1.3. Research Objectives

To address these research gaps, this study will conduct a ”what-if analysis” in the Amsterdam Transport Region to investigate the potential impacts on job accessibility for different groups and the equity of the whole transportation system if shared bikes are provided at transit stations as the egress mode. We specifically focus on investigating the impacts on the groups who cannot access cars. Absolute judgements will not be made regarding whether the transport systems are equal or not. Instead, from a planning perspective, the results will allow for the development of recommendations in integrating shared bikes and public transport to promote equity, both in the Amsterdam Transport Region and more broadly. In order to achieve the objective, the main research and six sub-research questions are proposed as follows.

## 1.4. Research Questions

**Main Research Question:**
*What would be the impacts on job accessibility for commuters without car access and the equity of the whole transportation system in the Amsterdam Transport Region if shared bikes were provided at transit stations as an egress mode?*

**Sub Research Questions:**
**1. What is the most suitable principle to define an equitable distribution in the context of job accessibility?**
When assessing the level of equity of a transport system, not only which equity indicator will be used needs to be justified, but also the equity principle that will be used as the assessment framework. Therefore, a literature review will first be carried out to show the state-of-the-art relevant research in the domain of equity and accessibility. It can help justify the suitability of using job accessibility as the indicator of equity evaluation. Afterwards, the advantages and disadvantages of different equity principles will be compared and discussed to justify the selection of the most suitable equity framework for job accessibility.

**2. What influencing factors are relevant in individuals' perceptions of job accessibility?**
As this study focuses on equity assessment on the accessibility for population groups rather than places. Introducing the individuals’ perception of accessibility provides a more accurate and realistic equity evaluation. Therefore, it is important to conduct a literature review about the influencing factors related to perceived accessibility from different perspectives. Afterwards, the influencing factors could be matched to the context of job accessibility.

**3. Which accessibility measure will be applied to incorporate individuals' perceptions to make a more realistic estimate of equity in job accessibility?**
There are different measures to calculate accessibility, and different measures have different benefits and drawbacks. Incorporating individuals’ perceptions into accessibility measures can more realistically indicate the opportunities that can actually be valued as being accessible and possibly be transferred to opportunities for individuals. It is important to select a suitable accessibility measure to introduce some influencing factors, especially factors in the individual component. Therefore, a literature review should be conducted to evaluate the pros and cons of different accessibility measures, and to understand their ability to incorporate these influencing factors.

**4. How can the impacts of providing shared bikes as an egress mode at transit stations on equity in job accessibility be evaluated based on the selected accessibility measure and equity principle?**
For the analysis of equity in job accessibility, the selected equity framework and equity index in sub-research question 1 will be applied as the guideline. Also, the selected accessibility measure in sub-research question 3 will be used to calculate the accessibility for different groups. In order to evaluate the impacts of shared bikes as the egress modes at transit stations on accessibility, the characteristics of transit-shared bike integration should be modelled. Locations and the number of transfer stations where travellers can shift from transit to shared bikes are relevant, as well as the renting price of the bike-sharing system. Therefore, a literature review regarding the bike-sharing system and modelling approach for integrating transit and shared bikes is needed.

**5. What are the potential implications of the outcomes of creating a more equitable transportation system in the Amsterdam Transport Region?**
The impacts of transit-shared bike integration will be presented in two comparative scenarios, with and without transit-shared bike integration. Therefore, to what extent this intervention would impact the accessibility for different commuters and the level of equity for the whole transport system can be examined. Meanwhile, a sensitivity analysis in terms of different renting costs will also be conducted. Based on the analysis results, it would be helpful to propose possible suggestions to create a more equitable transport system not only in the case study area but can be applied more broadly.

## 1.5. Methodology Framework

Approach to analysis of impacts of transit-shared bike integration on equity in job accessibility is displayed in Figure 1.1 to provide an overview of the steps to answer each research question.

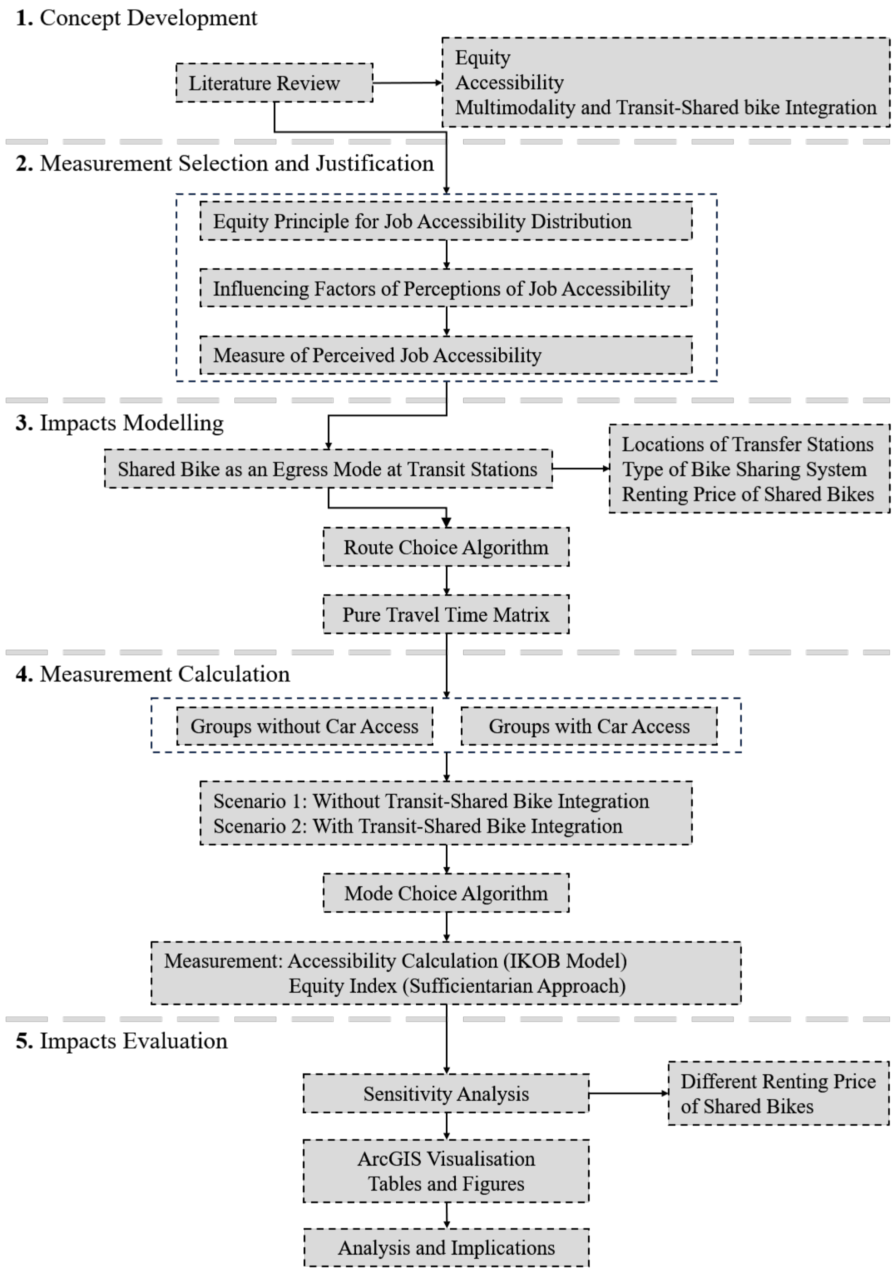



**Figure 1.1:** Methedology Framework: Steps to Analysis of Equity in Job Accessibility

# 1.6. Thesis Outline

The rest of the thesis is organised as follows: Section 2 reviews the work related to equity, accessibility, multimodality and transit-shared bike integration for measurement selection and research gaps identification. Section 3 explains the methodology for impact modelling, job accessibility calculation and equity evaluation of transit-shared bike integration. Section 4 introduces the basic information of the case study area. Section 5 evaluates transit-shared bike integration's impacts on accessibility and level of equity, including a sensitivity analysis of renting cost of shared bikes. Section 6 gives implications and discussions on results and research methodologies. Finally, Section 7 presents the conclusions and recommendations.

# 2

# Literature Review and Discussion

This chapter provides a literature review to demonstrate the state-of-the-art of relevant research and justify the research scope of this thesis by discussing some essential elements. Firstly, it discusses the definition, principles, indicators, and measures of transport equity. Secondly, it reviews the definition and measures of transport accessibility. These two steps help clarify the indicators and measures for social equity and accessibility. Thirdly, it reviews the multimodality, modelling methodology, and impacts of transit-bike integration and bike-sharing systems.

”Scopus”, ”Google Scholar”, and ”TU Delft Repository” were used as search engines, and the snowball technique was applied to obtain more relevant studies. When searching the papers, various combinations of keywords were searched to select the papers, and the abstract and conclusion were read to understand their relevancy. Keywords and their synonyms in each broad field are listed in Table 2.1.

**Table 2.1:** Literature Review: Keywords

| Field | Keywords |
|---|---|
| Accessibility | ”Transport Accessibility”; ”Job Accessibility”; ”Employment Accessibility”; ”Perceived Accessibility”; ”Subjective Accessibility” |
| Equity | ”Transport Equity”; “Justice”; ”Fairness”; ”Social Exclusion” |
| Transit-Shared Bike Integration | ”First/last mile”; ”Shared Bike”; ”Bike Sharing”; Transit-bike; ”Transit-Shared Bike”; ”Multimodal Accessibility” |

## 2.1. Equity

### 2.1.1. Equity Definition

Equity generally refers to the ”equitable distribution of benefits and burdens over members of society (Di Ciommo & Shiftan, 2017; Litman, 2022; Martens et al., 2019).” Unlike the similar term ”equality”, which implies treating everyone equally irrespective of the difference, equity is a moral judgement (González et al., 2022; Van Wee & Geurs, 2011). In the transport field, Anderson et al. (2017) defined transport equity as ”residents can reach destinations across the city in a time- and cost-effective manner, irrespective of their geographic location or socioeconomic status." Similarly, Chinbat et al. (2023) stated that "transportation equity is realised when different demographics have equal access to transportation, regardless of location, neighbourhood, age, gender, income, religion, or any other disaggregation." In addition, transport equity was defined by Pereira, Karner, et al. (2021) as "a way to frame distributive justice concerns in relation to how social, economic, and government institutions shape the distribution of transportation benefits and burdens in society ." Furthermore, equity can be distinguished into different types, such as horizontal and vertical equity. The former refers to everyone getting the same benefits and burdens with equal ability and need, while the latter focuses on protecting the disadvantaged groups (Di Ciommo & Shiftan, 2017; Van Wee & Geurs, 2011).

### 2.1.2. Equity Principle

Equity theory is a framework used to assess whether a particular distribution is ethically and socially acceptable (Di Ciommo & Shiftan, 2017). Equity principles have been well established in various domains like health care, education and housing (González et al., 2022; Jeekel & Martens, 2017; Martens et al., 2019). However, it has only become a popular topic in the transportation field, and there is still a debate about which equity principle should be used as a guideline. Equity principles are typically egalitarian in domains like healthcare and education. Although housing and mobility/accessibility share certain similarities as both heavily rely on the free market to provide services (Martens, 2016), there are significant differences between the organisation of the provision, the guiding principles, and the government policies of housing and mobility (Jeekel & Martens, 2017). Therefore, a unique sphere of equity assessment can be built specifically for the transport industry.

The three theories that have been extensively discussed in the literature are utilitarianism, egalitarianism and sufficientarianism (González et al., 2022; Thomopoulos et al., 2009; Van Wee & Geurs, 2011). The utilitarianism principle says one transport policy is equitable if it maximises the benefits for the overall society. Egalitarianism indicates one equitable policy if it minimises the inequalities between different groups and regions. Sufficientarianism means everyone should be provided with a basic level of service to satisfy their needs. Some researchers have also combined two equity theories to create evaluation frameworks. For example, Pereira et al. (2017) combined Rawlsian egalitarianism and the capability approach to achieve distributive justice. Similarly, Lucas et al. (2016) proposed a hybrid methodology that includes both egalitarianism and sufficientarianism to evaluate the socially relevant accessibility impact. Furthermore, Adli and Chowdhury (2021) proposed a framework to evaluate transit equity by combining egalitarianism and sufficientarianism.

### 2.1.3. Equity Indicator

Transport equity evaluation involves three fundamental steps (Martens et al., 2019): (1) define the benefits and costs, (2) identify the difference between population groups, and (3) select the equity theory. Concerning indicators for benefits and costs, different indicators can be used depending on the research context. For example, indicators can be accessibility, safety and environment (van Wee & Mouter, 2021). It can also be evaluated based on the accessibility to key activities, travel affordability and access to transport (Di Ciommo & Shiftan, 2017). Additionally, Pereira et al. (2017) stated that it could be analysed on transport resources, observed daily travel behaviour and transport accessibility level. Furthermore, Martens et al. (2019) also distinguished four types of transport equity indicators: mobility/accessibility, traffic-related pollution, traffic safety and Health.

### 2.1.4. Equity Measure

Some statistical and comparable indexes have been proposed in transportation to calculate the level of inequalities of distribution of resources, such as the Gini index, Theil index, Palma index, Atkinson index, Suit index and Coefficient of Variation (van Wee & Mouter, 2021). Among them, the egalitarian measure Gini index and Lorenz curve are the most frequently used index in transportation because it is easy to understand and communicate (Guo et al., 2020; van Wee & Mouter, 2021). The Gini index ranges from 0 to 1, the larger the Gini index, the more unequal the distribution (van Wee & Mouter, 2021). The Lorenz curve shows the cumulative distribution of a group of an ordered indicator like accessibility by the corresponding cumulative population distribution. Even though the Gini index has many advantages, there are also some limitations. For example, it cannot consider the additional characteristics of subgroups, making it difficult to analyse vertical equity (Guo et al., 2020).

Neutens et al. (2010) pioneered combined the Gini coefficient and Lorenz curve to evaluate inequality in accessibility. Since then, the Gini index, together with the Lorenz curve, has been extensively applied in transport accessibility and equity studies (Chinbat et al., 2023; Lucas et al., 2016; Pritchard, Stępniak, et al., 2019; Pritchard, Tomasiello, et al., 2019; Qin & Liao, 2022; Rubensson et al., 2020; Tahmasbi et al., 2019). The Gini index can be used for the overall population, but it is not sensitive to the top and bottom of the income level (Qin & Liao, 2022). Therefore, some other measures focusing on the better- and worse-off groups have been applied alternatively to measure the distribution of accessibility. For instance, Guzman and Oviedo (2018) applied the Palma ratio, the ratio between the average accessibility for the top 10% groups and the bottom 10% groups, to measure if the subsidies can provide the low-income groups with more job accessibility. In addition, the 20:20 ratio calculates the ratio of average accessibility of the richest 20% and the poorest 20% to examine the equality of access to shopping and leisure opportunities across municipalities (Qin & Liao, 2022). Furthermore, the Theil index considers both inequalities within the same groups and the inequalities between different groups, which has been used to minimise the difference in transport accessibility among groups (Caggiani et al., 2020).

In sufficientarian theory, focusing on disparities is replaced by focusing on providing a certain minimum level of resources. This goal is to identify the population groups below a specific threshold value to bring them above that value. This indicates that only the population groups above or below a specific threshold value should be focused. Martens (2016) suggested a deliberative and democratic process should determine this debatable value. However, it is also possible to define the thresholds more pragmatically by using descriptive statistics, such as averages, standard deviations or percentages for a specific value (van der Veen et al., 2020). For example, the proportion of people in a city that cannot reach a certain minimum number of activities (education, healthcare locations, jobs, etc.) within an acceptable travel time (González et al., 2022). Additionally, van der Veen et al. (2020) used the percentages (100% and 50%)

of the average car accessibility during peak hours as a high and a low threshold to identify the differences in accessibility between population groups with different mode availability, time of day and location in the case for Rotterdam. Martens (2016) used 10%, 20%, 30%, 40% 50% of average car accessibility during peak hours to explore the fairness of the transport-land use in Amsterdam Transport Region. Zweers (2023) used the accessibility of 25%and 50% of all job opportunities as the sufficiency thresholds to investigate the impact of transport affordability on job accessibility for low-income and unemployed households in the Parkstad region. Van Luven (2022) used the VF value ( displacement time factor) to evaluate the equity of an accessibility distribution of Public transport in Amstelland-Meerlanden, which is expressed as a ratio of the log sum travel cost by transit to the log sum travel cost by car.

## 2.2. Accessibility

### 2.2.1. Accessibility Definition

The focus on transport policies has shifted from mobility to accessibility over the past two decades (Ryan & Pereira, 2021). Mobility refers to the ease of movement through space, while accessibility refers to the ability to reach opportunities (Levinson & Wu, 2020). The concept of accessibility starts from the definition ”potential of opportunities for interaction” by Hansen (1959). Accessibility could be perceived as the ease of reaching several key activities and opportunities (Di Ciommo & Shiftan, 2017). In the transportation field, transport accessibility is defined 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) (K. T. Geurs & Van Wee, 2004).” Additionally, Lucas et al. (2016) stated that the broad definition of transport accessibility is related to physical access to goods and services and the transport system regarding its availability, affordability, reliability, safety and access to timetable information. In addition, three key features in the definition of accessibility were summarised by Ryan and Pereira (2021): (1) the ‘potential’ to reach opportunities, (2) the ‘ease’ with which said potential could be realised, and (3) the ‘extent’ to which opportunities can be reached. Therefore, there is still no consensus on how accessibility should be defined and measured even though accessibility-related research has been extensively conducted over the past decades (Ryan & Pereira, 2021; Sullivan & Novak, 2023).

### 2.2.2. Accessibility Measure

The classification of accessibility measures that have been most frequently referred to is from literature (K. T. Geurs & Van Wee, 2004), where four types are distinguished: infrastructure-based, location-based, person-based, and utility-based. Infrastructure-based measures analyse the performance or service level of the transport system through travel times, average travel speed, and congestion level of the road network. Location-based accessibility measures describe the accessibility to spatially distributed activities at a macroscopic level, often represented using contour and gravity-based measures. Person-based accessibility measures (individual) analyse the accessibility with spatial and temporal constraints for activities at an individual level. Utility-based accessibility measures are derived from travel behaviour theory, and indicate the benefits of accessibility by individuals.

Each accessibility measure has its advantages and disadvantages. Infrastructure-based measures do not consider the land-use, temporal and individual components of accessibility, and thus, not suitable for accessibility impacts evaluation of a land-use and transport policy (K. T. Geurs & Van Wee, 2004). In contrast, location-based and utility-based accessibility measures are suitable for the social and economic evaluation of land use and transport investment. However, both measures generally do not consider temporal constraints for activities. Additionally, utility-based accessibility measures need more detailed data, and are difficult to interpret and implement. For contour measures from location-based measures, they often do not consider the heterogeneity of individuals so that all opportunities are considered equally desirable from the same zone (Kumar, 2011). For gravity-based measures from location-based measures, competition effects can be taken into account. Moreover, they are able to reward proximity by assigning a weight to opportunities from the region, and incorporate individuals' perceptions of transport by using a travel time decay curve. Although space and time restrictions and individual variations are included for person-based measures, it has difficulties in data availability of individual activity–travel and. In addition, person-based measures do not account for competition effects, which results in less suitability for the analysis of opportunities with intense competition, like employments (K. T. Geurs & Van Wee, 2004).

### 2.2.3. Equity and Job Accessibility

In the field of transport equity analysis, different accessibility measures and equity principles have been applied to evaluate equity in accessibility. In order to find research gaps in the analysis of equity in accessibility, this section will review the relevant literature on relevant components in equity and job accessibility, which is summarised in Table 2.2. After reviewing the literature about equity and job accessibility, several key findings are also summarised:

Firstly, most studies focus on analysing equity in job accessibility by public transport (Boisjoly et al., 2020; Deboosere & El-Geneidy, 2018; Giannotti et al., 2022; Guzman & Oviedo, 2018; Herszenhut et al., 2022; Pucci et al., 2019; Van Luven, 2022), or comparing the accessibility and equity by different transport modes (Dixit & Sivakumar, 2020; van der Veen et al., 2020; Zhu & Shi, 2022; Zweers, 2023). Research about the impacts of multimodality on equity in job accessibility has received less attention except for literature (Hu & Sun, 2023; Pritchard, Stępniak, et al., 2019; Pritchard, Tomasiello, et al., 2019; Wang et al., 2022; Zuo et al., 2020). Secondly, it is found that most studies prefer to use the isochronic measure for accessibility calculation, and few studies adopt the person-based or utility-based measure for job accessibility (Dixit & Sivakumar, 2020; Qin & Liao, 2022; Van Luven, 2022). Thirdly, regarding the equity principle, sufficientarianism has not received much attention in analysing equity in job accessibility except for Van Luven (2022) and Zweers (2023). At the same time, the egalitarian measure, Gini index, and Lorenz curve are the most popular methods that have been extensively used to evaluate inequalities. Fourthly, except for Pritchard, Stępniak, et al. (2019) and Pritchard, Tomasiello, et al. (2019), who included dynamic temporal impacts, most scholars used static morning peak as the period. Finally, the individual component is often ignored in these studies of equity in job accessibility, even though some research has considered individual factors but mainly focuses on socio-economic and demographic characteristics, particularly income class (Boisjoly et al., 2020; Dixit & Sivakumar, 2020; Guzman & Oviedo, 2018; Herszenhut et al., 2022; Hu & Sun, 2023; Zuo et al., 2020; Zweers, 2023).

**Table 2.2:** Literature Review of Equity Assessment in Job Accessibility

| Equity Principle | Equity Measure | Accessibility Measure | Individual Component | Transport Mode | Temporal Component | Literature |
|---|---|---|---|---|---|---|
| Sufficientarianism | Accessibility Sufficiency Indicator | Isochronic | Income | Car, PT, Bike, Walking | None | Zweers (2023) |
| Vertical Equity | Accessibility improvements | Gravity-based | Income, race, ethnicity, sex | Transit+TNC | Peak and off-peak | Hu and Sun (2023) |
| Egalitarianism, Proportionality, Sufficientarianism | Gini index and Lorenz curve, actual accessibility, VF value | Utility-based | Income | PT | AM peak | Van Luven (2022) |
| Egalitarianism | Gini index | Isochronic | None | Shared Bike-Transit | AM Peak | Wang et al. (2022) |
| Egalitarianism | Gini index | Isochronic | House prices | PT, Car | AM Peak | Zhu and Shi (2022) |
| Egalitarianism | Gini index and Lorenz curve | Gravity-based | NS-SEC | PT | None | Giannotti et al. (2022) |
| Egalitarianism | Palma Ratio | Isochronic | Income | PT | AM Peak | Herszenhut et al. (2022) |
| Egalitarianism | Gini index | Utility-based | Age, Gender, Income | Car, Train, Bus, Walking | None | Dixit and Sivakumar (2020) |
| Sufficientarianism | Accessibility Fairness Index | Isochronic | None | Car (peak), Car, PT, Bike | Peak and off-peak | van der Veen et al. (2020) |
| Egalitarianism | Theil, Atkinson, and RMD | Isochronic | Race, Income | Bike-transit | None | Zuo et al. (2020) |
| Vertical Equity | Proximity to rapid transit, accessibility by PT | Isochronic | Income | PT | AM Peak | Boisjoly et al. (2020) |
| Egalitarianism | Gini index and Lorenz curve | Gravity-based | None | Bike-Transit | All hours of the day | Pritchard, Tomasiello, et al. (2019) |
| Egalitarianism | Gini index and Lorenz curve | Gravity-based | None | Bike-Transit | All hours of the day | Pritchard, Stępniak, et al. (2019) |
| Egalitarianism | Synthetic index (IAO) | Isochronic | None | PT | AM Peak | Pucci et al. (2019) |
| Egalitarianism | Palma Ratio, Gini index | Gravity-based | Income | PT | None | Guzman and Oviedo (2018) |
| Vertical Equity | Vertical equity indicator | Isochronic | Vulnerable residents | PT | AM Peak | Deboosere and El-Geneidy (2018) |

### 2.2.4. Subjective and Conventional Accessibility Measure

Accessibility measurements can also be classified into conventional (objective) or perceived (subjective) accessibility measures. Objective accessibility measures the separation of people from places based on aggregate travel time or generalised costs (van der Vlugt et al., 2019). Perceived accessibility is defined by Lättman (2018) as: "how easy it is to live a satisfactory life with the help of the transport system", which describes how individuals or groups perceive their own accessibility. However, Pot et al. (2021) suggested that there is no objective accessibility, so it is better to avoid this term. In this thesis, "objective accessibility" will be replaced with "conventional" accessibility to refer to the conventional calculated measure without taking into account individuals' perceptions in most literature.

Differences between perceived accessibility and conventional accessibility have been identified in some studies using self-reported surveys or interview (Curl, 2018; Curl et al., 2015; Lättman et al., 2018; Pot et al., 2023; Ryan & Pereira, 2021; van der Vlugt et al., 2019). This suggests an ambiguity in the meaning of "accessible" between the analysts and the people themselves. The opportunities that can actually be valued and concerted into the possibility of being accessible for a person are related to individual factors, such as capabilities, preferences and needs. By incorporating the perceptions of individuals in accessibility, perceived accessibility is more likely to link with actual individuals' travel behaviour than objective accessibility (Jamei et al., 2022; Lättman, 2018; Pot et al., 2023; Pot et al., 2021; van der Vlugt et al., 2019). However, the individual component is always overlooked in objective accessibility, resulting in problematic in equity evaluation (Curl, 2018; Pot et al., 2023; Ryan & Pereira, 2021).

Perceived accessibility has received interest only recently to capture individual perceptions. Most research calculates accessibility using location-based measures and introduces human components by distinguishing socioeconomic and demographic characteristics, as these data are more straightforward to derive. Levinson and Wu (2020) proposed a more general representation of accessibility based on the location-based accessibility definition in Hansen (1959). This general measure has taken into account more factors that affect individuals' perception than the other measures, such as time-of-day of opportunities, different types of opportunities, requirements of the available opportunities to individuals with specific skills, competition effects among opportunities and individual mode availability.

It is suggested that accessibility measures should ideally consider all four components: (1) Land use, (2) transportation, (3) temporal constraints of opportunities and (4) individual needs, abilities and opportunities (K. T. Geurs & Van Wee, 2004). However, in the transport field, most academic studies mainly use simple objective measures that only indicate the interaction between land use and transport. The influence of individual dimension is often ignored (Ryan & Pereira, 2021). It can be explained by the simplicity of objective measures (Chinbat et al., 2023; Ryan & Pereira, 2021), and limitations on data and computation when calculating accessibility in a subjective way (Pot et al., 2023; Ryan & Pereira, 2021). Understanding the factors that affect individuals' perception of accessibility and incorporating them as much as possible in accessibility measures would benefit a more realistic and accurate equity analysis. Pot et al. (2021) constructed a conceptual model (Figure 2.1) based on theoretical components of accessibility proposed by K. T. Geurs and Van Wee (2004) to understand the relationship between influencing factors and perceived accessibility. It will be used as the framework in this thesis to identify the factors that shape a person's perception of job accessibility. The categories of relevant factors in four components are summarised in Table 2.3.

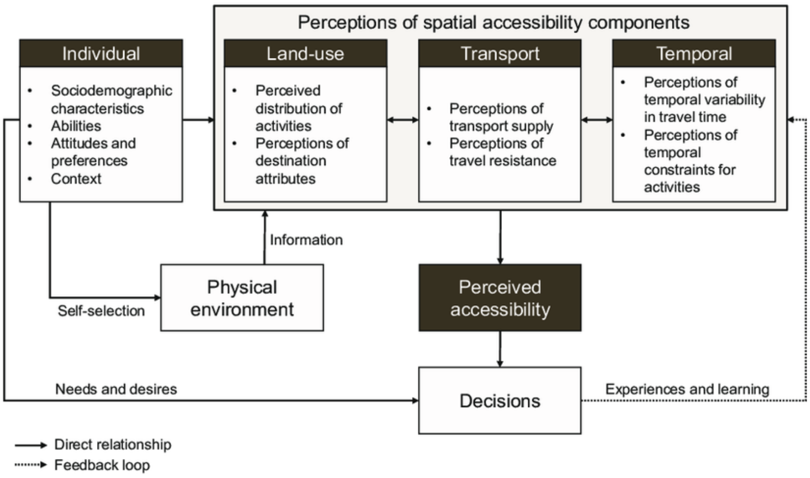



**Figure 2.1:** Conceptual Model of Perceived Accessibility: From (Pot et al., 2021)

**Table 2.3:** Influencing Factors in Perceived Accessibility

| **Influencing Factors** | **Literature** |
|---|---|
| **Land-use Component** | |
| Distribution of activity locations | Pot et al. (2021) and van Wee (2022) |
| Characteristics of activity locations | Pot et al. (2021) |
| Barrier-free environment | van der Vlugt et al. (2019) |
| Perceived safety | Friman et al. (2020), Jamei et al. (2022), Lättman et al. (2018), and van der Vlugt et al. (2019) |
| **Transport Component** | |
| Awareness of travel supply | Pot et al. (2021) |
| Travel resistance | Pot et al. (2021) |
| Functionality and service quality of public transport | Jamei et al. (2022) |
| **Temporal Component** | |
| Temporal constraints of activity locations | Pot et al. (2021), Ryan and Pereira (2021), and van Wee (2022) |
| Temporal constraints of Individuals | Pot et al. (2021) and Ryan and Pereira (2021) |
| **Individual Component** | |
| Socio-economic and demographic characteristics (Age, Gender, Income, Education) | Chen et al. (2022), Jamei et al. (2022), Pot et al. (2023), Pot et al. (2021), Ryan and Pereira (2021), and van der Vlugt et al. (2019), van Wee (2022) |
| Modal availability | Pot et al. (2023), Ryan and Pereira (2021), and van der Vlugt et al. (2019) |
| Physical ability | Pot et al. (2021), Ryan and Pereira (2021), and van Wee (2022) |
| Attitudes and preferences | Miller (2018), Pot et al. (2023), and Pot et al. (2021), van Wee (2022); |
| Whether low accessibility is voluntary | van Wee (2022) |
| People's social networks | van Wee (2022) |
| Digital access | Pot et al. (2021) and van Wee (2022) |

## 2.3. Multimodality and Transit-Bike Integration

### 2.3.1. Multimodality and Modelling Methodology

Travellers in unimodal trips only use single modes like car, tram, metro and train, and there is no transfer between one to other modes network. In contrast, multimodal trips are where two or more modes are used for a single trip between origin and destination. As walking can be considered part of any trip, it is often not considered in a multimodal trip. Figure 2.2 illustrates the travel time/cost difference between unimodal and multimodal trips.

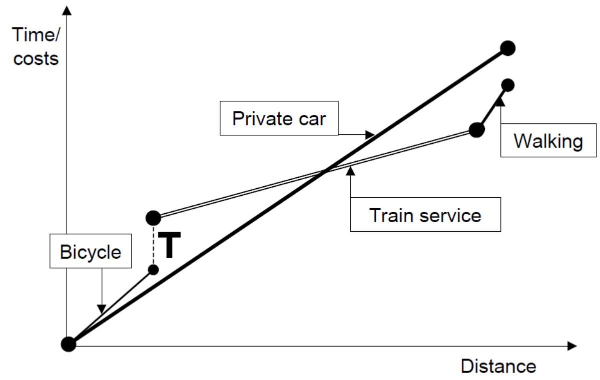



**Figure 2.2:** Unimodal and Multimodal Trips: From Van Nes (2002)

Transfers are locations where the shift between multiple modes happens, which are an essential part of multimodal trips. These transfer locations are often called hubs that integrate multimodal transport modes together. Multimodal hubs can offer a wide range of benefits to the public, such as improving the service coverage of transit service, facilitating multimodal door-to-door trips, reducing traffic congestion on the road, promoting environmental sustainability, supporting economic development and providing equitable access to a choice of transport modes (Arseneault, 2022; CoMoUK, 2019). The definition of hubs has not been unified as it has different features in the urban context, location and functionality (Blad et al., 2022; Enbel-Yan & Leonard, 2012; Rongen et al., 2022; Roukouni et al., 2023). According to their functionalities, hubs can be divided into three types: (1) Home-end; (2) Activity-end; (3) Transfer, which is shown in Figure 2.3.

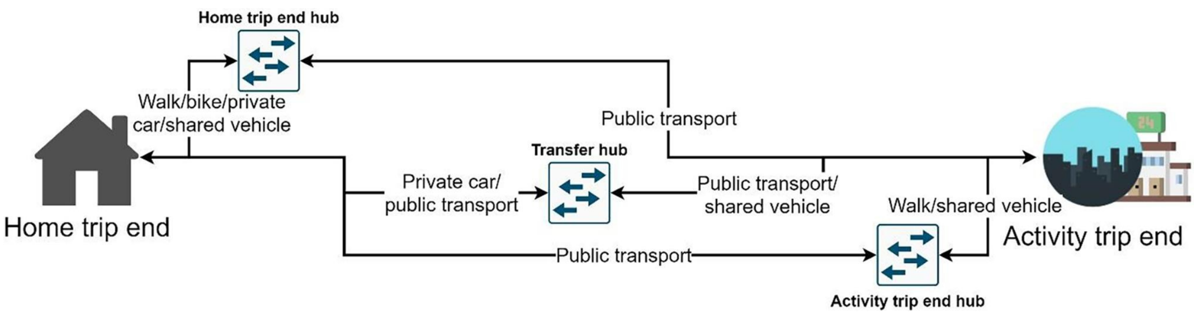



**Figure 2.3:** Multimodal Trips in Hubs: From Blad et al. (2022)

Four types of travel demand models have been distinguished by Vovsha (2019): (1) aggregate trip-based models, (2) aggregate tour-based models, (3) disaggregate activity-based models

(ABMs) and disaggregate agent-based models (AgBMs). As multimodal modelling is mainly investigated from the trip-based perspective, two commonly used models that can be used to handle the complexity of multimodal trip were summarised in van Eck et al. (2014): (1) pre-defined mode-chain approach and (2) supernetwork model.

In the pre-defined mode-chain approach, a set of mode-chain trips are pre-defined as additional artificial modes (Fiorenzo-Catalano, 2007). Mode choice and route choice are modelled separately, and the generalised costs of each mode chain are calculated similarly in the unimodal models. Instead of a multimodal logit choice model, a nested logit model is used because of the correlations in the mode chains. Although this approach is argued to result in implausible predictions of multimodal travel behaviour, it is popular in practice because the additional mode-chain trips can be easily incorporated into classical models and have minor computational complexity.

In the supernetwork approach, the unimodal networks are interconnected through transfer links representing the possible transfers between different modes (Fiorenzo-Catalano, 2007). Those artificial links contain information about the transfer resistance. Mode and route choice are modelled simultaneously. The supernetwork approach meets the multimodal modelling requirements mentioned in van Eck et al. (2014). However, it is little applied in practice due to the high computational time due to the need for a priori choice set generation.

### 2.3.2. Transit-Bike Integration

As public transport does not offer the flexibility in door-to-door accessibility, shared mobility services have been introduced to encourage the multimodal trips of travellers by providing flexibility in their first/last-mile segments (Rongen et al., 2022; Shaheen & Chan, 2016). Cars provide better door-to-door trips than other transport modes and thus have superior accessibility in nearly all circumstances (Martens et al., 2022; Pritchard, Stępniak, et al., 2019; Qin & Liao, 2022). Integrating bikes and transit could combine the benefits of high speed of transit and high accessibility for short first/last mile trips, which makes it promising to compete with the car (Tavassoli & Tamannaei, 2020). Therefore, implementing multimodal hubs is gaining popularity to improve travellers' accessibility and potentially promote the transport system's equity (Arseneault, 2022; CoMoUK, 2019; Frank et al., 2021; K. Geurs et al., 2022). Compared to the existing Park + Ride (P+R) facilities that mainly benefit people who already have a car, integrating shared bikes with transit stations could be an effective intervention for people without car access.

Some research has already investigated the impacts of the integration of bike and transit on accessibility and equity using different measurements. One typical result is that integrating transit and bike could be beneficial in improving accessibility, as well as equity of transport systems (Boarnet et al., 2017; K. T. Geurs et al., 2016; Pritchard, Stępniak, et al., 2019; Pritchard, Tomasiello, et al., 2019; Qin & Liao, 2022; Wang et al., 2022; Zuo et al., 2020). However, integrating transit and cycling cannot compete with superior accessibility by car even though they can make more opportunities accessible than walking as the access or egress mode (Pritchard, Stępniak, et al., 2019; Pritchard, Tomasiello, et al., 2019; Qin & Liao, 2022). Another argumentation is that bicycle-train integration policies are more effective in improving job accessibility than increasing the frequency of transit (Boarnet et al., 2017; K. T. Geurs et al., 2016).

Table 2.4 provides a summary of the important elements in the transit-bike integration impacts analysis, which helps identify research gaps related to accessibility and equity. Firstly, the sufficientarian principle has not been applied to the equity assessment of transit-bike integration. Secondly, the impacts of providing bikes as an egress mode of transit have not been specially explored. Thirdly, Bikes are often roughly modelled as the access or egress mode by replacing the travel distance of walking to cycling and are assumed to be possible for transferring at each zone, which is not the case in reality. Fourthly, except for (Boarnet et al., 2017; Zuo et al., 2020), most literature ignores the heterogeneity among different population groups, which would affect the result of equity assessment (Curl, 2018; Pot et al., 2023; Ryan & Pereira, 2021). Last but not least, when it comes to employment, competition effects need to be taken into account, which was only carried out by (Boarnet et al., 2017). More detailed relevant literature about transit and bike can be found in Kosmidis and Müller-Eie (2023).

**Table 2.4:** Literature Review of Impacts of Transit-Bike Integration on Accessibility and Equity

| Bike as Access/Egress | Accessibility Measure | Equity Measure | Individual Component | Opportunity | Temporal | Literature |
|---|---|---|---|---|---|---|
| Access | Space–time accessibility | Gini Index and 20:20 ratio | None | shopping and leisure | All hours of the day | Qin and Liao (2022) |
| Both | Isochronic measure | Gini index | None | Jobs | None | Wang et al. (2022) |
| Both | Isochronic measure | Theil, Atkinson and RMD indexes | Race and Income | Jobs | None | Zuo et al. (2020) |
| Access | Gravity-based measure | Gini index and Lorenz curve | None | Jobs | All hours of the day | Pritchard, Tomasiello, et al. (2019) |
| Access | Gravity-based measure | Gini index and Lorenz curve | None | Jobs | All hours of the day | Pritchard, Stępniak, et al. (2019) |
| Both | Isochronic measure | None | Low-income | Jobs | None | Boarnet et al. (2017) |
| Both | Gravity-based measure | None | None | Jobs | None | K. T. Geurs et al. (2016) |

## 2.3.3. Bike Sharing System at the Egress-side

In the Netherlands, using a bike at the activity-end trips is less popular than the home-end trips, as shown in Figure 2.4. On the home-end side, bikes are used as first/last mile trips for 43% of all train trips and much lower (11%) on the activity-end side. It can be explained by the fact that bikes are less available at the stations for activity-end trips (Brand et al., 2017; Mathijs de Haas, 2020; Shelat et al., 2018). Furthermore, bikes are used for around 11% of all bus, tram or metro (BTM) trips on the home side and only 2% of all trips on the activity side. The reason behind this is that the distances from BTM to homes or destinations are usually within walking distance (Brand et al., 2017; Mathijs de Haas, 2020). In addition, Shelat et al. (2018) showed that transit users are willing to travel smaller egress distances from transit stations (0.7km for BTM & 2.7km for Train) than the access distances to stations (1.5km for BTM & 4km for Train). Furthermore, with higher transit service quality (frequency or speed), travellers are willing to travel further (Brand et al., 2017; Shelat et al., 2018).

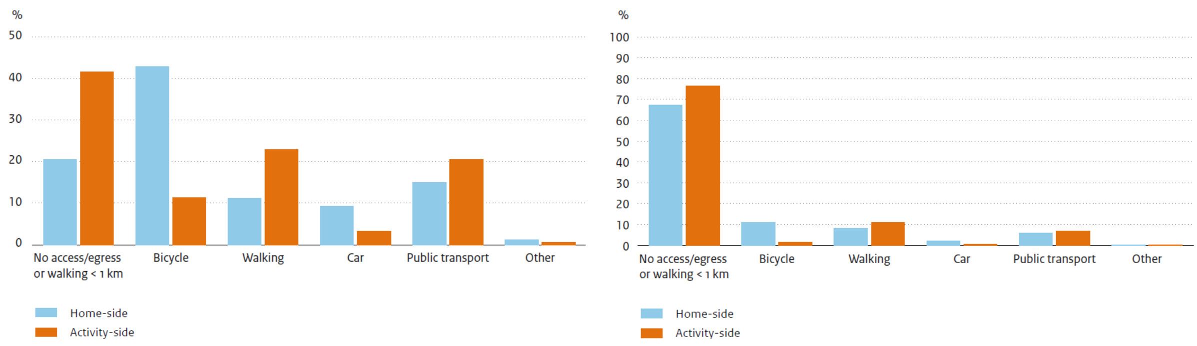



**Figure 2.4:** Access-Egress Transport for Train Trips (Left) and Bus-Tram-Metro (Right) on the Home- and Activity-side. From Mathijs de Haas (2020)

There are three ways to use bikes as the egress mode of public transport: (1) Park a private bike at the transit station near the destination; (2) Take a private (folding) bike along with the transit trip; (3) Use shared bikes. For the first way, a second private bike is needed if travellers also use a bike as the access mode to transit, which increases the monetary costs of buying an extra bike. Also, it may result in capability problems for the parking facilities, increasing access time. For the second way, bikes can only be carried in the designated bicycle carriage of the NS train with an extra charge. Meanwhile, taking bicycles is not permitted during peak hours, which is unsuitable for commuters. Even though a folding bike can be taken on the train free of charge (NS, 2023b), it takes up certain space and brings inconvenience, especially during peak hours. Therefore, there is a large potential for shared bikes to be provided at the transit stations to help travellers' first/last miles on the activity side.

Bike-sharing systems are always classified into two types based on their return forms: station-based (docked) and free-floating (dockless). A station-based sharing model can offer one-way (Back to one) or round-trip access (Back to many) (Environment, 2023; Machado et al., 2018). Unlike station-based round-trip, which requires the users to return bikes to the same pick-up location, one-way sharing models allow users to return bikes at other locations provided by the service company. By contrast, users can park their bikes at any location within the service coverage area using a free-floating system. An example of a station-based round-trip bike-sharing system is shared bikes "OV-fiets" provided by the Dutch Railway operator (NS), which can be rented at over 300 stations in the Netherlands (NS, 2023a). The return form of "Cargoroo" is the same as "OV-fiets" (cargoroo, 2023), but "Cargoroo" are electric bicycles and equipped especially with a box that goods or kids can be carried inside. Another famous bike-sharing company is "Donkey Republic", users must return the bikes to one of the drop-off locations (Republic, 2023). Furthermore, one popular free-floating e-bike sharing system is "GO Sharing", where users can park the bikes anywhere within the service area (Sharing, 2023).

Although implementing multimodal hubs, including shared mobility, is gaining popularity in recent years as it can improve travellers' accessibility by seamlessly integrating different modes and potentially promote the transport system's equity (Arseneault, 2022; CoMoUK, 2019; Frank et al., 2021; K. Geurs et al., 2022). However, the debates about the relation between public transport and shared mobility have been discussed extensively (Kong et al., 2020; Montes et al., 2023). Some researchers argued that shared mobility could complement public transport as it offers more flexibility for door-to-door trips and increases the coverage of public transport service, but only in low-density areas. However, some researchers argued that shared mobility would replace bus trips as short trips will be replaced by bikes as their lower price and travel time (Leth et al., 2017). Therefore, the synergy between public transport and shared mobility is important in order to guarantee the distribution of the benefits to the target groups.

## 2.4. Job Accessibility

This section will discuss the equity principle, influencing factors, and shared bike-transit integration in relation to job accessibility based on the first three sub-research questions.

### 2.4.1. Equity Principle for Job Accessibility

**Sub-research question 1:** What is the most suitable principle to define an equitable distribution in relation to job accessibility?

Several aspects can explain the popularity of using job accessibility as the equity indicator. Firstly, access to jobs is one of the most important activities in individuals' daily lives, and commuters are the main consumers of transport services. However, most people are not free to choose their employment locations, which means their ability to reach their workplaces is largely determined by their access to transportation systems. Secondly, scientific research has revealed a positive relationship between job accessibility and the possibility that a person can find a job (Bastiaanssen et al., 2020), which means that higher levels of job accessibility will increase employment probabilities. Last but not least, the data about employment distribution is available and reliable. Therefore, this thesis focuses on job accessibility as the indicator for transport equity analysis, but other types of opportunities can also be equally applied.

Equity principles have been well established in various domains like health care, education and housing (González et al., 2022; Jeekel & Martens, 2017; Martens et al., 2019). Equity principles are typically egalitarian in domains like healthcare and education. Although housing and mobility/accessibility share certain similarities as both heavily rely on the free market to provide services (Martens, 2016). However, there are significant differences between the organisation of the provision, the guiding principles, and the government policies of housing and mobility (Jeekel & Martens, 2017). It has only become a popular topic in transportation, and there is still a debate about which equity principle should be used as a guideline. Therefore, a unique sphere of equity assessment can be built specifically for the transport industry.

Achieving equality in accessibility is not as straightforward as in education and healthcare, as accessibility cannot be entirely equal for everyone (Martens, 2016). Among the equity theories, if a transport policy is directed at reducing inequalities, the egalitarianism principle can potentially measure this through a quantitative index. However, the egalitarian index only measures the level of equity and cannot identify the groups at risk of social exclusion (Lucas et al., 2016). Similarly, Martens (2016) argued that egalitarianism in disparity analysis could be problematic as it does not indicate whether people are provided with a basic level of accessibility that enables them to participate in society fully. Therefore, simply minimizing disparities does not guarantee that everyone receives a basic level of accessibility. In other words, a transport system that is regarded as equitable from an egalitarian approach may still leave most of the population in an area with insufficient accessibility. Therefore, a sufficientarianism approach is more suitable, which ensures that everyone is provided with a basic level of accessibility to reach their key activities.

### 2.4.2. Influencing Factors of Perceptions in Job Accessibility

**Sub-research question 2:** What influencing factors are relevant in individuals' perceptions in job accessibility?

Based on the literature review of perceived accessibility in 2.2.4, relevant influencing factors that contribute to unequal distribution of job opportunities will be explained from the perspective of land use, transportation, temporal and individuals in the context of transit and shared bike integration.

**Transport Component**
Regarding the influencing factors of perceptions in accessibility, (Pot et al., 2021) concluded perception of transport supply and perception of travel resistance. Transport supply refers to individuals' awareness of transport modes and possible routes to a considered activity location. For travel resistance, factors like comfort, costs, safety and convenience are suggested to be taken into account in generalised transport costs. As monetary expenses are often regarded as a major barrier limiting people's access to their desired destinations, Many researchers have addressed the importance of taking into account traveller's affordability as a component of resistance with travel time (El-Geneidy et al., 2016; Jamei et al., 2022; Ryan & Pereira, 2021). However, the travel time is often easy to measure, but it is difficult to quantify user's different perceptions of the time value of costs. Additionally, the impact of functionality and service quality of public transport systems on individuals' perception of accessibility have been emphasised by Friman et al. (2020) and Jamei et al. (2022). Moreover, several researchers have pointed out that the safe feeling of travellers plays a significant role in the perception of accessibility (Friman et al., 2020; van der Vlugt et al., 2019), which might be more important than public transport cost.

**Land use Component**
For land-use-related factors, the characteristics of employment distribution would have an impact (Pot et al., 2021). Furthermore, jobs are often argued as scarce resources, which represents it has competition effects. Even though one region has a dense distribution of employment, job accessibility might still be low as more people are going to this region, which may reduce the possibility of being employed because of competition effects. Therefore, job accessibility will be overestimated without taking competition effects into account.

**Individual Component**
Accessing a specific job does not only mean physical access by the transportation system but also relates to a person's capability. Suppose most jobs are densely distributed but specially

matched for groups with high education levels. In that case, even though these employments might be easy to reach, it is not perceived as accessible opportunities for groups who are less educated. Therefore, accessibility for low-income groups is often overestimated if we do not consider the competence of different groups.

The most important factors in relation to individuals' perceptions of accessibility are their socio-economic and demographic characteristics. For travellers, mode availability restricts their choice and thus influences their accessibility. Additionally, different people have different income levels and thus have different values of time and cost, resulting in different experienced travel times for a trip. Furthermore, different people have different preferences. If someone prefers walking, providing bike service does not help them as they would not be willing to use it even though it is beneficial. Some other factors are also correlated, like physical ability and people's social networks.

**Temporal Component**
For temporal factors that affect access to opportunities, not only time constraints of the activity locations matter but also the time availability of the individuals (Pot et al., 2021). Job accessibility has a weak correlation with the time availability of a person as the working time is often regularly fixed. At the same time, it is also largely related to the job nature for a specific group as it determines the travelling period and thus will experience different transportation systems. Therefore, temporal heterogeneity exists among different individuals based on their employment characteristics.

### 2.4.3. Measure of Perceived Job Accessibility

**Sub Research Question 3:** Which accessibility measure will be applied to include individuals' perceptions to make a more realistic estimate of equity in job accessibility?

As each accessibility measure has its strengths and weaknesses, selecting the most appropriate measure based on the research objectives is important. As this study aims at analysing equity for population groups rather than locations, it is ideal to take individuals' perceptions of accessibility into account as much as possible to make a more realistic and accurate estimate of accessibility, resulting in a better impact evaluation of transport interventions on equity.

Four accessibility measures have been distinguished by K. T. Geurs and Van Wee (2004): infrastructure-based, location-based, person-based, and utility-based. Infrastructure-based accessibility measures do not include land use, temporal and individual components, thus not suitable for analysis of equity in accessibility. Location-based measures have been most applied in literature as they are easy to implement and interpret. However, one of the biggest criticisms of this measure is that heterogeneity among groups is often aggregated, resulting in people from the same zone having the same accessibility. Nonetheless, individuals' perceptions can be incorporated in gravity-based measures using a travel time decay function, but it is difficult to determine the shape of the function, which would involve many assumptions (Pot et al., 2021). Meanwhile, gravity-based measures can include the competition effects.

Person-based measures determine the accessibility at the individual level using space-time prisms. Information on activity locations and individual activity schedules throughout the day are needed (Fransen & Farber, 2019), resulting in highly complex data computations. Additionally, person-based measures do not account for competition effects and thus are less suitable for the analysis of opportunities with intense competition, like employment. Utility-based measures are directly derived from travel behaviour theory, so there is no need to make prior assumptions on the representative of the individual perceptions. Therefore, utility-based measures are theoretically the most appropriate to reflect a person's perception and evaluate the benefits individuals derive from transport interventions. However, this measure cannot be easily interpreted and implemented without detailed data. Moreover, Pot et al. (2021) pointed out that expected utility rather than experienced utility will be measured in utility-based measures if data are from stated preferences, while benefits of interventions in the short term might be overestimated because individuals cannot aware of the change initially if data are from revealed preferences.

This thesis will apply a more general gravity-based measure, which has been implemented into the IKOB model (Voerknecht, 2021) to the research context. The IKOB model is able to generate a more realistic estimation of job accessibility by incorporating individuals' perceptions. Although not all influencing factors are considered, more than other location-based measures have been applied in the literature. Firstly, the IKOB model includes competition effects of employment and rewards proximity by using the travel decay function to represent the perception of activity locations. Secondly, the IKOB model distinguishes the type of employment into different income levels to indicate that some jobs can only be accessible to individuals with the required education and skills. Thirdly, the IKOB model takes into account temporal components during three time periods: morning peak, rest of the day and evening peak. Fourthly, individuals' perceptions of monetary travel cost for each income class group are included in the experienced travel time. Lastly, the IKOB model classifies population groups based on income level, car ownership, and mode preferences. The difference in perceived accessibility is reflected by constructing the travel time decay function for each group.

## 2.5. Summary

This chapter shows the relevant research in the domains of equity, accessibility and transit-bike integration to select and justify the elements in the analysis of equity in job accessibility in terms of equity principle and accessibility measure. Meanwhile, the first three sub-research questions are answered, which provides a theoretical basis for the research methodology.

Firstly, sufficientarianism is argued as a more appropriate theory than egalitarianism to evaluate the level of equity in this thesis. As this study focuses on equity in job accessibility between groups with/without car access, it is important to identify the group experiencing accessibility inequity and how this group contributes to the overall severity of accessibility inequity. However, utilitarianism does not take into account the distribution effects, and the egalitarian indies only measure the level of equity and fail to identify the groups at risk of social exclusion (Lucas et al., 2016). Additionally, egalitarianism often neglects the heterogeneity within the aggregated groups, a transport system might be regarded as equitable using an egalitarian approach, but most people in that area still have insufficient accessibility to reach the desired opportunities (Martens et al., 2022).

Secondly, job accessibility is selected as the indicator of equity as access to jobs is one of the most important activities in individuals' daily lives, and commuters are the main consumers of transport services. However, most people do not have much freedom in choosing their workplaces so that transport systems largely determine their accessibility. When calculating job accessibility, the heterogeneity among individuals and their perceptions of job accessibility are often ignored, which results in an unrealistic estimation of the severity of accessibility inequity for disadvantaged groups. The influencing factors that relate to individuals' perceptions of job accessibility are classified into transport, land use, and individual and temporal components. Some factors are easy to incorporate as the characteristics are observable, so this data type is easy to measure. However, some subjective factors are more difficult to take into account because of the complexity of observing and measuring. These factors are always derived from the stated preference survey or interview, and some assumptions should be made to reflect the actual travel behaviour.

Thirdly, utility-based measures are argued to be more suitable than other measures to estimate accessibility as they can directly reflect an individual's travel behaviour, and there is no need to make prior estimations. However, this measure cannot be easily interpreted and implemented without detailed data. Therefore, this thesis will apply gravity-based accessibility in the IKOB model to calculate accessibility. Firstly, perceptions of employment are represented in a travel time decay curve, which gives less weight to the further away locations. Secondly, competition effects are included. Additionally, the type of employment links to income class, which determines whether individuals are competent to access them. Moreover, travel decay curves are constructed based on differences of individuals in income class, car ownership and mode preference to reflect their behaviour. Even though some other important factors are not included in this model, it can offer a more realistic estimation than other location-based measures that have been applied in the literature.

Lastly, In order to investigate how shared bikes provided at transit stations as egress mode would impact equity in job accessibility. This chapter reviewed the relevant literature in relation to transit-shared bike integration and equity in job accessibility, and identified the research gaps in this topic. A brief summary of the key findings and research gaps about transit-shared bike integration based on the literature review is as follows:

1. Most literature simply assumes homogeneous characteristics among different individuals, influencing factors of perceptions in land use, transport, temporal and individual components are not taken into account, especially the individual components.

2. There are no scientific studies specifically looking at the impacts of shared bikes as egress modes at transit stations on equity in job accessibility. Additionally, transit-shared bike integration is often roughly modelled by assuming that it is possible for transfer in all areas, which is not the case in reality.

3. To the author's best knowledge, no literature uses the sufficientarianism principle to assess the impacts of transit-bike integration on equity in job accessibility.

# 3

# Methodology for Equity Assessment

## 3.1. Introduction

To assess the impacts of transit-shared bike integration on equity in job accessibility, the approach proposed by Martens (2016) will be applied as the guideline for equity evaluation. This methodology will be performed to assess the level of accessibility fairness in each neighbourhood and the contribution of different commuters to the overall accessibility deficiency. Additionally, the IKOB model proposed by Voerknecht (2021) will be adapted to the context of transit-shared bike integration and calculate the perceived accessibility for different subgroups.

### 3.1.1. IKOB Model

Integrale Kijk Op Bereikbaarheid (IKOB) model was proposed by Voerknecht (2021) based on theoretical accessibility of Hansen (1959) and Levinson and Wu (2020). The IKOB model can calculate job accessibility with consideration of an individual's characteristics, income level, mode preferences and car ownership. These influencing factors play an important role in people's perceived accessibility. Moreover, all combinations of transport modes are modelled through a super network, where the unimodal networks are interconnected through transfer links (Fiorenzo-Catalano, 2007). Therefore, it can be used to analyse the impacts of transit-shared bike integration on accessibility and social equity. The IKOB model has several advantages compared to traditional models:

1. Firstly, instead of one generalised measure, the IKOB model calculates perceived accessibility by distinguishing different groups based on their heterogeneity in car ownership, mode preference, and income level. Furthermore, the matching of jobs for different groups has been classified based on income, class, and education level.

2. Secondly, using the travel time decay curve, the IKOB model considers the rewards of the destination's proximity. It can overcome the limitation of border effects in the isochrone accessibility measure. More importantly, travel time decay curves are constructed for different transport modes and mode preferences to reflect individuals' heterogeneity in perceived accessibility better.

3. Thirdly, the IKOB model could take into account the effect of competition within the demand when calculating perceived accessibility, which is suitable for the analysis of opportunities with competition.

4. Lastly, the IKOB model includes multiple chain trips through super-network rather than traditional single modality. The accessibility benefits of multimodalities can be fully included in the IKOB model, which is not considered in conventional models.

The perceived accessibility calculation in the IKOB model is summarised into five steps: (1) Groups Distribution; (2) Experienced Travel Time; (3) Weights for Unimodal and Multimodal Options; (4) Potential Accessibility; (5) Competition Effects. Figure 3.1 illustrates the overview of steps, and the algorithm in each step will be explained in the following subsections.

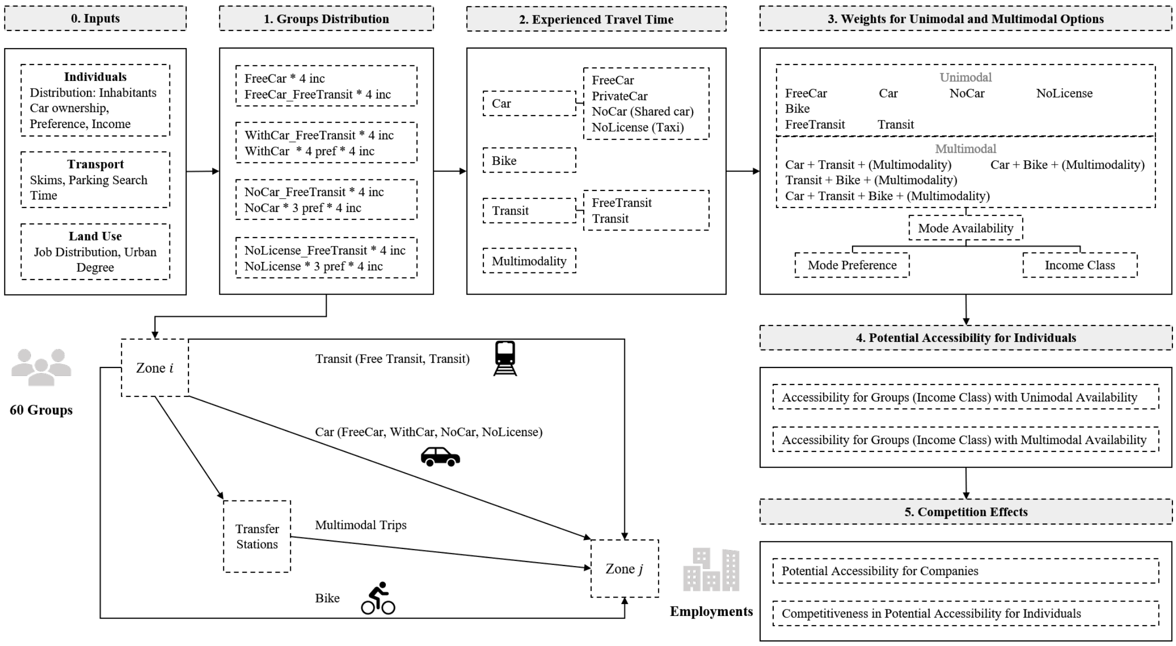



**Figure 3.1:** Steps Overview of the IKOB Model

## 3.1.2. Sufficientarian Approach

The concept of incorporating fairness into transport planning has been underpinned by both theoretical and practical perspectives in Karel Martens's Book "Transport Justice: Designing Fair Transport Systems" (Martens, 2016). Instead of disparity analysis, Karel Martens argued that transportation justice is about providing everyone with sufficient accessibility under most circumstances, irrespective of the differences. In order to complement accessibility measurement with an indicator that can only indicate the contribution of the transport component to accessibility, Karel Martens developed a new analytical framework based on accessibility and **Potential Mobility Index (PMI)**, which is the ratio of the Euclidean distance and the travel time on the transport network between origin and destination. PMI is suitable for determining the contribution of the transportation system to accessibility as it captures the impact of both speeds on the links of the transport network, as well as the network structure.

Except for identifying groups who are experiencing accessibility insufficiency, Karel Martens also proposed an index **Accessibility Fairness Index (AFI)** to represent the level of fairness of the transport system in a region. It is also possible to determine the contribution of each population group to the overall level of accessibility deficiency, which can help policymakers prioritise the groups experiencing the most accessibility insufficiency. Other researchers have also practised this methodology and confirmed its applicability in identifying groups suffering from unfair accessibility (van der Veen et al., 2020; Zweers, 2023). Since the sufficientarian approach allows comparing different population groups, this methodology is suitable in this thesis to investigate the impacts of transit-shared bike integration on different commuters. The sufficientarian approach has ten steps, shown in Figure 3.2.

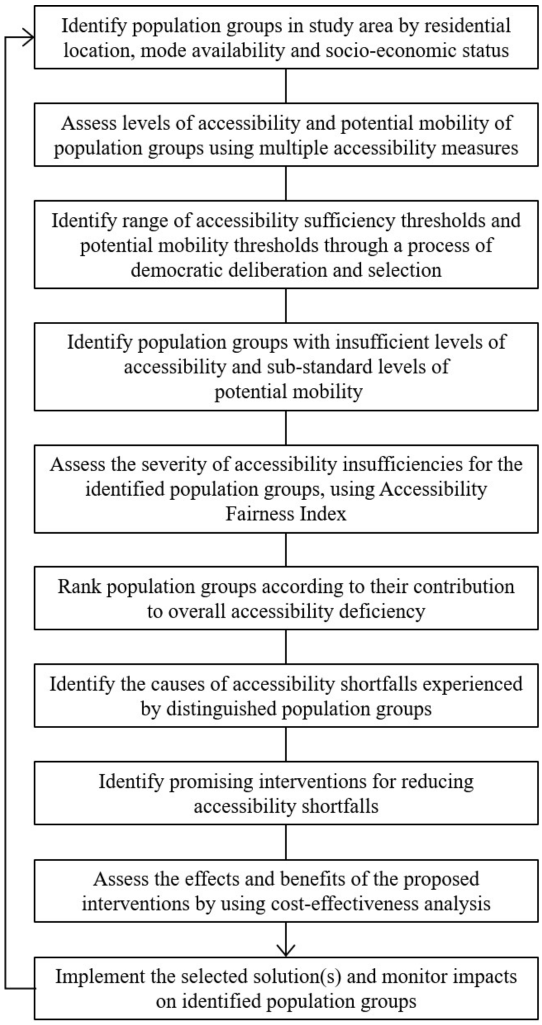



**Figure 3.2:** The Rules of Transport Planning Based on Principles of Justice: From Martens (2016)

This research will not include the last step, which is to implement the solutions and monitor their impacts on identified population groups. In addition, this research will only use one gravity-based accessibility rather than using multiple accessibility measures. Furthermore, the impacts of interventions on equity in job accessibility will be assessed rather than conducting the cost-effectiveness analysis. Finally, instead of democratic deliberation and selection, a more pragmatic approach by using descriptive statistics will be applied based on the population-weighted average accessibility and PMI for the whole networks. As some steps are highly correlated in the evaluation framework, steps 2 to 6 and steps 7 to 8 will be combined into one step. Afterwards, all steps are organised into four phases: (1) Differentiate the population groups; (2) Identify the severity of accessibility insufficiency and the contribution to overall accessibility deficiency for different population groups. (3) Identify the causes of accessibility shortfalls and propose interventions. (4) Evaluate the impacts of the proposed interventions. Among the steps, the distribution of population groups and accessibility calculation will be carried out using the IKOB model.

### 3.1.3. Methodology Steps

The following sections will explain the details of these two methodologies, respectively, and the required data will be summarised. The three steps for the impacts evaluation of transit-shared bike integration on equity in job accessibility are illustrated in Figure 3.3.

1. Firstly, the context of a shared bike as an egress mode at the transit stations will be modelled firstly using a separate algorithm in the IKOB model Voerknecht (2021). The renting costs and the locations where users can shift from transit to shared bikes will be modelled. Also, a route choice algorithm assumes all users will choose the hubs that provide the minimum travel time between origins and destinations will be applied.

2. Secondly, the IKOB model proposed by Voerknecht (2021) will be adapted to calculate accessibility for different subgroups within different scenarios. For the purpose of this thesis, groups will be classified into with/without car access only based on their car ownership. Then, experienced travel time, including pure travel time and travel costs, is calculated for a certain group with different income classes by a certain transport mode, including transit-shared bike integration. Next, the single weight from origins and destinations will be determined by the travel time decay curve function with consideration of individual's mode preferences, and the combined weight will be calculated to represent the mode choice for the different subgroups from each origin to destination based on their mode availability. For each origin and destination, accessibility for a certain group (income level, mode availability, mode preferences) takes the mode that provides maximum weight across each mode, and then accessibility for a group will be weighted based on its population to represent the average. Therefore, the final output files of the IKOB model are the perceived accessibility for the two distinguished groups with different income levels.

3. Finally, approach proposed by Martens (2016) will be applied as the guideline for equity evaluation. The PMI will be calculated using the Euclidean distance between each origin and destination and pure travel time by a specific mode. Then, thresholds of potential accessibility and potential mobility will be decided based on population-weighted average accessibility and mobility for the whole network. Population groups with lower accessibility than the thresholds indicate they suffer from accessibility insufficiency. The Accessibility Fairness Index will indicate the severity of accessibility deficiency. In the end, the contribution to the overall level of accessibility insufficiency for different groups of commuters will be determined.

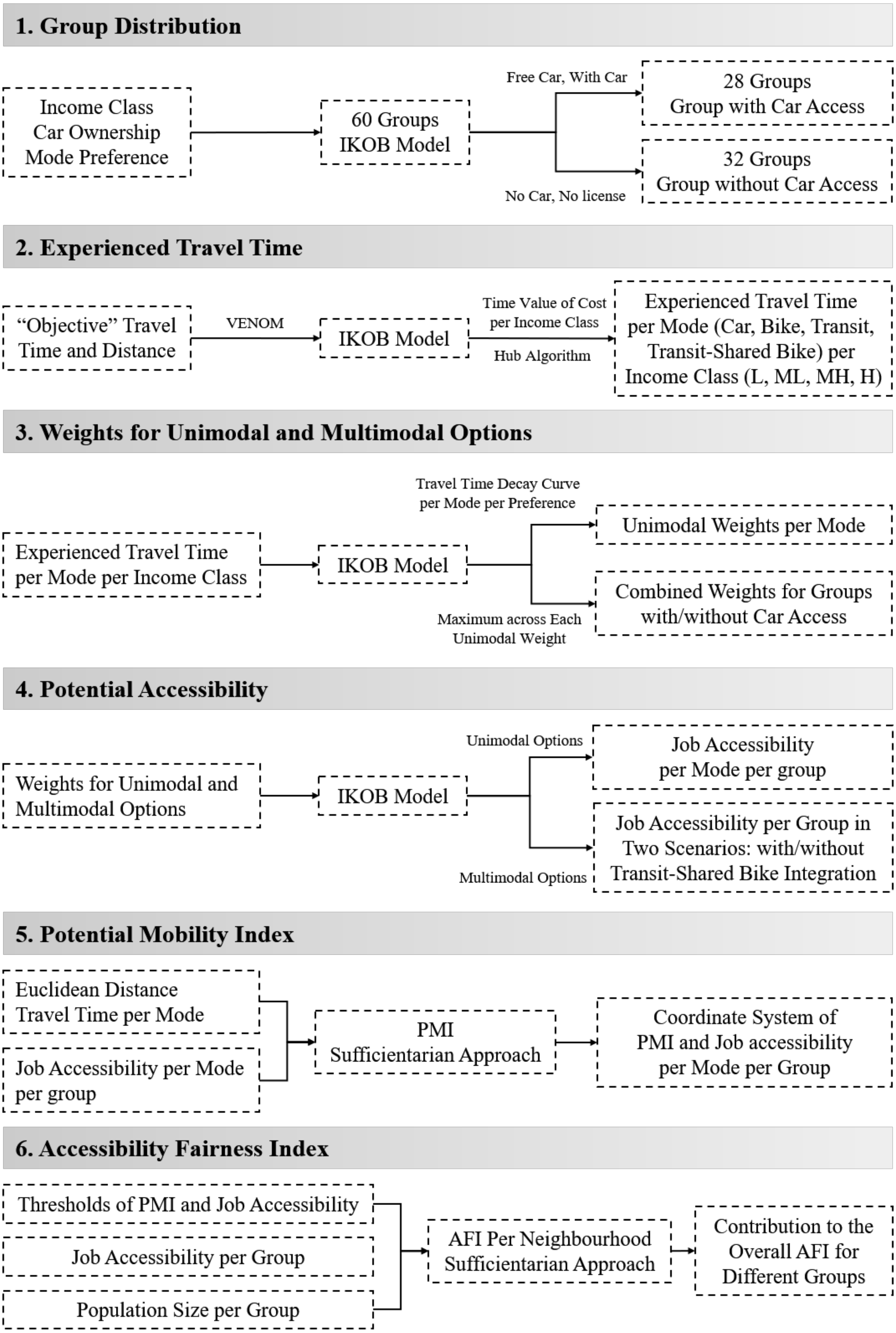



**Figure 3.3:** Research Methodology for Assessment of Equity in Job Accessibility

## 3.2. Accessibility Calculation: IKOB Model

### 3.2.1. Transit-Shared Bike Integration Modelling

This sections explains the calculation method of the "pure" travel time of door-to-door trips by transit-shared bike integration and the route (transfer stations with shared bikes) choice. The total travel time has several components: (1) Pre-transit time (Walking); (2) Transfer time; (3) Waiting time; (4) In-vehicle time (Transit) and (5) Post-transit time (Shared bike), which is shown in Equation 3.2 and Figure 3.4. In the context of transit-shared bike integration, exit stations belongs to a set of public transport stations where integrates shared bikes. The route choice is based on one of the transit stations that gives travellers the minimum total travel time.

$$R_{hbou,transitbike} = VT_{ho} + T_o + T_{ou,invehicletime} + W + T_u + NT_{ubsharedbike} \tag{3.1}$$

Where $R_{hbtransitbike}$ denotes the "pure" door-to-door travel time between origin $h$ and destination $b$, passing by boarding transit stop $o$ and exit station $u$ with transit-shared bike integration; $VT_{ho}$ is the transit pre-transportation time from origin $h$ to boarding stop $o$; $T_o$ is Transfer time on boarding station $o$; $T_{oh,invehicletime}$ is the travel time in the vehicle between origin $o$ and destination $h$; $W$ is the waiting time due to transfers; $T_u$ is the transfer time from transit to shared bikes at exit station $u$; $NT_{ub}$ is the transit post-transportation time from exit station $u$ to destination $b$;

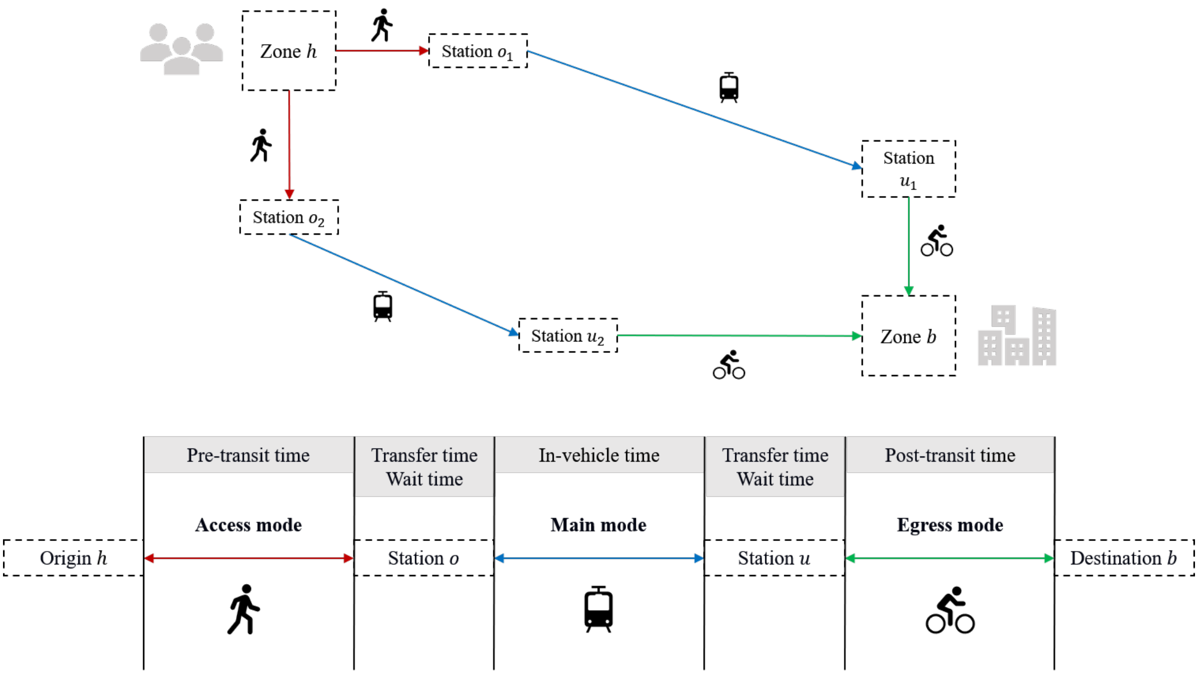



**Figure 3.4:** Simple Representation of Route Choice and Travel Time for Transit-Bike Integration

The minimum total travel time among all of the pre-defined transfer stations with shared bikes:

$$R_{hbou*,transitbike} = min(R_{hbou,transitbike}) \tag{3.2}$$

Where transfer stations $u$ belongs to U, a set of stations where integrates shared bikes; $u^*$ is the transit station that gives travellers the minimum total travel time.

The in-vehicle travel distance of the transit part$A_{hbou^*,invehicledistance}$ by transit-shared bike integration is then calculated:

$$A_{hbou*,invehicledistance} = A_{hbou*,invehicledistance} \tag{3.3}$$

### 3.2.2. Groups Distribution

Population are classified into 60 groups in the IKOB model based on their car ownership, gratis public transport, income class and mode preferences, which is shown in Figure 3.5.

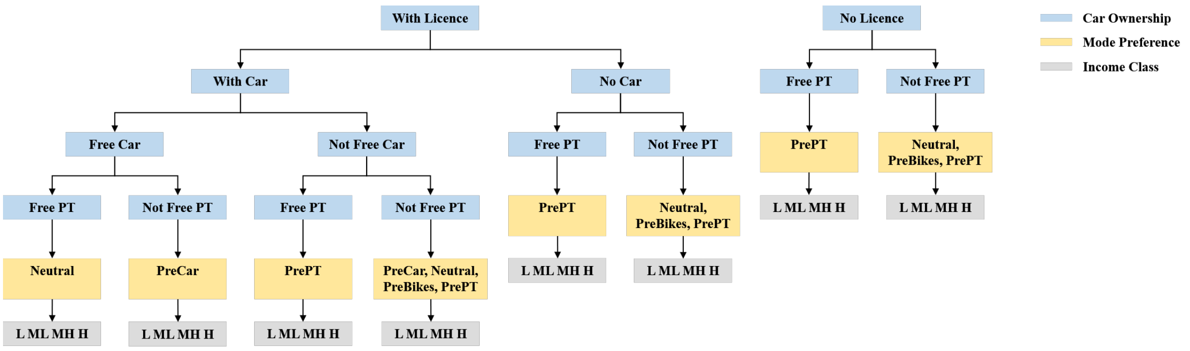



**Figure 3.5:** Overview of Groups Distribution in the IKOB Model

Car ownership includes four groups: (1) FreeCar (Company car); (2) WithCar (Private-owned Car); (3) NoCar (Without private-owned car but with a driving license); (4) Nolicense (Without driving license), and public transport has 2 groups: (1) FreePT; (2) Not FreePT. 8 groups (4*2) are firstly classified by combining car ownership and public transport.

The decision rule for preference divides groups into 15: (1) For groups of No Car and No License, they do not have a preference for a car; (2) For groups of No Car and No License, but Free Transit, their preference is transit; (3) For groups of Free Car and Free Transit, their preference is neutral; (4) For groups of Free Car without free transit, their preference is car; (5) For groups with free transit and without free car, their preference is transit.

In the end, groups are distributed into 60 (15*4) based on four income classes (low, middle low, midlle high, high).

This thesis focuses explicitly on how providing shared bikes at the transit station as an egress mode would benefit commuters with and without car access. Therefore, the question of what it means to have no car access should be answered. It is a debatable topic as travellers who do not have a driving license can still take a taxi, and travellers who do not own a car but have a driving license can use shared vehicles. This especially makes sense to the groups with the affordability of these transport services, as their ability to access ”car” is not restricted. However, in the context of job accessibility, it is not likely for commuters to take shared cars or taxis on a daily basis. Therefore, it is reasonable to make the simplifying assumption that the groups with/without car ownership are only determined by their car ownership. The adapted distribution for groups with/without car access is shown in Figure 3.6.

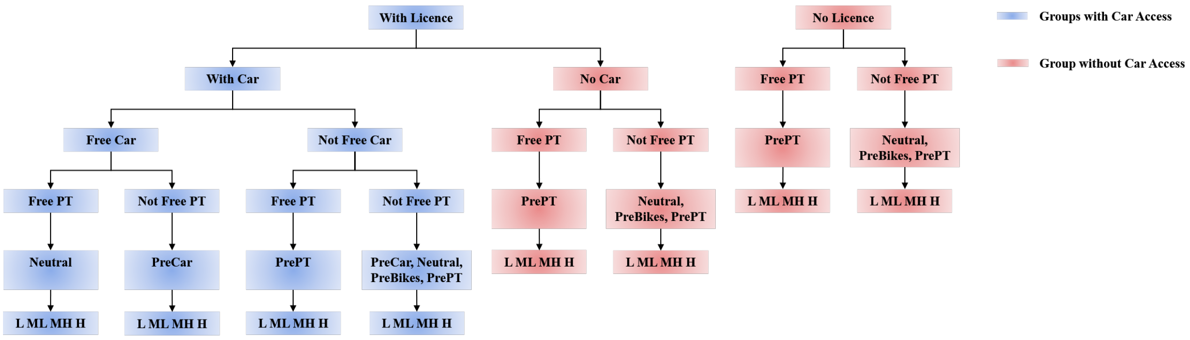



**Figure 3.6:** Overview of the Classified Groups with Car Access and Without Car Access in this Thesis

### Determining Income Class

The percentages of income classes per zone and the urbanisation degree of zone are derived from the CBS district and neighbourhood data.

### Determining Preferences

Preferences for transport modes per urbanisation degree for those who own a car and those who do not own a car are from OVIN and survey by the municipality of Amsterdam, which can be found in tables A.6 and A.7.

### Determining Car Ownership

The percentage of car ownership excluding Free Car and Free PT is determined on the basis of urbanisation degree and income class from CBS data, which can be found in tables tables A.1 to A.3. Percentage of population with free car per income class are accessed from Vereniging Zakelijke Rijders (Business Association in the Netherlands), which can be found in Table A.4. Percentage of people with Free PT per urbanisation degree are estimated based on NS data, and 3% is used in the IKOB Model.

The "theoretical" car ownership $AZ_{z,theor}$ (With Car), $GA_{z,theor}$ (No Car) and $GR_{z,theor}$ (No License) for each income class are calculated:

$$AZ_{z,theor} = \sum_i AZ_{si} P_{iz} \tag{3.4}$$

$$GA_{z,theor} = \sum_i GA_{si} P_{iz} \tag{3.5}$$

$$GR_{z,theor} = \sum_i GR_{si} P_{iz} \tag{3.6}$$

Where $AZ_{si}$, $GA_{si}$ and $GR_{si}$ are car ownership per urbanisation degree $s$ and income class $i$ for the three groups; $P_{iz}$ is percentage share of income class $i$ per zone $z$.

According to the CBS district and neighbourhood data, the actual number of cars per household per zones may be equal to, smaller or larger than the theoretical car ownership. If the actual number of cars per household per zone $AA_{hz}$ is smaller than theoretical car ownership $AZ_{z,theor}$, car ownership per zone $AZ_z$ equals to $AA_{hz}$. Otherwise, $AZ_z$ equals to $AZ_{z,theor}$. There, the car ownership per zone per income class $AZ_{iz}$ (With car), $GA_{iz}$ (No car) and $GR_{iz}$ (No License) are then expressed with a correction factor:

$$AZ_{iz} = \frac{AA_{hz}}{AZ_{z,theor}} * AZ_{iz,theor} \tag{3.7}$$

$$GAiz = \frac{1 - AA_{hz}}{1 - AZ_{z,theor}} * GA_{iz,theor} \tag{3.8}$$

$$GR_{iz} = \frac{1 - AA_{hz}}{1 - AZ_{z,theor}} * GR_{iz,theor} \tag{3.9}$$

The ownership of free car $GrA_{iz}$ per income class $i$ in zone $z$ is calculated:

$$GrA_{iz} = GrA_i * AZ_{iz} \tag{3.10}$$

### 3.2.3. Experienced Travel Time

The experienced travel time for a specific subgroup $g$ from origin $h$ to destination $b$ by mode $v$ includes objective travel time and subjective travel costs:

$$ER_{g_ihbv} = R_{hbv} + TVOM_i(Ktotal_{ghbv}) \tag{3.11}$$

Where $g$ represents the classified subgroup according to their car ownership, mode preference and income class. $R_{hbv}$ denotes the "pure" door-to-door travel time between origin $h$ and destination $b$ with transport modes $v$; $TVOM_i$ is the time value of costs for income class $i$; $Ktotal_{ghbv}$ is the total costs from origin $h$ to destination $b$ for subgroup $g$ with transport mode $v$.

As travel costs are perceived very differently per population group, which are converted into unit of time by multiplying the corresponding time value of costs per income class. The value of costs for commuting motive can be found in Table A.10.

**Car (FreeCar, WithCar, NoCar, NoLicense)**
For "pure" travel time of car:

$$R_{hbcar} = PZA_z + PZV_z + T_{hb,invehicletime} \tag{3.12}$$

Where $PZA_z$ and $PZV_z$ are the parking search time when arrival and departure in zone $z$; $T_{hb,invehtime}$ is the travel time in the vehicle between origin $h$ and destination $b$.

For total costs of car:

$$Ktotal_{ghbcar} = (Kcost_{g,car} + Kcharge_{g,car}) * A_{hb,invehtime} \tag{3.13}$$

Where $Kcost_{g,car}$ is the variable costs per km for subgroup $g$ with transport mode $v$; $Kcharge_{g,car}$ is the charge per minute for subgroup $g$ with transport mode $v$; $A_{hb,invehtime}$ is the distance in the vehicle between origin $h$ and destination $b$. Both variable costs and charge of the Free car are null; Variable costs of the private car is 0.16/km; Variable costs of the shared cars is 0.3/km and charge is 0.05/min; Variable costs of the taxi is 2.4/km and charge is 0.4/min.

**Walking+Transit+Walking (FreeTransit, Transit)**
Figure 3.7 shows the components of travel time of public transport, it only considers objective travel time, penalties due to individual's perceptions of waiting times are not taken into account. Additionally, cycling or walking can be set as the access and egress mode in the whole trip by transit. Walking will be used as the access and egress mode for mode "Transit" in order to make a distinction with Mode "transit-shared bike" whose egress mode is shared bike.

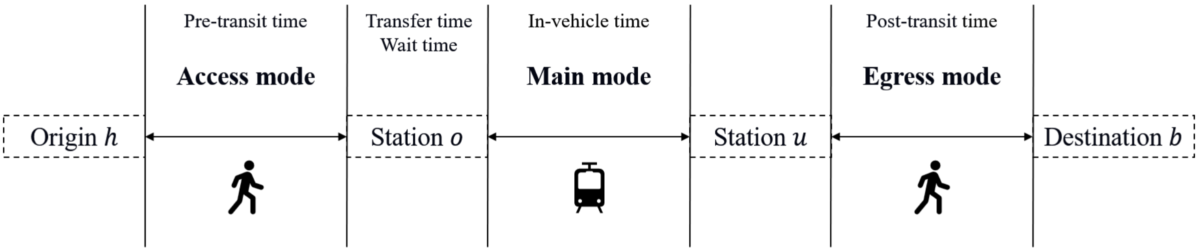



**Figure 3.7:** Components of Travel Time by Transit

For "pure" travel time of transit:

$$R_{hbtransit} = VT_{ho} + T_o + T_{ou,invehicletime} + W + NT_{ub} + T_u \tag{3.14}$$

Where $VT_{ho}$ is the transit pre-transportation time from origin $h$ to boarding stop $o$; $T_o$ is Transfer time on boarding station $o$; $T_{ou,invehicletime}$ is the travel time in the vehicle between origin $o$ and destination $u$; $W$ is the waiting time due to transfers; $NT_{ub}$ is the transit post-transportation time from exit station $u$ to destination $b$; $T_u$ is the transfer time at exit station u.

For total costs of transit:

$$Ktotal_{hbov} = Kcost_{g,ov} * A_{ou,invehdistance} + Kopstap \tag{3.15}$$

Where $Kcost_{g,transit}$ is the variable costs per km for subgroup $g$ by mode $v$; $A_{ou,invehdistance}$ is the distance between boarding stop $o$ and exit stop $u$; $Kopstap$ is the boarding rate. For groups with "FreeTransit", both of the variable costs and boarding rate are null. Otherwise, variable costs per km $Kcost_{ov}$ is 0.121 Euro/km and boarding rate $Kopstap$ is 0.75 Euro.

**Bike**
For the "pure" travel time of private bike:

$$R_{hbbike} = T_{hb,invehtime} \tag{3.16}$$

The variable costs of the bike have been set at 0.

**Walking+Transit+Shared Bike (Transit-Shared Bike Integration)**
For "pure" travel time of transit and shared bike integration, which is explained in 3.2.1. Total costs includes fee using both transit and shared bikes:

$$Ktotal_{ghbintegration} = Kcost_{g,ov} * A_{ou*,invehdistance} + Kopstap + Kcharge_{g,sharedbike} \tag{3.17}$$

Where $A_{ou*,invhedistance}$ is the distance in the vehicle between boarding stop $o$ and the transit station provides minimum travel time $u*$.

The transfer time from transit to shared bikes is set at 5 minutes. The cost of using a shared bike is set at 0, 1, 2 euro for sensitivity analysis.

### 3.2.4. Weights for Unimodal and Multimodal Options

**Weights for Unimodal Option**

In order to avoid the boundary effects in the frequently used isochrone measure, the IKOB model uses gravity-based measure rewards to the destination's proximity by using travel time decay curve. Therefore, the destinations with a shorter experienced travel time weight relatively more heavily than destinations with a longer experienced travel time.

The weight of a trip from origin $h$ to destination $b$ for subgroup $g$ (car ownership, mode preference and income class) by mode $v$ is:

$$G_{ghbv} = RTV_{pv}(ER_{ghbv}) \tag{3.18}$$

Where $RTV_{pv}$ is the decay function of preference $p$ and mode $v$; $ER_{ghbv}$ is the experienced travel time for subgroup $g$ between origin $h$ and destination $b$ with transport mode $v$.

$$RTV_{pv} = w_{pv} * (\frac{1}{1 + e^{\alpha_{pv}*(-\omega_{pv}+ER_{ghbv})}}) \tag{3.19}$$

Where $\omega_{pv}$, $\alpha_{pv}$ and $w_{pv}$ are the turning point, steepness and weighting value of decay curve of groups with preference $p$ by mode $v$.

As different individuals will have different willingness to pay for different transport modes according to their perceptions of accessibility, the travel time decay function per transport mode is constructed based on individuals' mode preferences in the IKOB model. The parameters for different groups' travel time decay curves can be found in Table A.11, and the generated travel time decay curve is illustrated in Figure 3.8.

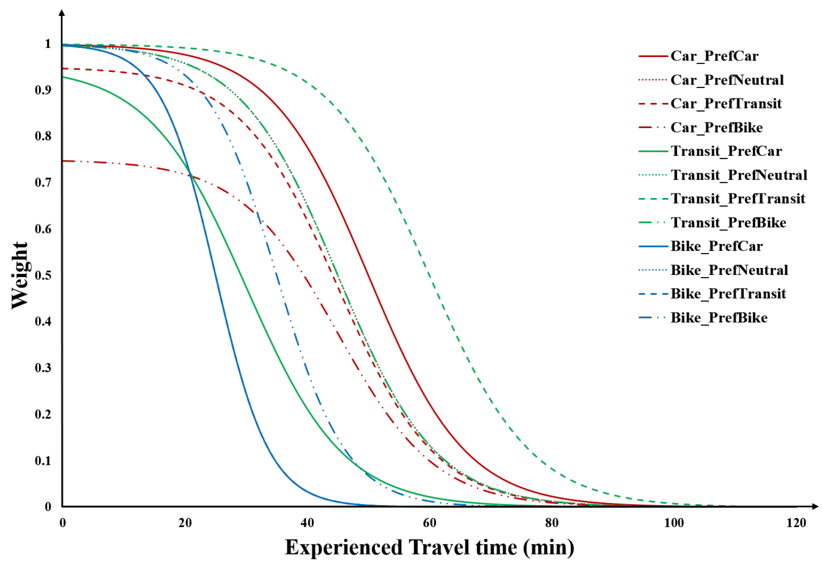



**Figure 3.8:** Travel Time Decay Curve Based on Transport Modes and Preferences

The travel time decay parameters reflect individual differences by adjusting the curve's turning point and steepness. However, these parameters are subjective and difficult to calibrate and validate without empirical data. In the IKOB model, they have been chosen based on expert judgement. In addition, the weighting factors were calibrated/validated by assessing whether the selected values would more or less reproduce the shares per target group as in the Onderzoek Verplaatsingen in Nederland (OViN, Research on Travel in the Netherlands).

**Weights for Transit-Shared Bike Integration**

In this thesis, the travel decay curve of groups using transit-shared bike integration is assumed to be equal to the transit curve as the transit is the main trip, which has a larger impact on an individual's perception. However, this simple assumption might result in an underestimate of the accessibility benefits of integrating transit and shared bikes, which is one of the methodology limitations in the thesis.

**Weights for Multimodal Options**

The maximum weight across the single transport modes per origin-destination cell will be the weights when individuals have multimodal availability. The weights for multimodal options for subgroup $g$ origin $h$ destination $b$ is expressed as follows:

$$GC_{ghb} = Max(v)G_{ghbv} \tag{3.20}$$

**Multimodal Options for Groups with/without Car Access**

For each origin-destination, mode choice for groups with/without car access is assumed as the maximum weight across their mode options. The weight is determined by the experienced travel time and the decay function for a specific group by a specific mode. The mode choice for each trip is also related to individual characteristics, which is visualised in Figure 3.9.

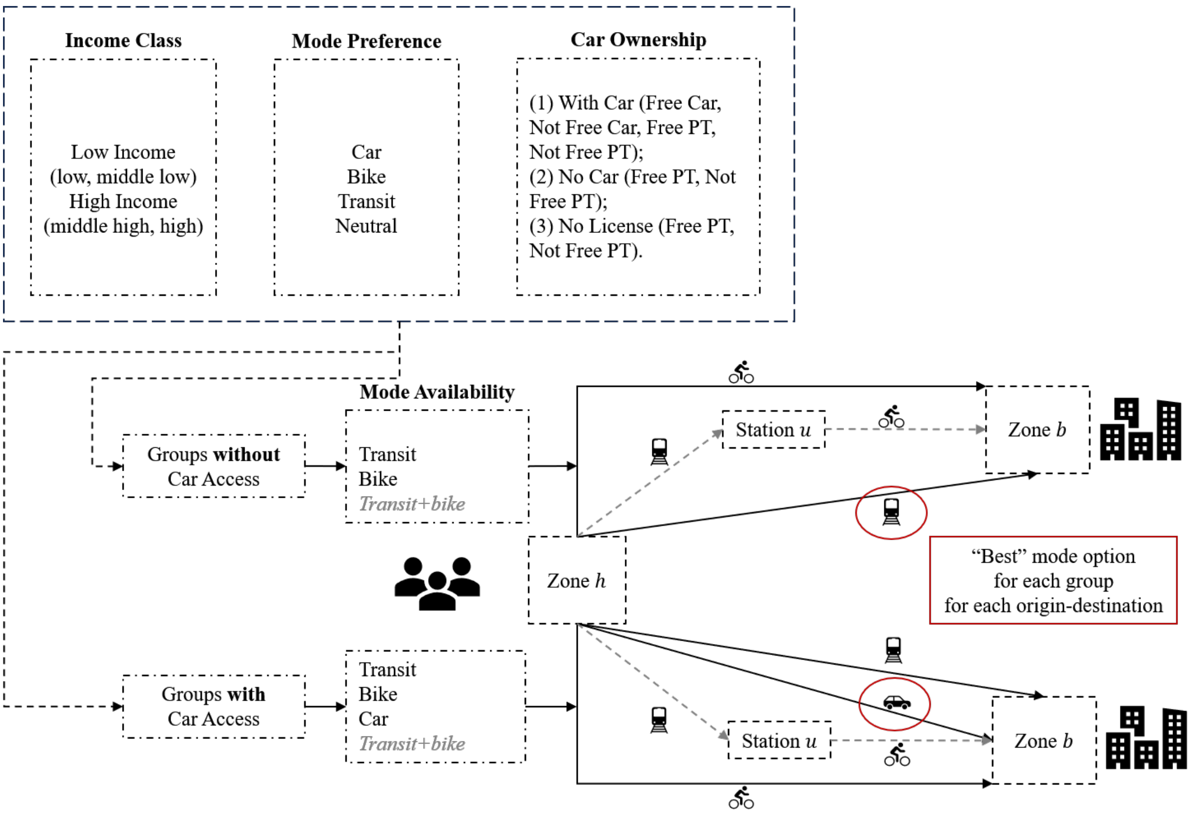



**Figure 3.9:** Determining Weights for Groups with/without Car Access based on Multimodal Options

For these two groups, the difference between their mode availability is that groups without car access do not have car-based trips. For each trip, individuals are likely to choose the ”best” mode they perceive as the most accessible based on their travel resistance. One debatable question is that groups with car access might always choose a car as it offers less travel resistance than other modes in most situations, but this might not always be true. For example, when the road is congested during peak hours, or it is hard to find a parking space for a private car, public transport or cycling to the destinations might be better choices than a car. Even though it is a rough assumption, which might not represent the actual travel behaviour of individuals, it would be acceptable as it is more important to understand the relative accessibility. Additionally, introducing this simple mode choice assumption could incorporate the impacts of transit-shared bike integration by creating base and intervention scenarios.

### 3.2.5. Potential Accessibility

The number of opportunities measures potential accessibility in the IKOB Model can be reached from a particular neighbourhood/region for a certain group (income class, mode preference, car ownership) with a certain unimodal or multimodal availability (public transport, car, bike, multimodal trips) with a motive (Work, daily shopping/healthcare, non-daily shopping/education), at a certain time of day (morning peak, rest of day, evening peak). Furthermore, the IKOB model calculates weighted average accessibility by taking into account the population size of each group in each neighbourhood. This consideration makes it possible to more accurately represent the experienced accessibility by a certain group or from a certain place than simple arithmetic average value. In this thesis, the calculation of job accessibility for groups with-/without car access is adapted in the IKOB model to match the context of transit-shared bike integration.

The population share for the target group in a neighbourhood is the sum of all the subgroups $g$ in the neighbourhood.

$$V_{Gh} = \sum_{g} V_{gh} \tag{3.21}$$

Where $V_{gh}$ is the share of subgroup $g$ in neighbourhood $h$; $V_{Gh}$ is the share of the target group $G$ (Groups with/without car access) in the neighbourhood $h$.

Number of jobs in destinations $b$ can be reached for each subgroup $g$ in origin zone $h$ for transport mode (combination) $v$ is:

$$B_{ghv} = \sum_{b} V_{gh} * G_{ghbv} * A_{ib} \tag{3.22}$$

Where $A_{ib}$ is the number of jobs only for income class $i$ in destination zone $b$; $i$ is the income class to which subgroup $g$ belongs.

The weighted average number of accessible jobs for the target group $G$ (groups with/without car access) from the origin zone $h$ by transport mode (combination) $v$ is:

$$B_{Ghv} = \frac{\sum_{g} B_{ghv}}{V_{Gh}} \tag{3.23}$$

When we want to calculate the average accessibility from a neighbourhood, municipality or the whole case area, it can be calculated in the same way by weighting the population.

### 3.2.6. Competition Effects

As competition exists in the employment market because of unbalanced demand and supply, the IKOB model takes into account the competition effects to make the estimate of job accessibility more realistic. The number of inhabitants (subgroup or the target group) that companies and institutions can reach will be calculated in the same way as accessibility for individuals.

Total number of subgroup $g$ in origin $h$ by transport mode (combination) $v$ can be attracted by companies in destination zone $b$:

$$B_{gbv} = \sum_{h} I_{gh} * G_{ghbv} \tag{3.24}$$

Where $I_{gh}$ is the number of of inhabitants in subgroup $g$ in origin zone $h$.

The number of inhabitants for the target group $G$ can be attracted by companies in destination zone $b$ from the origin zone $h$ by transport mode (combination) $v$ is:

$$B_{Gbv} = \sum_{g} B_{gbv} \tag{3.25}$$

The competitiveness in terms of job accessibility for individuals in the target group $G$ in origin zone $h$ for mode (combination) $v$ is:

$$C_{Ghv} = \sum_{g} \frac{A_{ib}}{B_{Gbv}} * G_{ghbv} \tag{3.26}$$

## 3.3. Equity Evaluation: Sufficientarian Approach

### 3.3.1. Accessibility and Potential Mobility Index (PMI)

Accessibility cannot provide direct information about to what extent the transportation system contributes to accessibility, as it is not only a result of the transportation system but also land-use and individual characteristics. Transport policy only focuses on people who are experiencing insufficiency in both accessibility and the quality of the transport system. If population groups experience accessibility insufficiency but have good transport mobility, land-use policies are more likely to solve the accessibility issue than transport interventions. Therefore, it is necessary to complement accessibility measurement with an indicator that can only indicate the contribution of the transport component to accessibility. Martens (2016) proposed a measure called Potential Mobility Index (PMI), which is expressed as the quotient of the Euclidean distance and the travel time on the transport network between origin and destination. PMI is suitable for determining the contribution of the transportation system to accessibility as it captures the impact of both speeds on the links of the transport network, as well as the network structure. The PMI for a specific mode within a specific zone is expressed as formula 3.27:

$$PMI(im) = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{d_m(i, j...n)}{T_m(i, j...n)} \tag{3.27}$$

Where $PMI(im)$ is the average aerial speed for zone $i$ by mode $m$, $d_m(i, j...n)$ and $T(i, j...n)$ are the aerial distance and travel time on the network between zone $i$ and zone $j$ by mode $m$.

A coordinate system was constructed by Martens (2016) including potential mobility and accessibility simultaneously. From the perspective of sufficientarianism, accessibility inequity means neighbourhoods with insufficient accessibility. By setting thresholds of potential mobility and accessibility, this coordinate system can identify the population groups who are suffering from limited accessibility because of the transportation system. Figure 3.10 shows an adapted framework based on the original work.

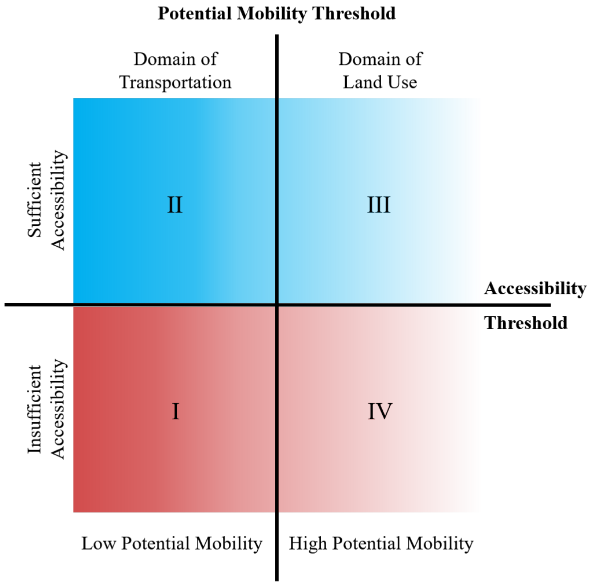



**Figure 3.10:** The Coordinate System of Potential Mobility and Accessibility: Adapted From (Martens, 2016)

Horizontally, the blue area indicates groups have sufficient accessibility, while the red area means groups are suffering from accessibility shortfalls. Vertically, the darker the colour, the more relevant it is to the transportation system. For instance, insufficient accessibility for groups located at the bottom-left area (Quadrant I) is largely caused by a poorly functioning transportation system. However, if groups in the bottom-right area (Quadrant IV) have sufficient potential mobility but still experience accessibility deficiency, the influence of land-use-related factors is predominant.

### 3.3.2. Accessibility Deficiency Index (ADI)

Except for identifying groups experiencing accessibility insufficiency, Martens (2016) also proposed an index to represent the level of fairness of the transport system in a region, the Accessibility Fairness Index (AFI). In contrast to what this name suggests, AFI reflects the severity of accessibility deficiency. To avoid ambiguity regarding the meaning, the Accessibility Deficiency Index (ADI) will be used in this thesis, which is expressed as formula 3.28.

$$ADI(r) = \frac{1}{N}\sum_{i=1}^{q} n_i \cdot (\frac{z - y_i}{z})^2 \quad (3.28)$$

where $N$ is the total population in region $r$; $q$ is the number of groups in region $r$ experiencing accessibility deficiency (below the threshold of accessibility and potential mobility); $n_i$ the size of the $i-th$ group in number of persons; and $y_i$ is the accessibility level experienced by the $i-th$ group below the sufficiency threshold $z$.

ADI not only considers how many population groups experience insufficiency, but also how far they are below the sufficient threshold. It is determined by three influencing components, which are shown in Figure 3.11: (1) the defined threshold value of accessibility; (2) the share of the population who are experiencing accessibility insufficiency and (3) the difference between the actual accessibility and the threshold value. All these components combined determine the severity of the accessibility deficiency in the region. The severity of accessibility insufficiency varies between 0 and 1, with values closer to 1 indicating a higher proportion of the population experiencing more severe accessibility insufficiency. thus the unfairer transportation system. A group or neighbourhood with a large value of ADI can be due to extremely low accessibility, a very large number of group sizes, or a combination of both.

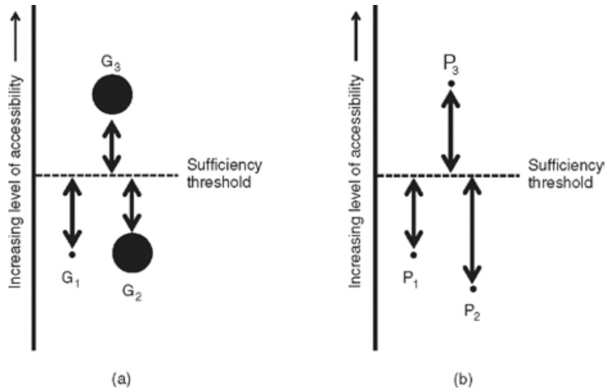



**Figure 3.11:** Visual Representation of the Prevalence of Accessibility Shortfalls (a); and the Intensity of Accessibility Shortfalls (b): From (Martens, 2016)

ADI is a good indicator for policymakers to know which neighbourhoods are experiencing the most severe accessibility insufficiency. More importantly, the contribution of a specific group or neighbourhood to the overall ADI in a region can be calculated by weighting the population size. By singling out the neighbourhoods or groups who are particularly affected by the accessibility deficiency in the region, it is beneficial for policymakers to prioritise policies.

The contribution of a neighbourhood to the overall ADI in a region is expressed in Equation 3.29, and the contribution for a specific group can be calculated in the same way.

$$Contribution_r = \frac{ADI_r * n_r}{\sum_r^R ADI_r * nr} \quad (3.29)$$

where $n_r$ the population size of neighbourhood $r$ in region $R$.

## 3.4. Data Preparation

The data required for this research was extracted from the dataset provided by Hans Voerknecht. The data is at a neighbourhood level; from 2015, the most recent year, data is publicly available. This data will be used to apply the aforementioned research methodologies: accessibility calculation and equity evaluation. The source of each dataset in land use, transport and individual components will be introduced respectively, and partial data can also be found in Appendix A.

**Land-use Component:**

- The distribution of employment categories per neighbourhood can be derived from the LISA file (Landelijk Informatiesysteem van Arbeidsplaatsen), which is the employment register database. The relationship between level of education and job categories can be obtained from CBS data. As there is a strong correlation between education and income level, the distribution of income levels based on education levels was generated by the CBS data and analyses of the municipality of Amsterdam, which is shown in Table A.8. Therefore, the number of jobs in each neighbourhood can be classified into different income levels.
- The dataset for the urban degree can be obtained from the CBS District and Neighbourhood data.
- The zone ID of hub locations where commuters can shift from transit to shared bikes can be obtained by corresponding to the neighbourhood and zone ID in ArcGIS.

**Transport Component:**

- Travel time and distance by transport modes (Car, Bike, Transit) are derived from the regional traffic model VENOM.
- Travel time and distance by Transit-Share bike integration are calculated in the IKOB Model.
- Euclidean distance matrix per transport mode for Potential Mobility Index is generated in ArcGIS.

**Individual Component:**

- Inhabitants per income class and number of cars per household are accessed from CBS District and Neighbourhood data.
- Car ownership: CBS (With car, No car and No license); Vereniging Zakelijke Rijders, VZR (Free car); NS data (Free PT).
- The mode preferences for groups with/without cars in different urbanisation degrees are derived from travel research in the Netherlands: Onderzoek Verplaatsingen in Nederland (OVIN) and a survey by the Gemeente Amsterdam.

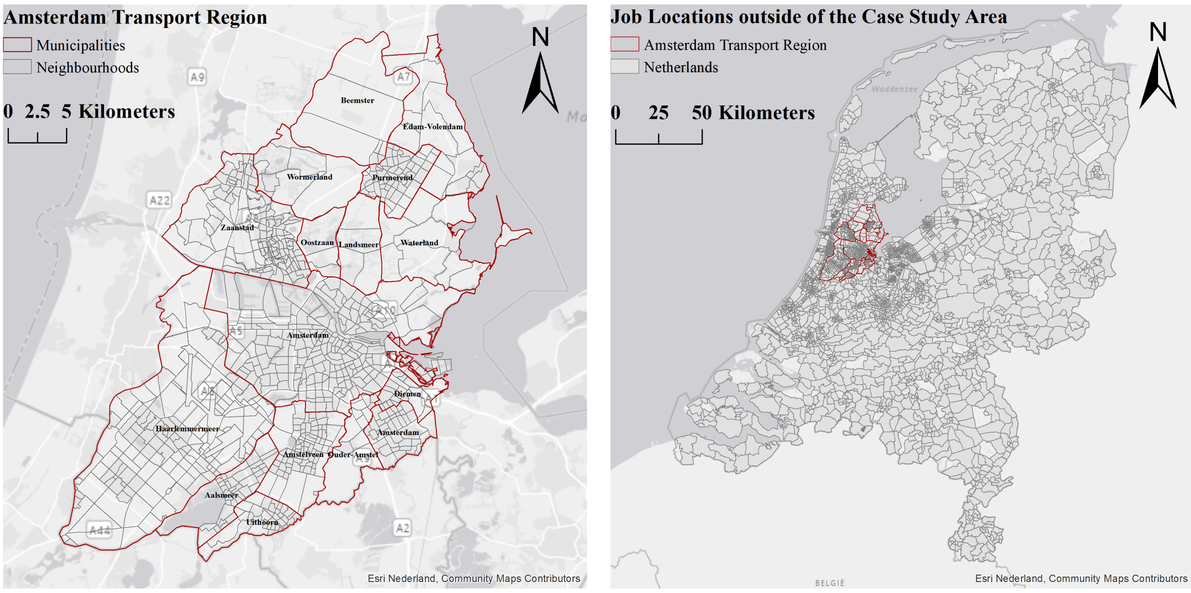
# 4
# Case Study

This chapter will introduce the case study area selected in this thesis to examine how integrating transit and shared bikes would impact equity in job accessibility: Amsterdam Transport Region. Background information regarding the public transport networks and PMI distribution for groups with/without car access (transport component), distribution of employment and locations of transit-shared bike integration (land-use component), and distribution of inhabitants (individual component) will be provided to help understanding how the interactions between each component would influence the job accessibility for a specific group within a specific neighbourhood.

## 4.1. Case Study Area

Amsterdam Transport Region is a regional transport authority connecting the municipality of Amsterdam and 14 surrounding municipalities, which are shown in Figure 4.1a. It was selected as a case study because it includes multiple municipalities with different characteristics in transport, land use and individual components. The resulting different levels of accessibility in various contexts can explain the potential reasons for accessibility inequity and give implications for possible interventions for the policymakers to promote a more equitable transport system, not only restricted to this case study but also applicable more broadly to other transportation-land use systems.

As the number of accessible jobs is also influenced by the cordon range outside of the case study area. Individuals are potentially able to access more jobs when more possible locations of workplaces are included. More importantly, including cordon effects could avoid the skewed results in accessibility for groups living in peripheral regions as they will have more significant travel resistance than groups in central regions. In this thesis, the job locations distributed in the whole Netherlands are considered, shown in Figure 4.1b. Even though some destinations would be out of the range in travel distance or time for commuters in the Amsterdam Transport Region, it is not problematic as the gravity-based measure used in the IKOB model will assign near-zero weight to the trips whose destinations are these locations. There are 841 neighbourhoods in the Amsterdam Transport Region and 3741 neighbourhoods in the Netherlands. Its grid becomes increasingly dense when the neighbourhood approaches the Amsterdam Transport Region.

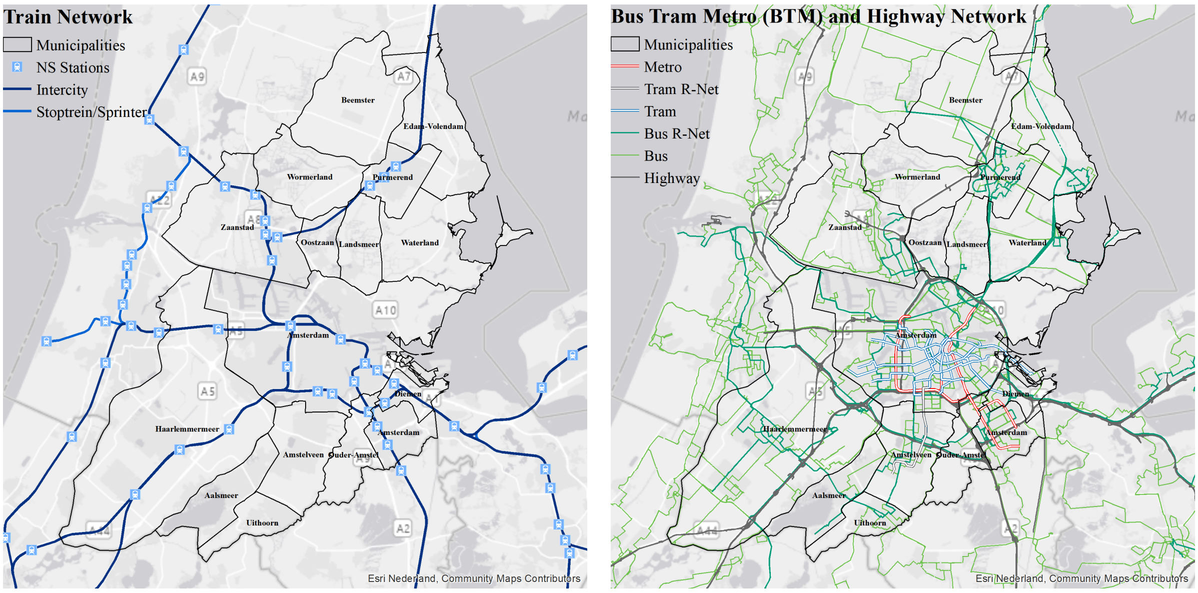



(a) (b)

**Figure 4.1:** Amsterdam Transport Region (a); Extra Jobs Considered outside of the Case Study Area (b)

# 4.2. Public Transport Networks

Public transport networks in the Amsterdam Transport Region are displayed in Figure 4.2 in terms of train network and Bus, Tram Metro (BTM) network.




(a) (b)

**Figure 4.2:** Public Transport Network in Amsterdam Transport Region: Train Network (a); Bus Tram Metro (BTM) and Highway Network (b)

Public transport services are more densely distributed in the municipality of Amsterdam, especially metro and tram services, which are only operated here. In addition, some peripheral municipalities do not have train lines, and the bus is the only public transport service. More seriously, there are no highways that pass by several municipalities (Oostzaan, Landsmeer, Waterland, Edam-Volendam, Aslsmeer, Uithoorn), whose inhabitants might be highly dependent on car access because of less accessible public transport services.

## 4.3. Locations of Transit-Shared Bike Integration

In this thesis, several sources were combined together to find the possible locations of transit-shared bike integration. The first one is the NS train stations where OV-fiets are available at most stations (NS, 2023a). The second source is obtained from the distribution of service points of shared bikes (Donkey Republic, FlickBike, Cargoroo and GoAbout) and hubs in the municipality of Amsterdam (Amsterdam, 2023). Only hubs and service points close to the transit stations will be included. The third source is based on the locations of the P+R facilities in the Amsterdam Metropolitan Area (Mobility, 2023).

Instead of precise geographical coordinate data, the locations of transit-shared bike integration are represented by the neighbourhood. Therefore, some neighbourhoods with significant bias of the location will be excluded because of the large geographical area. Additionally, the neighbourhood with multiple locations will be regarded as one. After filtering out the locations overlapping and outside of the Amsterdam Metropolitan Area based on these sources, 103 transfer stations where integrated transit and shared bikes were selected and the final distribution of the locations is visualised in Figure 4.3. Detailed information about the selected locations is listed in Table C in Appendix.

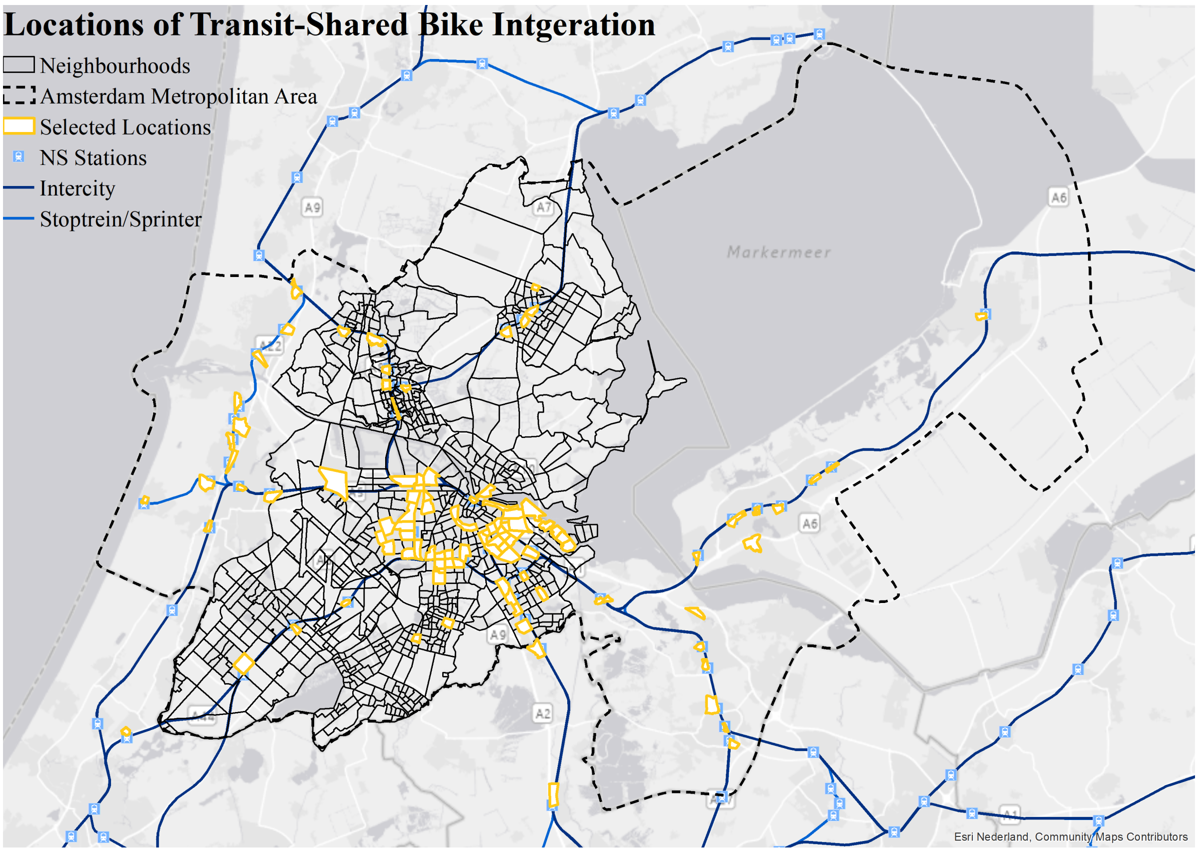


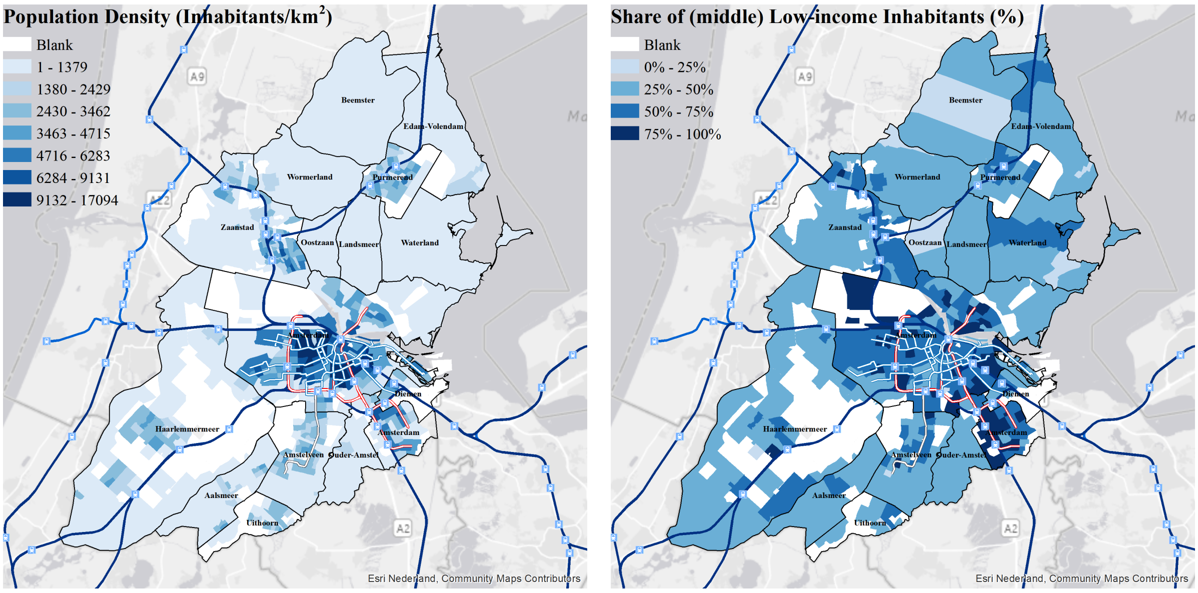

**Figure 4.3:** Locations of Transit-Shared Bike Integration where Integrates Transit and Shared Bike

# 4.4. Distribution of Population

There are 667 neighbourhoods that have inhabitants in the Amsterdam Transport Region. 174 neighbourhoods are labelled as blank because no inhabitants or data are missing. The figure in Figure 4.4 illustrates the distribution of population density and the proportion belonging to the low-income class. Population density quantifies the number of people residing in a specific area, providing valuable insights into its concentration. The map's central area appears darker than other regions, indicating that Amsterdam is the most densely populated.

Sub-figure 4.4b reflects the share of (middle) low-income inhabitants of each neighbourhood. Most parts of the central area show darker blue (higher than 50%) compared with other areas, which means the number of (middle) low-income inhabitants is higher than the number of high-income inhabitants in these areas. Additionally, the centre of Amsterdam shows light blue (25%-50%), denoting that more high-income inhabitants are living there.

Upon closer look at sub-figure 4.4b, it is evident that the darker areas, characterised by a share of (middle) low-income inhabitants exceeding 50%, are mainly near the indicated transit stations. A generalised observation can be made: a higher concentration of (middle) low-income inhabitants tends to reside close to transit stations as opposed to high-income inhabitants.



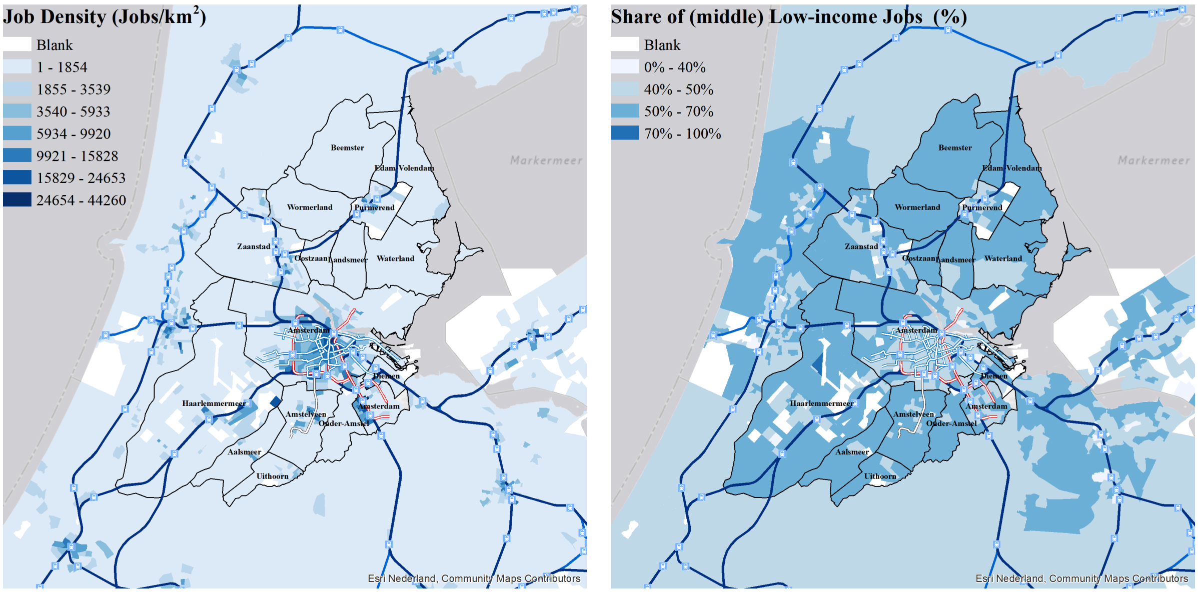

(a) (b)

**Figure 4.4:** Population Density (Inhabitants/$km^2$) within the Amsterdam Transport Region (a); and Share of (middle) Low-income Inhabitants in Each Neighbourhood (b)

# 4.5. Distribution of Employments

The distribution of the Job density and the proportion of low-income jobs in the Amsterdam Transport Region are illustrated in Figure 4.5. In sub-figure 4.5a, the central area (Amsterdam) appears darker compared to other regions, suggesting a greater job concentration.
Conversely, sub-figure 4.5b reveals an opposing pattern, where the surrounding areas appear

darker than the central area of Amsterdam. It shows the proportion of (middle) low-income jobs in each neighbourhood, calculated by dividing the number of jobs available to low-income groups by the total number of jobs in each neighbourhood. The central area only offers around 40%-50% of jobs to low-income groups, while the surrounding areas offer up to 70% or even 100%. Furthermore, the share of low-income jobs in the neighbourhoods near the train stations ranges from 40% to 50%. Combined with sub-figure 4.4b, this suggests that even though jobs are highly concentrated close to train stations, low-income individuals may not be able to access them since they are mismatched.



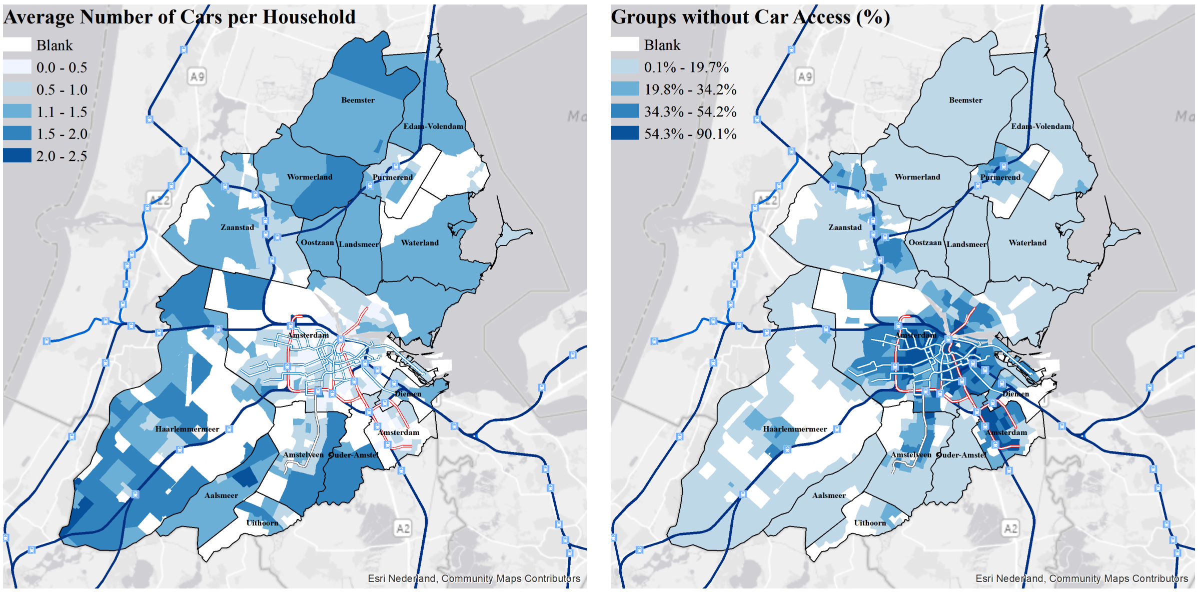

(a) (b)

**Figure 4.5:** Job Density (Jobs/$km^2$) including outside of Amsterdam Transport Region (a); Share of (middle) low-income jobs in Each Neighbourhood (b)

# 4.6. Distribution of Groups without Car Access

The data reveals that 60.8% of the population has car access, while 39.2% does not across the entire Amsterdam Transport Region. The distribution of the average number of cars per household and the percentage of inhabitants without car access in the Amsterdam Transport Region is shown in Figure 4.6. In sub-figure 4.6a, which illustrates the average number of cars per household for each neighbourhood, it becomes apparent that households in the central area generally have 0-1 car on average. It is essential to consider that a household may consist of several individuals. This observation suggests that many people do not own a car.

The sub-figure 4.6b shows the distribution of the share of groups without car access. A darker neighbourhood represents higher proportions of groups without car access than groups with car access, which are the municipality of Amsterdam and neighbourhoods close to transit stations. It is reasonable since more convenient access to transit services is essential for people without a car. A general conclusion can be made: people without car access are mainly concentrated in Amsterdam or next to transit stations.




**(a)** **(b)**

**Figure 4.6:** Average Number of Cars per Household (a); and Percentage in Groups without Car Access (b)

# 5

# Results

This chapter will conduct a sensitivity analysis to explore the impacts of offering shared bikes as an egress mode at transit stations, given that renting costs vary due to different operating systems and price strategies for different companies. The analysis will be performed in one base scenario, which does not involve transit-shared bike integration, and three intervention scenarios with different rental prices of shared bikes: 0, 1, and 2 euros per trip.

Understanding the base scenario at different disaggregated levels, from whole networks to neighbourhoods and subgroups, is meaningful. The base scenario will be first introduced to have an overview of job accessibility and the severity of accessibility deficiency in the Amsterdam Transport Region. Three different levels of population composition are classified: (1) Group level-1 (All groups); (2) Group level-2 (Groups with/without car access); (3) Group level-3 (Groups with/without car access and from low/high-income levels). Subsequently, the impacts of transit-shared bike integration will be assessed in group level 3 to understand how this intervention in different rental prices would affect job accessibility for different commuters and the level of equity in the whole transport-land use systems. We primarily focus on the groups without car access, who are expected to benefit the most from this intervention. Results regarding the improvements in job accessibility and equity within the four scenarios will be visualised in ArcGIS and analysed based on statistics.

## 5.1. Base Scenario: No Integration

### 5.1.1. Coordinate System: Statistics for Accessibility Deficiency

The ”Euclidean Distance” matrix is generated using the centroids of each neighbourhood in the Amsterdam Transport Region. It is then used to calculate the potential mobility index for groups with and without car access. The potential mobility index is assumed to be the arithmetic average value of available mode options, as travel time is calculated for each transport mode. For example, the PMI value for groups with car access in each neighbourhood is calculated as the average of car, transit, and bike. The PMI value for groups without car access in each neighbourhood is calculated as the average of transit and bike. Furthermore, population-weighted average PMI is calculated for each neighbourhood and the whole case study area to represent the average level. Nevertheless, the PMI value for groups with car access may be underestimated since they may primarily travel by car. Even though this method does not represent the precise speed on the transport network, it can still reflect the relative difference in mobility between groups with and without car access.

In this thesis, a coordinate system, including group level-1 and level-2, is firstly constructed to help select the suitable thresholds, which is visualised in Figure 5.1. The severity of accessibility deficiency is not only related to how far the groups are between the defined threshold line, but also their population size, or both. Each marker represents the group in a neighbourhood (a total of 667 neighbourhoods), and the size of the markers reflects the group population in each neighbourhood. This figure helps to select the suitable threshold values for the PMI and accessibility. Additionally, it is important to note that only groups falling below both accessibility and PMI thresholds contribute to the AFI value. Therefore, groups to the right of the PMI threshold line are not taken into account.

Ideally, the threshold values of PMI and accessibility are determined through a democratic process, but descriptive statistics would be more practical (Martens, 2016). Several possible alternatives exist for the threshold lines shown in Figure 5.1. Different threshold line determinations will make the results different. For example, if the weighted average PMI and accessibility for groups with car access are thresholds, groups without car access will experience a deficiency in all neighbourhoods and most low-income groups with car access. However, when the weighted average for all groups is taken, the situation for groups with car access becomes much better. There is no good or bad between these thresholds. The difference is only regarding how to define the criteria for whether people have accessibility deficiency or not. The population-weighted measure considers the uneven distribution of population within a neighbourhood, which better represents the average level of accessibility for a specific subgroup in a specific area. Therefore, the population-weighted average PMI (16.45 $km/h$) and potential accessibility (126517 jobs) for all groups in the whole Amsterdam Transport Region during peak hours are selected as the threshold values.

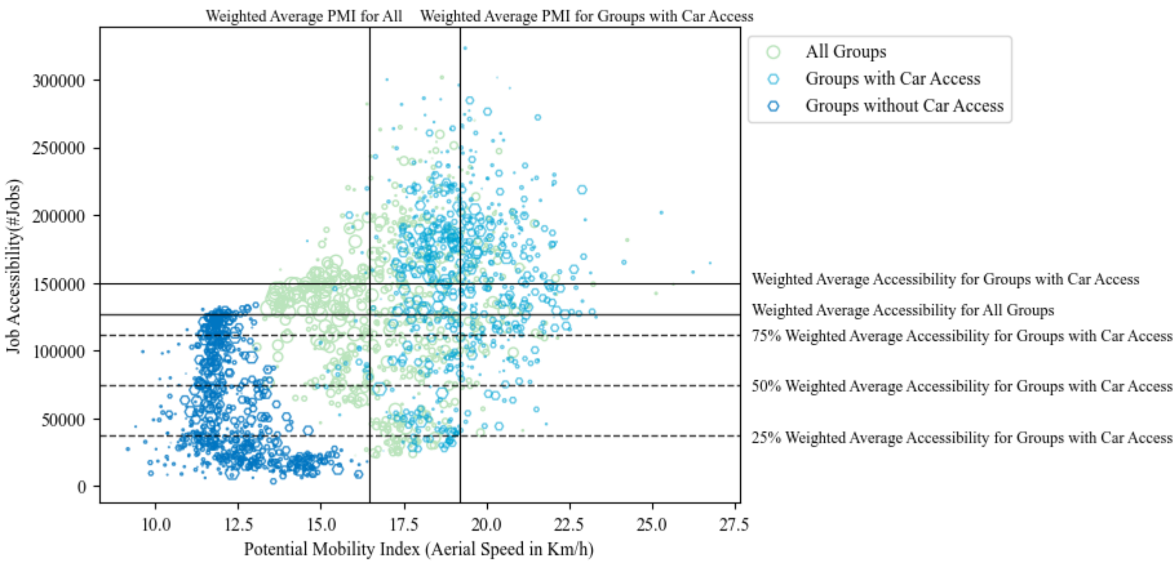



**Figure 5.1:** PMI and Accessibility Coordinate System

After determining the thresholds of PMI and job accessibility, the coordinate system in group level-3 is visualised in Figure 5.2. It is observed that low-income groups without car access are suffering from accessibility deficiency in all neighbourhoods. Only a small group of neighbourhoods can offer sufficient job accessibility for high-income groups without car access. Additionally, although groups with car access are expected to own higher job accessibility, it is not the case for low-income groups who still have limited accessibility in most neighbourhoods. However, they have higher potential mobility than the average PMI and thus are not regarded as groups with accessibility deficiency. Therefore, we primarily focus on looking at the groups located lower than both threshold lines (in the black dotted rectangle), as they are the most potential groups to benefit from the transit-shared bike integration and possibly can be elevated above the sufficiency threshold line.

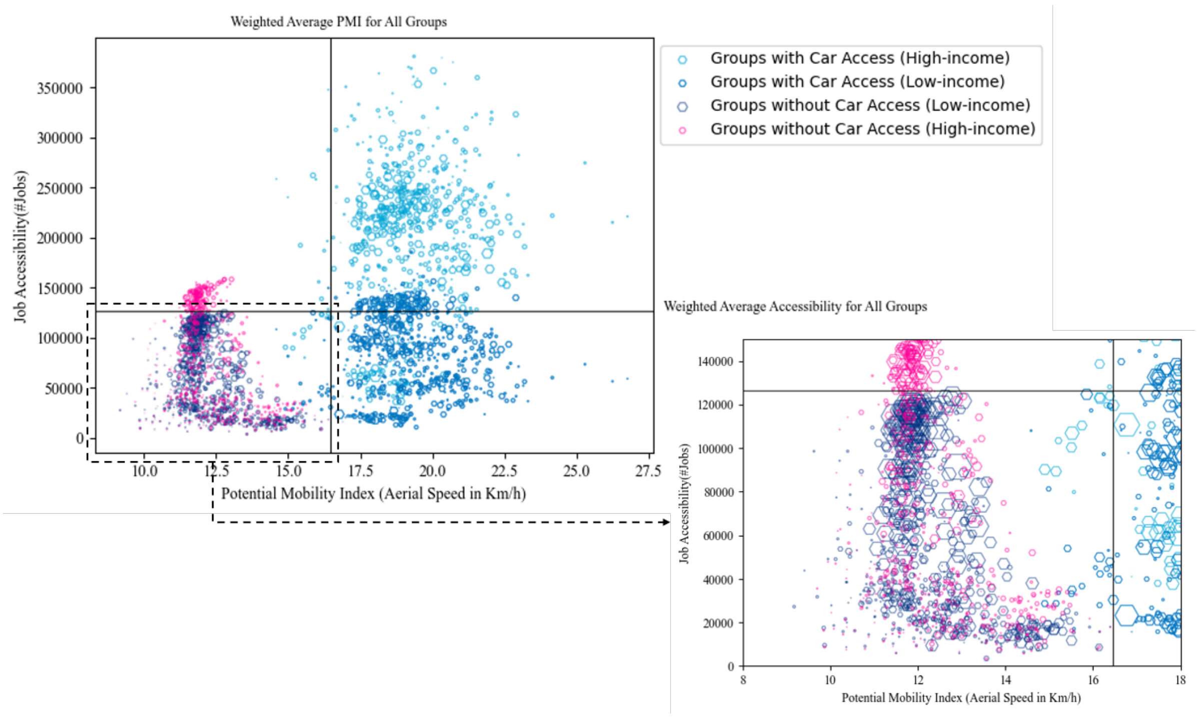



**Figure 5.2:** Coordinate System for Groups with/without Car Access from Low/high Income Class

In addition to the simple visualisations, the more detailed data about the accessibility deficiency in three different group levels are summarised in Table 5.1 and Table 5.2, which provides a statistical overview of the accessibility deficiency situation in the case study area.

When examining the level equity of the whole case study area using the population-weighted average accessibility for all groups, only 106 neighbourhoods are regarded as having accessibility insufficiency. If we divide the population into groups with/without car access, groups without car access are experiencing accessibility deficiency in 650 neighbourhoods. In contrast, groups with car access only have accessibility deficiency in 16 neighbourhoods. If we look from group level-3, low-income groups with car access are experiencing complete accessibility deficiency in all neighbourhoods (667), and 564 neighbourhoods of high-income groups without car access.

From the population share of deficiency and contribution to the overall severity deficiency, low-income groups without car access are the most disadvantaged group, who contribute 85.85% of the overall accessibility deficiency as all of them are below the sufficient thresholds. The situation for high-income groups without cars is slightly better. 39.36% of this group are experiencing accessibility and account for 11.92% contrition to the overall severity of accessibility deficiency. In contrast, the contribution of groups with car access to the overall deficiency is subtle, 2.00% for the low-income groups and 0.23% for the high-income groups.

Another observation is that only 17.04% of the total population will be regarded with accessibility deficiency at group level 1, while 37.1% (0.8% + 36.30%) in group level 2 and 35.29% (0.38% + 0.46% + 31.39% + 3.06%) in group level 3. It can be explained by the fact that the much higher accessibility for groups with car access compensates for the low accessibility for groups without car access, resulting in the ignorance of the disadvantaged group even though they are still present in the networks.

**Table 5.1:** Sufficiency and Insufficiency at Neighbourhood-level and Group-level

| Disaggregate Level | Weighted Average Job Accessibility | Sufficiency in Neighbourhoods | Deficiency in Neighbourhoods |
|---|---|---|---|
| **Group Level-1** | 126517 | 561 | 106 |
| **Group Level-2** | | | |
| Groups with Car Access | 149369 | 651 | 16 |
| Groups without Car Access | 90869 | 17 | 650 |
| **Group Level-3** | | | |
| Group_1 ($With\_car\_low$) | 90037 | 644 | 23 |
| Group_2 ($With\_car\_high$) | 193956 | 651 | 12 |
| Group_3 ($Without\_car\_low$) | 84975 | 0 | 667 |
| Group_4 ($Without\_car\_high$) | 114653 | 99 | 564 |

**Table 5.2:** Overview of Groups with Accessibility Deficiency

| Disaggregate Level | Population Share | Share of Deficiency in Group | Share of Deficiency in Total Population | Contribution to the Overall Deficiency |
|---|---|---|---|---|
| **Group Level-1** | 100% | 17.04% | 17.04% | 100% |
| **Group Level-2** | | | | |
| Groups with Car Access | 60.87% | 1.31% | 0.80% | 1.23% |
| Groups without Car Access | 39.17% | 92.69% | 36.30% | 98.77% |
| **Group Level-3** | | | | |
| Group_1 ($With\_car\_low$) | 26.11% | 1.44% | 0.38% | 2.00% |
| Group_2 ($With\_car\_high$) | 34.76% | 1.34% | 0.46% | 0.23% |
| Group_3 ($Without\_car\_low$) | 31.39% | 100% | 31.39% | 85.85% |
| Group_4 ($Without\_car\_high$) | 7.78% | 39.36% | 3.06% | 11.92% |

In summary, aggregated results tend to ignore the groups that are really experiencing accessibility inequity. The significant difference between the accessibility perceived by high-income groups with car access and that of disadvantaged groups results in the inequity issue being overlooked. Therefore, this suggests that it is essential to conduct a disaggregate analysis of equity in accessibility to better understand who is more likely to experience accessibility deficiency and the extent of severity they might experience.

### 5.1.2. Spatial Distribution: Job Accessibility

Figure 5.3 presents the population-weighted average job accessibility for each neighbourhood in the Amsterdam Transport Region, with darker areas indicating a higher average job accessibility. The accessibility threshold of 126517 jobs is used to distinguish between different levels of accessibility, making it easier to understand the distribution.

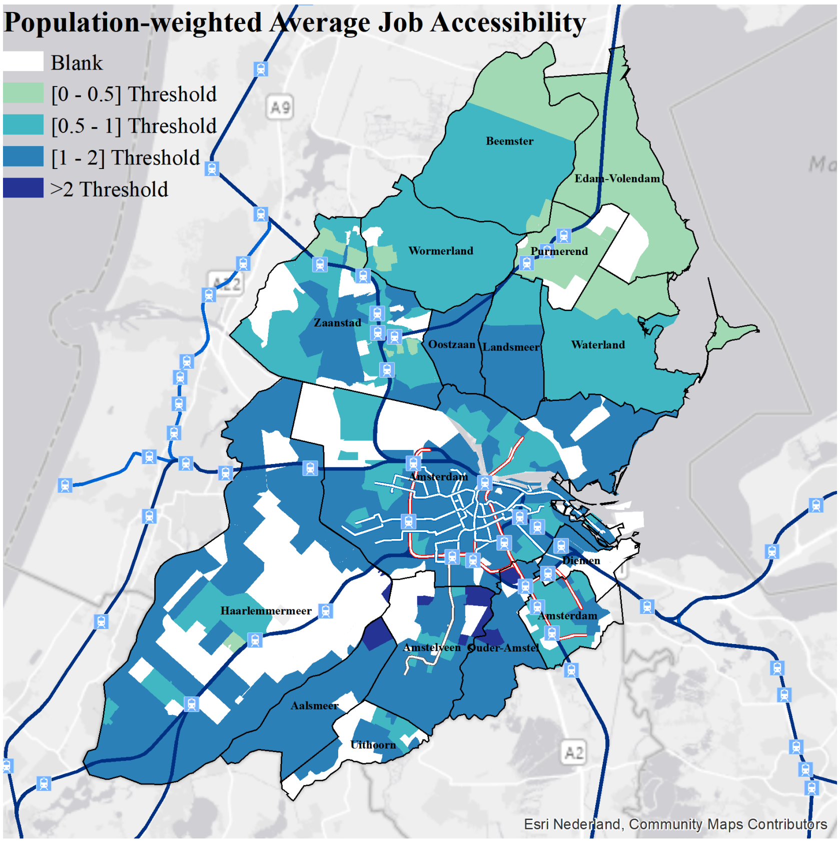



**Figure 5.3:** Weighted Average Accessibility in Each Neighbourhood

A division in average job accessibility exists between the northern municipalities and others. The northern municipalities are mostly represented in colours that indicate lower job accessibility than the sufficiency line. In contrast, people in central and southwestern municipalities can access jobs surpassing the threshold. Interestingly, the central area, Amsterdam, where public transport is densely distributed, does not have the highest job accessibility as expected. Although the average accessibility in Amsterdam exceeds the threshold, the shares of groups without car access and low income are high. This indicates that the opportunity to access the neighbouring low-income jobs they can match is also low.

When looking at the distribution in detail, most commuters living near train stations outside of Amsterdam cannot access sufficient job opportunities. As we learned from section 4.4, this is mainly because a significant proportion of residents in these areas have low incomes and do not have private cars. At the same time, low-income jobs are relatively less concentrated in these areas. Despite being located near the train station and having easy access for their first-mile leg trips, their job accessibility remains limited.

Figure 5.4 displays the distribution of weighted average job accessibility of four subgroups, respectively. Note that the same colours have the same representations of the magnitude of job accessibility in the four different sub-figures. Some important findings are summarised as follows:

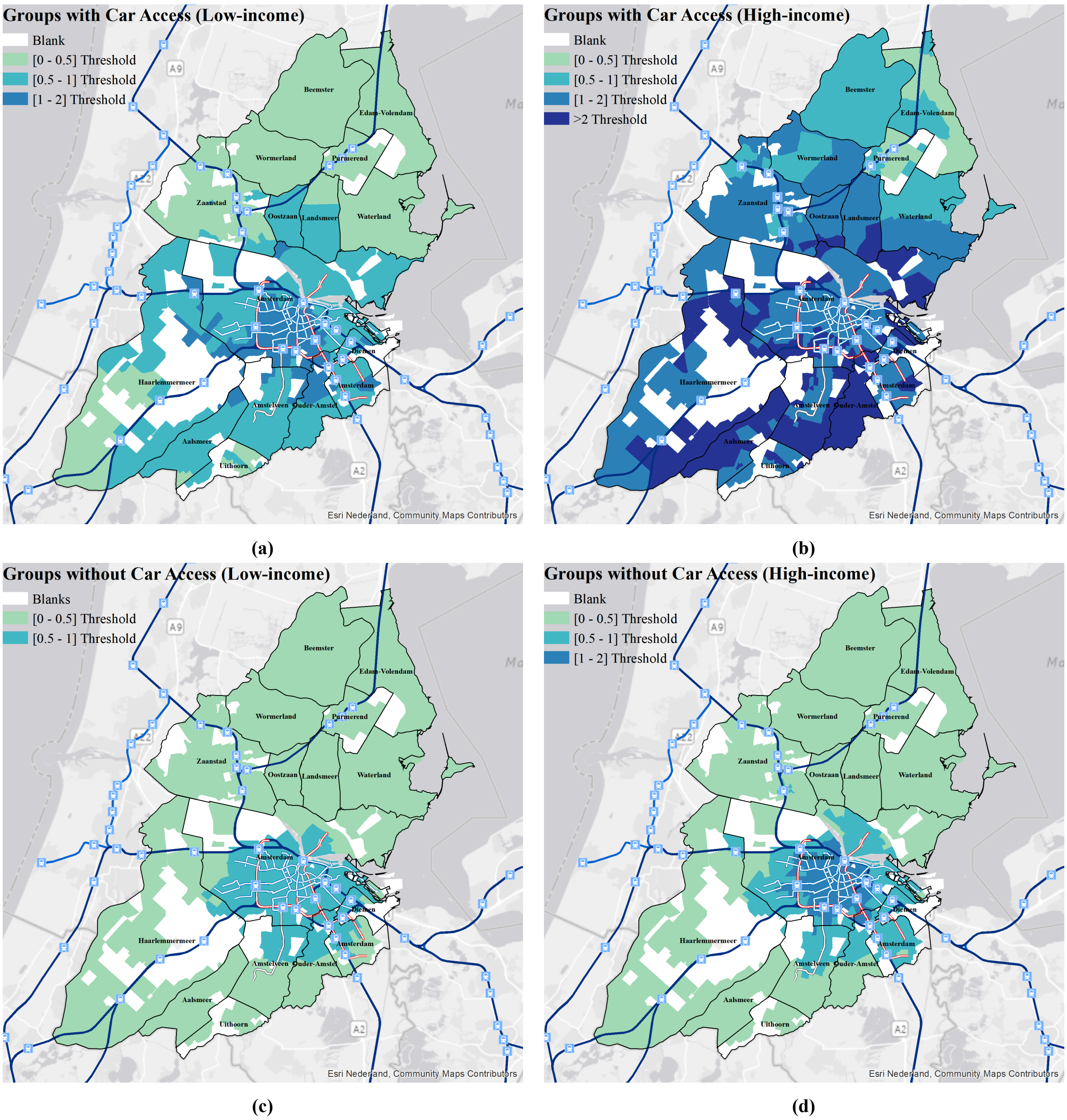



**Figure 5.4:** Job Accessibility Distribution: Low-income Groups with Car Access (a); High-income Groups with Car Access (b); Low-income Groups without Car Access (c); High-income Groups without Car Access (d)

- A common pattern for the four sub-figures is that the peripheral municipalities have lower weighted average job accessibility than the central municipalities. To be more specific, northern Municipalities (Beemster, Edam-Volendam, Purmerend, Wormerland, Waterland) have the lowest job accessibility for both groups with and without car access. Less developed transit and more sparse distributed employment could be related to this phenomenon.

- For groups with car access, low-income people who can access sufficient jobs are mainly distributed in Amsterdam. In contrast, average accessibility for high-income people is observed as sufficient in most municipalities except for partial northern areas.

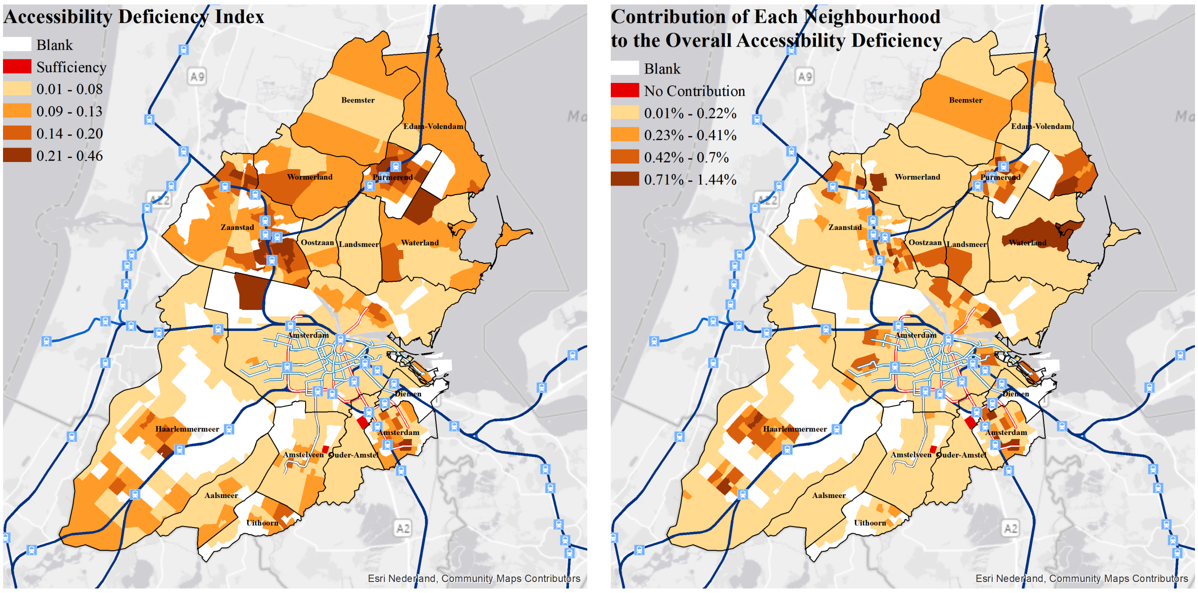
- For groups without car access, job accessibility for low-income people is below the threshold. In contrast, high-income people can only access sufficient jobs within the central area of Amsterdam. The typical pattern of average job accessibility distribution for low-income and high-income groups is that groups can access more jobs when they live close to Amsterdam, proving the importance of public transport systems to enhance job accessibility for groups without car access.

### 5.1.3. Spatial Distribution: Accessibility Deficiency Index

It is no problem to use population-weighted aggregate results to represent the average accessibility for a neighbourhood. However, it is problematic when it comes to evaluating the level of accessibility deficiency of the neighbourhood, as some neighbourhoods might regarded as sufficiency. However, some subgroups are experiencing severe accessibility deficiency. Therefore, the severity of accessibility deficiency of a specific neighbourhood in this thesis will be determined by the summation of population-weighted ADI in Euqation 3.28 for a total of four sub-groups. By using this measure, neighbourhoods will be regarded as having accessibility deficiency if one of the four groups has. This measure would lead to only two neighbourhoods with accessibility sufficiency, which is labelled in red in figure 5.5a.

ADI is a good indicator to reflect the severity of accessibility deficiency each neighbourhood is experiencing. However, it is more important to know to what extent each neighbourhood or group contribute to the overall severity of accessibility deficiency, which can help policy-makers prioritise transport policy for disadvantaged neighbourhoods and groups. Therefore, instead of ADI, the contribution to the ADI in the whole case study area is visualised in this thesis. The contribution of each neighbourhood to the overall ADI is shown in Figure 5.5b.

It is observed that commuters living outside Amsterdam, particularly those living near train stations, significantly contribute to the overall severity of accessibility deficiency even though their first-mile segments are convenient. This is primarily due to the high share of disadvantaged groups living in these neighbourhoods. This suggests an important insight that merely facilitating the first mile to transit stations may not fully address the broader issue of limited job accessibility for transit-dependent inhabitants.




(a) (b)

**Figure 5.5:** AFI in Each Neighbourhood (a) and Contribution to the Overall AFI (b)

Subsequently, the contribution to the overall ADI between different subgroups in each neighbourhood is displayed in Figure 5.6. As it is more important to know groups in which neighbourhoods contribute significantly to the overall accessibility deficiency rather than numerical value, the same colours indicate differently in the four different sub-figures. Some important findings are summarised as follows:

- Accessibility deficiency experienced by the groups with car access is mainly distributed in the northern neighbourhoods.

- Additionally, for groups without car access, a consistent distribution pattern emerges—proximity to Amsterdam correlates with lower contributions to the severity of accessibility deficiency. It can be explained by Figure 5.4, neighbourhoods in Amsterdam can offer the highest job accessibility for them compared to others.

- Furthermore, it is noted that northern municipalities contribute more to the overall severity of accessibility deficiency than their southern counterparts, where job accessibility is below the threshold value for most subgroups.

- Moreover, low-income groups without car access contribute to the accessibility deficiency in all neighbourhoods. In contrast, high-income groups without car access can still enjoy sufficient accessibility in areas of Amsterdam where public transport is densely distributed.

- Another observation is that more significant contributions to the overall severity of accessibility deficiency are evident around transit stations irrespective of different income and car ownership groups.

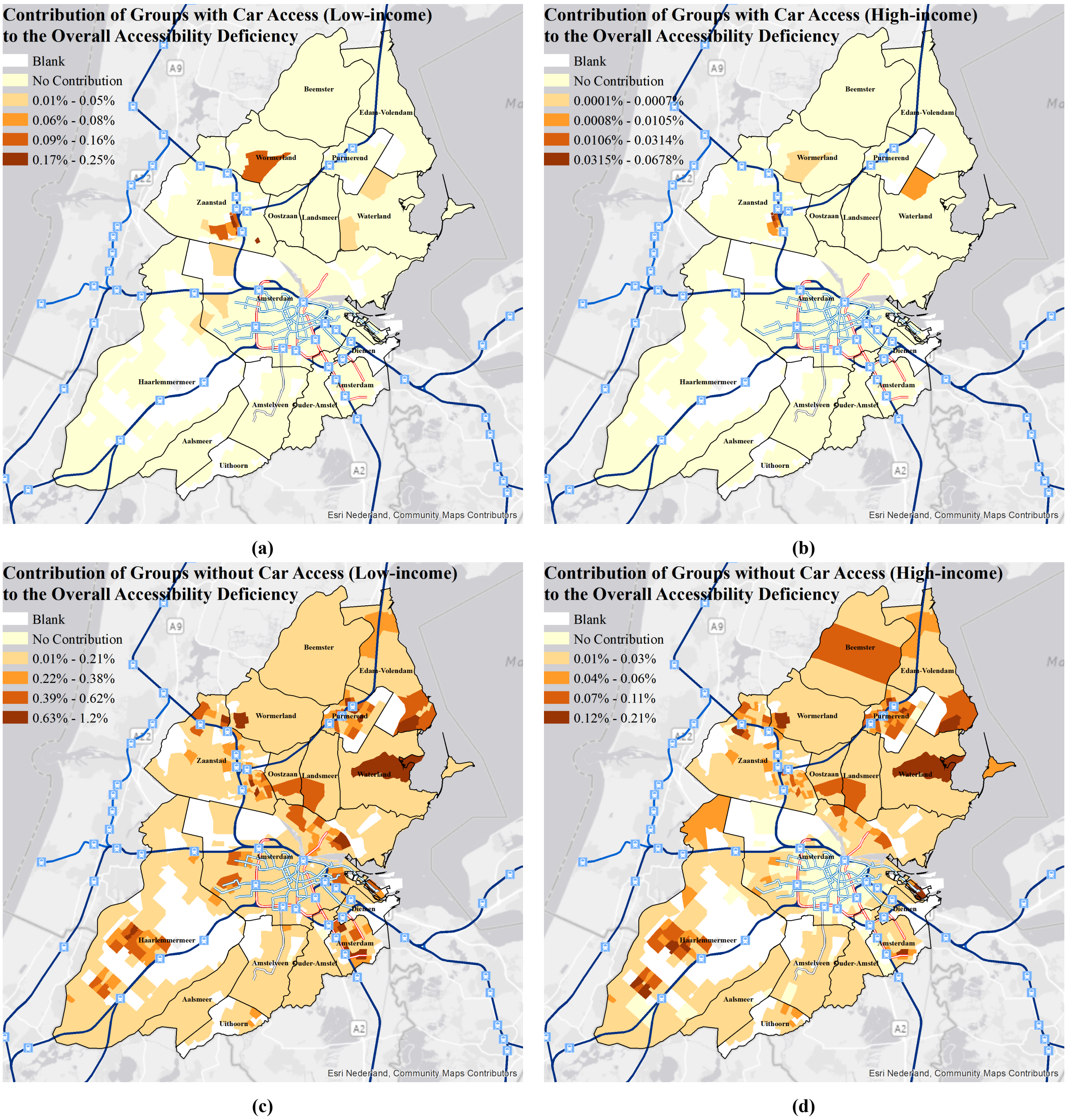



**Figure 5.6:** Contribution to the Overall ADI: Low-income Groups with Car Access (a); High-income Groups with Car Access (b); Low-income Groups without Car Access (c); High-income Groups without Car Access (d)

# 5.2. Intervention Scenario: With Integration

## 5.2.1. Sensitivity Analysis

In the case study area, shared bikes operate under diverse pricing strategies across multiple companies. This heterogeneity presents a challenge in determining a standardised price for a trip with a shared bike. To address this complexity, a sensitivity analysis becomes essential. This analysis specifically examines cost scenarios set at 0, 1, and 2 euros per trip. The inclusion of a 0-euro scenario is based on the assumption that certain companies or governments may provide allowances for employees without car access to utilise shared bikes. Meanwhile, the

2-euro threshold is established as the upper limit, aligning with approximately half the price of using the ”OV-fiets” per trip (priced at 4.45 euros). This range of pricing scenarios allows for thoroughly exploring the potential impacts of transit-shared integration.

### 5.2.2. Statistics for Improvements in Job Accessibility

This section analyses the improvements in job accessibility with transit-shared bike integration in three scenarios with different renting prices. Figure 5.7 illustrates the variations in average job accessibility improvements (percentage) across different group levels (levels 1 and 2). In the case study area, an overall enhancement of 4.97% in average job accessibility is evident when the shared bike price is set at 0. In contrast, this improvement diminishes considerably to a mere 0.36% when the price is increased to 2 euros.

Further examining the impact on groups with and without car access, the figure highlights distinct patterns. Those without car access experience more substantial improvements in average job accessibility compared to their counterparts with car access. Notably, when the price is set at 0, there is a noteworthy 12.83% improvement in average job accessibility for groups without car access. However, these benefits notably decline with increasing rent prices.

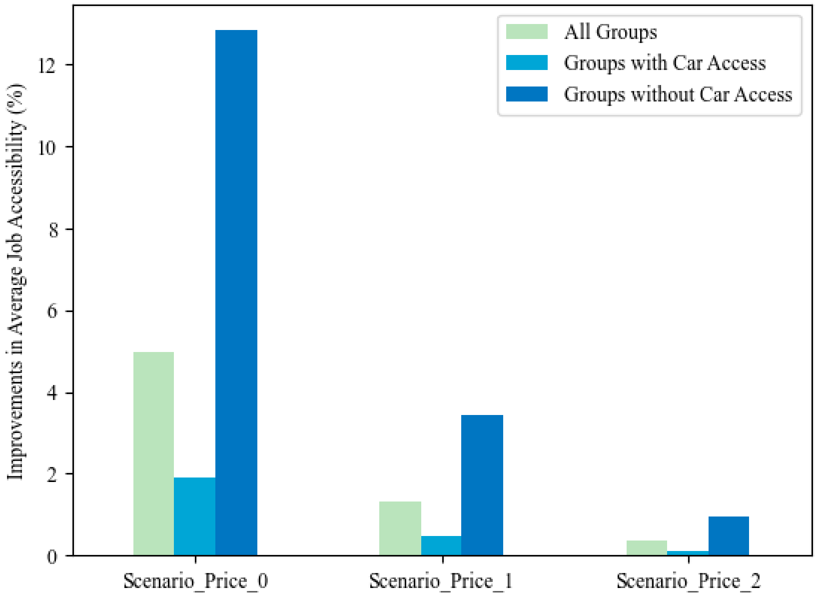



**Figure 5.7:** Improvements in Weighted Average Job Accessibility at Different Prices: Group level 1&2

Table 5.3 presents the proportion of different groups benefiting from transit-shared bike integration relative to their respective populations. Notably, more groups without car access consistently gain benefits than those with car access across all scenarios, irrespective of increased job accessibility. Among groups with car access, a slightly higher percentage of low-income individuals benefit at 0 and 1 euro prices. However, there is a significant decrease for low-income groups as the price increases, dropping from 90.62% (0 euro) to 81.78% (1 euro) and further to 44.91% (2 euro). In contrast, even at 2 euros, 89.86% of low-income groups without car access still benefit. The most substantial benefits are observed in high-income groups without car access, exceeding 99% of the population obtain job accessibility improvements in all pricing scenarios.

**Table 5.3:** Population Share of Transit-Shared Bike Benefits

| Scenarios | Scneario_price_0 | Scenario_price_1 | Scenario_price_2 |
|---|---|---|---|
| Group_1 ($With\_car\_low$) | 90.62% | 81.78% | 44.91% |
| Group_2 ($With\_car\_high$) | 86.93% | 81.56% | 70.42% |
| Group_3 ($Without\_car\_low$) | 99.68% | 97.79% | 89.86% |
| Group_4 ($With\_car\_high$) | 99.97% | 99.75% | 99.35% |

The bar chart presented in Figure 5.8 provides a detailed perspective on the improvements in average job accessibility when examining at group-level 3. This visual representation allows for a detailed understanding of how these benefits are potentially distributed among the four subgroups. Notably, high-income groups without car access can experience the most substantial improvements across all scenarios. Particularly significant is their sustained 3.33% improvement in average job accessibility even when the pricing is increased to 2 euros, a significant contrast to the negligible improvements observed in the other groups.

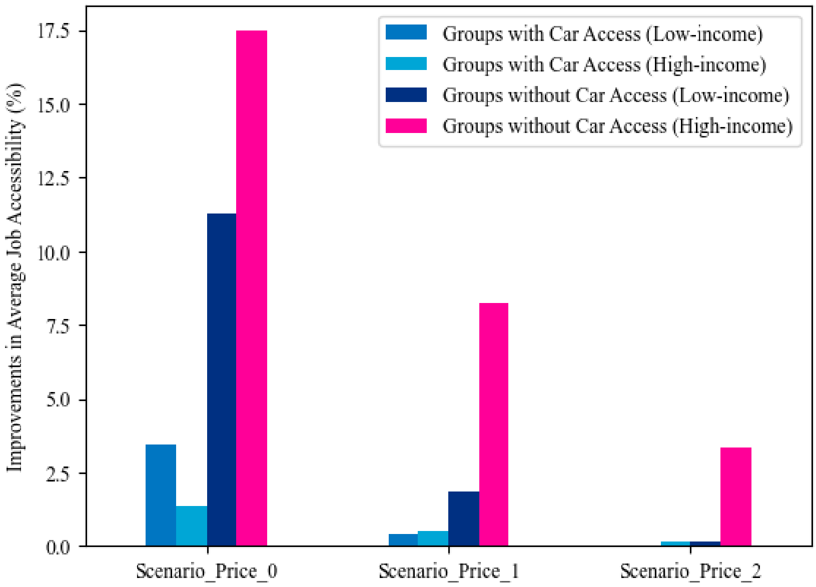


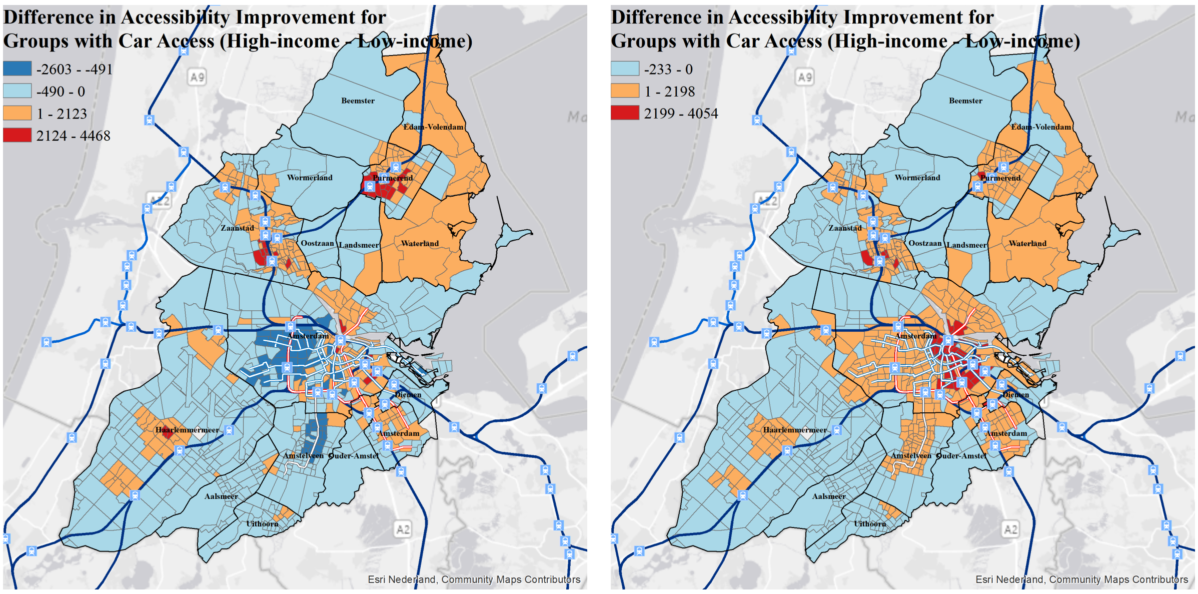

**Figure 5.8:** Improvements in Weighted Average Job Accessibility at Different Prices: Group level 3

In order to explain the difference in accessibility improvement, it is necessary to discuss it from a mathematical perspective. The accessibility improvement is weighted by population, representing that average improvement per group is related to both the population size and the magnitude of numeric improvement.

For without car access, it is intriguing to note that high-income groups consistently derive more significant benefits, even when the renting price of shared bikes is at 0. For population size, there are 31.39% low-income groups with car access and 7.78% high-income groups without car access in the Amsterdam Transport Region. Therefore, the improvement in average accessibility for high-income groups would be more obvious than for low-income groups. Theoretically, given that they primarily rely on transit and bikes for commuting, this phenomenon can also be explained by the cost structure, which includes transit and shared bike costs. Transit cost dominates the overall expense for a journey, making the benefits of transit-shared bike integration less effective in alleviating the economic burden and potentially diminishing its attractiveness to commuters on longer trips. In this context, high-income groups tend to perceive less resistance to same-distance trips as they are willing to pay more for longer travel. Consequently, even though both groups lack car access, high-income individuals are more likely to utilise the potential benefits of integrating transit and shared bikes.

For groups with car access, low-income groups can experience higher improvements in average job accessibility than high-income groups only if shared bikes are provided free; otherwise, there will be fewer improvements for them. Firstly, there are 26.11% low-income groups with car access and 34.76% high-income groups with car access in the Amsterdam Transport Region. Assuming these two groups receive the same benefits in all neighbourhoods, the average accessibility improvement for low-income groups would be higher than for high-income groups because of their difference in population size.

Figure 5.9 illustrates the contrast in accessibility improvement between high-income and low-income groups with car access when the rental price is 0 and 1 euro. Both figures show that low-income groups can benefit more than high-income groups in light and dark blue neighbourhoods. Based on the distribution figures, it is concluded that the higher population size of high-income groups leads to lower accessibility improvement compared to low-income groups when price = 0. In contrast, when price = 1, the higher magnitude of improvements for high-income groups




(a) (b)

**Figure 5.9:** Difference in Accessibility Improvement between High-income and Low-income Groups with Car Access: When Renting Price = 0 (a) and Renting Price = 1 (b)

### 5.2.3. Statistics for Reduction in Accessibility Deficiency

To assess the impacts of transit-shared bike integration on addressing accessibility deficiency, the primary consideration is whether this intervention effectively transitions groups initially experiencing accessibility challenges to a state of sufficiency. Table 5.4 provides insights into the number of neighbourhoods where four subgroups transition from experiencing accessibility deficiency to sufficiency after implementing shared bikes at transit stations for egress.

Firstly, it is evident that this intervention does not lead to sufficiency for low-income groups with car access. Secondly, high-income groups with car access and low-income groups without car access can achieve sufficiency in only 3 and 47 more neighbourhoods when the pricing is set at zero, respectively. In contrast, high-income groups without car access can benefit from this intervention across all pricing scenarios.

**Table 5.4:** Number of neighbourhoods for Groups from Accessibility Deficiency to Sufficiency

| Disaggregate Level | Scenario_Price_0 | Scenario_Price_1 | Scenario_Price_2 |
|---|---|---|---|
| Group_1 ($With\_car\_low$) | 0 | 0 | 0 |
| Group_2 ($With\_car\_high$) | 3 | 0 | 0 |
| Group_3 ($Without\_car\_low$) | 47 | 0 | 0 |
| Group_4 ($Without\_car\_high$) | 45 | 25 | 11 |

Secondly, we examine the contribution of each group to the overall severity of accessibility deficiency in all scenarios, as presented in Table 5.5. Surprisingly, the contribution of high-income groups to the overall severity of accessibility deficiency is reduced, but low-income groups still account for a higher share of the contribution. This suggests that the equity-related benefits are primarily distributed to high-income groups.

**Table 5.5:** Contribution to the Overall Accessibility Deficiency in the Base and Intervention Scenarios

| | Base Scenario | Price_0 | Price_1 | Price_2 |
|---|---|---|---|---|
| Group_1 ($With\_car\_low$) | 2.00% | 2.18% | 2.05% | 2.01% |
| Group_2 ($With\_car\_high$) | 0.23% | 0.17% | 0.20% | 0.22% |
| Group_3 ($Without\_car\_low$) | 85.85% | 86.41% | 86.44% | 86.09% |
| Group_4 ($Without\_car\_high$) | 11.92% | 11.22% | 11.31% | 11.68% |

### 5.2.4. Spatial Distribution: Improvements in Job Accessibility

**Groups with Car Access**

Figure 5.10 visually represents job accessibility improvements among groups with car access from different income classes at three shared bike rental prices. A noteworthy trend emerges as the cost of renting increases. There is a diminishing impact on the number of accessible jobs and neighbourhoods receiving improvement, particularly affecting low-income groups with car access. It implies that higher rental expenses are a deterrent, resulting in less attractive transit-shared bike integration for these commuters.

Even with free shared bike rentals (price = 0), not all groups with car access experience the benefits of transit-shared bike integration. This is particularly evident for those residing in peripheral municipalities, where the intervention fails to compete with the convenience of private car usage, resulting in no impact on job accessibility.

Significant improvements in job accessibility have been observed among groups with car access in Amsterdam municipality and proximity to transit stations such as Zaanstad and Purmerend train stations. This can be attributed to their advantageous location next to transit hubs, which reduces travel resistance for the first-mile journey to public transport. Integrating transit and shared bikes further facilitates the last mile of their commuting journey, making the whole trip more seamless.

Given the dense distribution of shared bike transfer stations in Amsterdam and the concentration of jobs, commuters outside Amsterdam are expected to experience significant improvements due to enhanced last-mile connectivity. However, it is evident that individuals within Amsterdam benefit more through the integration of transit and shared bikes, especially those working in a city with high job density and well-developed public transport.

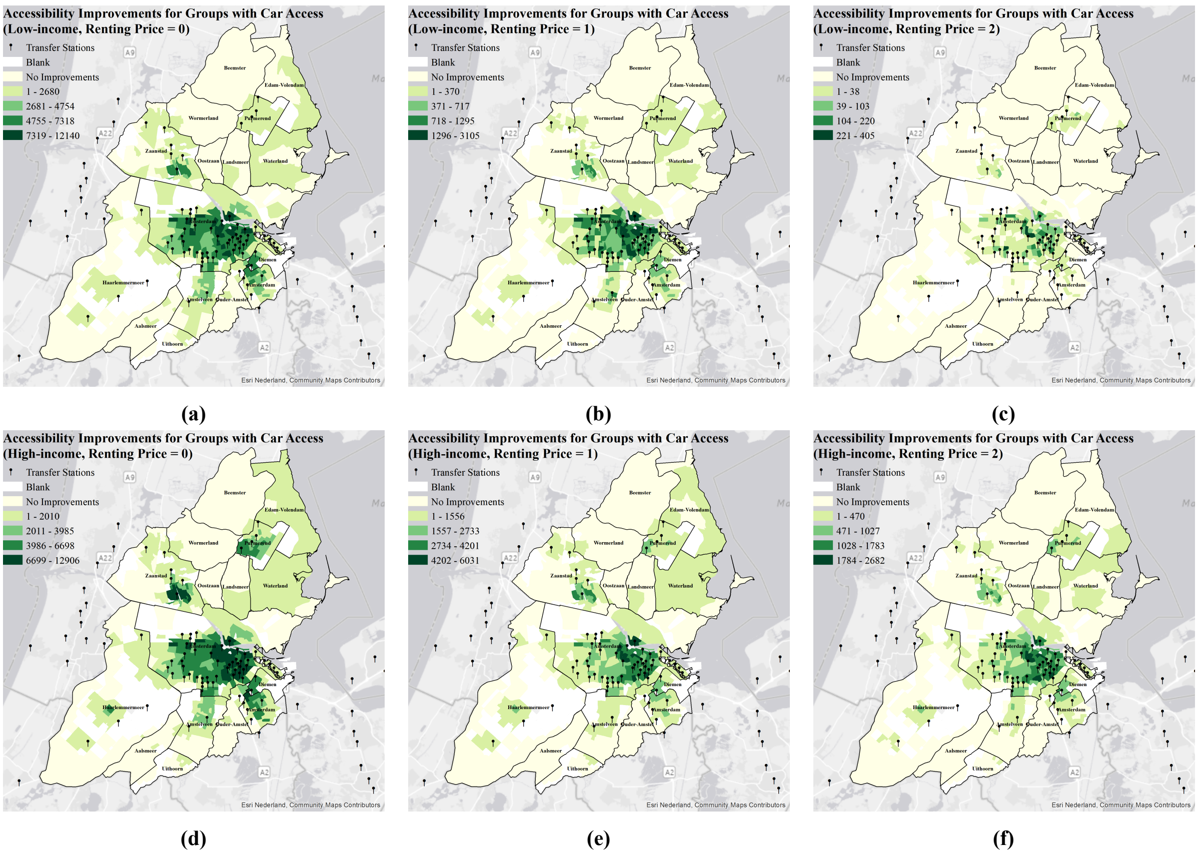



**Figure 5.10:** Improvements in Job accessibility for Groups with Car Access: Low-income, Renting Price = 0 (a); Low-income, Renting Price = 1 (b); Low-income, Renting Price = 2 (c); High-income, Renting Price = 0 (d); High-income, Renting Price = 1 (e); High-income, Renting Price = 2 (f)

**Groups without Car Access**

Figure 5.11 visualised the improvements in job accessibility for groups without car access from different income classes within the three different prices of renting shared bikes. Compared to improvements for groups with car access, improvements in job accessibility for groups without car access are observed in more neighbourhoods and higher in magnitude.

When price = 0 euros, groups without car access can have more job accessibility in most neighbourhoods, except for several neighbourhoods on the border. There is a diminishing impact on the number of accessible jobs when the cost of renting shared bikes increases. When the price =2 euros, high-income groups can still benefit in most neighbourhoods, except for several neighbourhoods on the border. In contrast, the number of neighbourhoods where low-income groups without cars can have improvements reduced significantly.

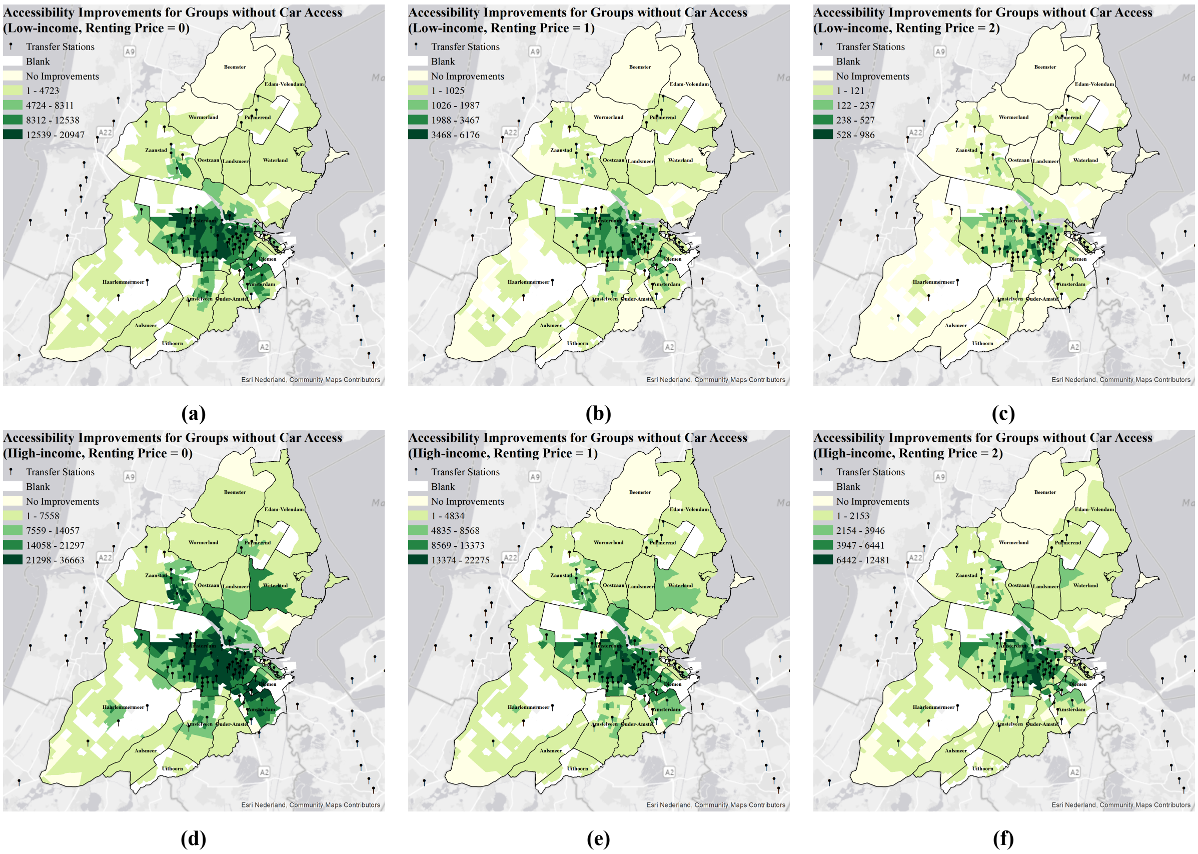



**Figure 5.11:** Improvements in Job accessibility for Groups without Car Access: Low-income, Renting Price = 0 (a); Low-income, Renting Price = 1 (b); Low-income, Renting Price = 2 (c); High-income, Renting Price = 0 (d); High-income, Renting Price = 1 (e); High-income, Renting Price = 2 (f)

## 5.2.5. Spatial Distribution: Improvements in Equity

**Groups with Car Access**

Figure 5.12 visualised the reduction in the severity of accessibility deficiency for groups with car access from different income classes within the three different prices of renting shared bikes. In all scenarios, the reduction in ADI is mainly distributed in Zaanstad train stations. When the rental price is zero, high-income groups with car access in three neighbourhoods within Zaanstad shift from deficiency to sufficiency. In other neighbourhoods, the improvements in accessibility are insufficient to alter their state of deficiency.

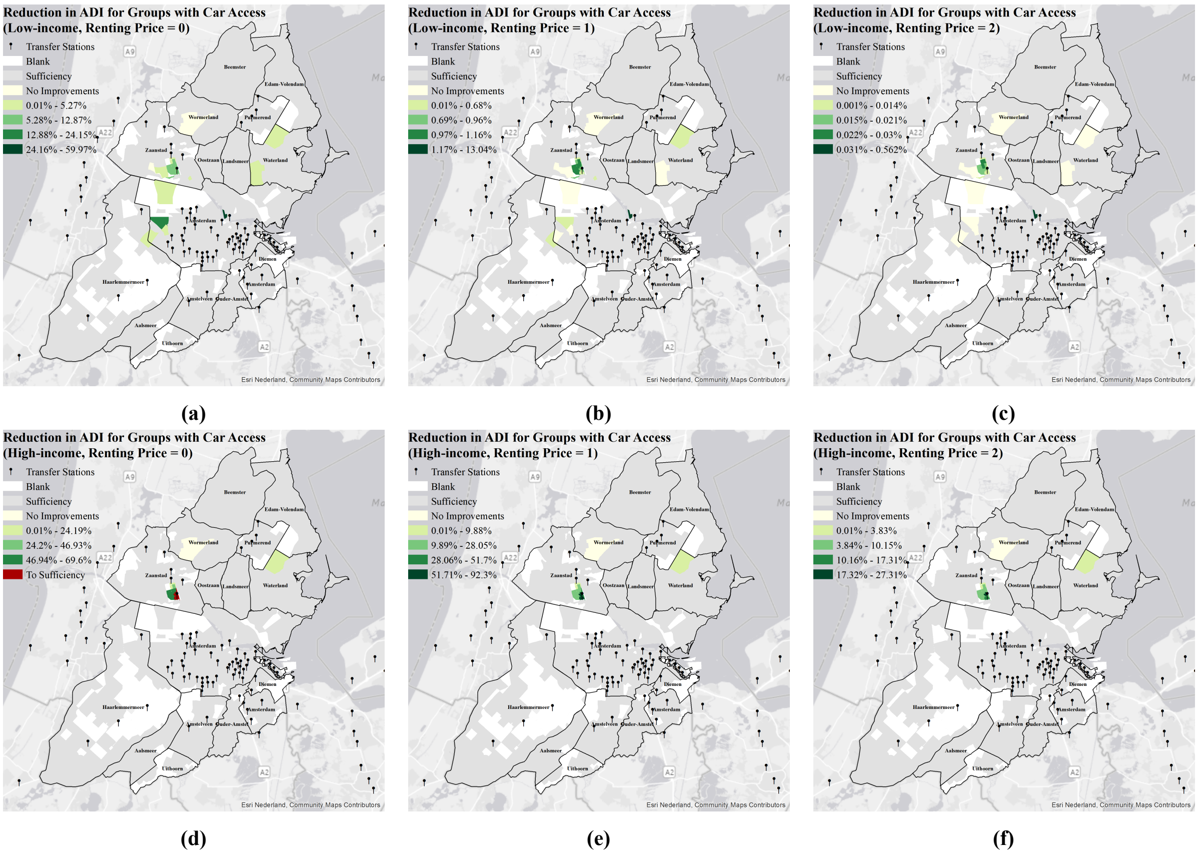


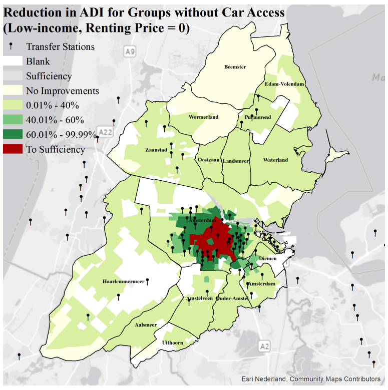

**Figure 5.12:** Reduction in ADI for Groups with Car Access: Low-income, Renting Price = 0 (a); Low-income, Renting Price = 1 (b); Low-income, Renting Price = 2 (c); High-income, Renting Price = 0 (d); High-income, Renting Price = 1 (e); High-income, Renting Price = 2 (f)

### Groups without Car Access

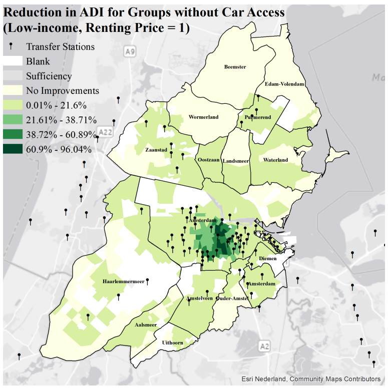
In Figure 5.13, the reduction in the severity of accessibility deficiency for groups without car access, spanning different income classes and three shared bike rental prices, is visually presented. Regions marked in red indicate groups previously identified as deficient, but with the intervention, they now have access to a sufficient number of jobs.

The spatial distribution of the reduction in ADI is concentrated in the central area of Amsterdam, highlighting the potential of transit-shared bike integration to enhance social equity for neighbourhoods located near areas that already have sufficient accessibility. This pattern suggests that the intervention's impact is more apparent in areas with developed public transport systems.

When shared bikes are not free, a key distinction emerges between low-income and high-income groups without car access. Low-income groups face accessibility deficiencies across all neighbourhoods, while high-income groups can consistently access sufficient jobs in more neighbourhoods. This disparity underscores the significant influence of rental costs on equity outcomes, particularly for low-income groups.




(a)

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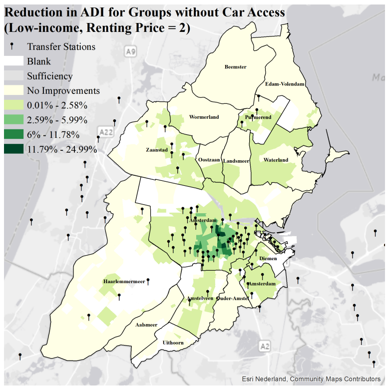


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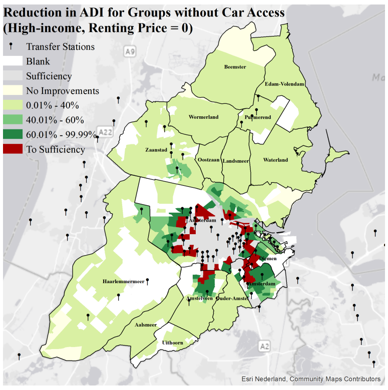


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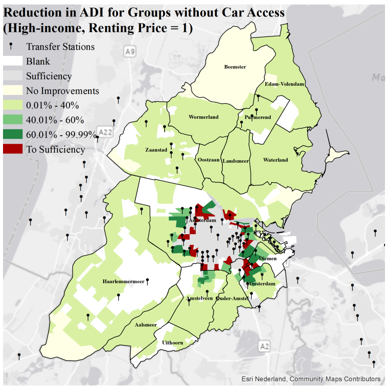
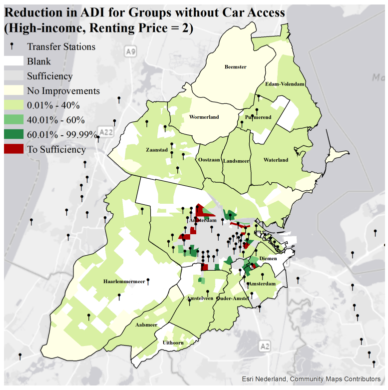



(e)




(f)

**Figure 5.13:** Reduction in ADI for Groups without Car Access: Low-income, Renting Price = 0 (a); Low-income, Renting Price = 1 (b); Low-income, Renting Price = 2 (c); High-income, Renting Price = 0 (d); High-income, Renting Price = 1 (e); High-income, Renting Price = 2 (f)

# 6
# Discussion

This chapter discusses key findings based on results in the case study presented in Chapter 5. This step demonstrates whether these findings can be applied to a generalised context in the academic field. Furthermore, the assumptions and limitations of the research methodologies that may have influenced the results are discussed to provide valuable insights to guide future research.

## 6.1. Discussion of Results

**Key Findings: Base Scenario**

In the base scenario analysis, the different results in the distribution of job accessibility and accessibility deficiency at different disaggregate levels imply that the ”disadvantaged groups” who are more likely to suffer from insufficient job accessibility tend to be ignored if the analysis only focuses on an aggregated average. To help policymakers prioritise transport policy for disadvantaged neighbourhoods and groups, it is necessary to analyse equity issues in a disaggregate manner. It is beneficial to understand who is more likely to experience accessibility deficiency and the extent of severity they may experience.

In the Amsterdam Transport Region, groups in the northern municipalities whose mode options are limited and heavily dependent on vehicles are likely to suffer from accessibility deficiency compared to central and southern municipalities. One reason is that the mismatch between the concentrated jobs and the residential locations results in longer travel distances. Additionally, more travel time is needed due to the undeveloped road infrastructure and poor public transport service. For groups without car access, it is observed that peripheral municipalities cannot provide commuters with sufficient job accessibility because of the low service quality of public transport.

The most disadvantaged groups, who do not have car access and are from low-income levels, concentrate in neighbourhoods near train stations. Unfortunately, a low percentage of jobs are available and match their ability at these locations. Despite having a convenient first-mile segment, groups still struggle with low job accessibility, contributing significantly to the overall deficiency. This problem could be alleviated by improving public transportation systems.

One observation in this report differs from the literature, suggesting that job accessibility near transit stations is always good. This misunderstanding can be explained by the fact that most studies usually apply a generalised accessibility measure, which does not consider the influencing factors about transport, individual and land use components. For example, accessibility is often calculated by only using pure travel time. At the same time, the cost of transport modes, the heterogeneity in perception of monetary costs for different groups, and whether individuals' ability can match the jobs based on their skills are ignored. The simplification of calculation in accessibility often results in misunderstanding, thereby particularly problematic in equity analysis. Therefore, it is essential to consider the factors that affect individuals' perceived accessibility when evaluating equity and thus can make a more realistic and representative situation for different groups.

**Key Findings: Intervention Scenarios**

It has been observed that the integration of transit and shared bikes tends to benefit high-income groups in terms of accessibility and equity. However, there is an exception to this trend. Low-income groups who own cars can experience more improvements in job accessibility than high-income groups with cars, especially when the rental price is set at 0. It can be explained by the mathematical calculation of population-weighted average accessibility, where population size and magnitude of improvement collectively affect the improvement. In the case study, high-income groups with car access failed to overcome the effects of the smaller population size of low-income groups with car access through the bigger magnitude of accessibility improvement. Apart from this exception, high-income groups benefit more than low-income groups. It can be explained by the fact that high-income groups are less sensitive to travel costs, which means they are less likely to be deterred by travel expenses than low-income groups.

Surprisingly, the equity-related benefits after introducing transit-shared bike integration may favour high-income groups, as the contribution of high-income groups to the overall severity of accessibility deficiency is reduced in all scenarios. However, low-income groups still account for a higher share of the contribution. This highlights the need for additional protection for low-income people when implementing this transport intervention.

In this thesis, the locations integrating transit and shared bikes are mainly assigned to Amsterdam. Theoretically, this intervention will facilitate the last mile of transit trips for commuters who live and work in Amsterdam and those who live outside and work in Amsterdam. However, the geographical distribution of benefits of transit-shared bike integration in accessibility is mainly concentrated in the municipality of Amsterdam and neighbourhoods near train stations. For each group, the most significant improvements in accessibility are all observed in the central region of Amsterdam. The equity improvements are mainly concentrated in central Amsterdam. The neighbourhoods can be shifted from deficiency to sufficiency in central Amsterdam (Exception: high-income groups with cars can access sufficient jobs in additional neighbourhoods near Zaamstad stations). Meanwhile, together with the observation that fewer neighbourhoods in peripheral municipalities will obtain improvements in accessibility and reduction in accessibility deficiency when the renting price increases, it indicates that transit costs play an essential role in the improvement in accessibility and equity.

## 6.2. Discussion of Methodologies

**IKOB Model: Advantages**

The IKOB model considers the heterogeneity in individuals' perception, which can more accurately represent the opportunities to be valued as accessible and possibly experienced by each group in real life. Meanwhile, accessibility is weighted by each subgroup/neighbourhood population, more representative of the average level than using a simple arithmetic average method. For the individual component, it distinguishes groups into 60 subgroups based on their car ownership, mode preference and income levels. For the transport components, it calculates the generalised travel cost, including objective travel time and subjective monetary cost for individuals from different income levels, which is especially important for equity analysis. For the land use component, the IKOB model links the type of employment to the individuals' abilities and skills of matching the jobs, which is less frequently considered in existing literature but could reflect a more realistic situation for different groups, particularly for the disadvantaged groups, whose accessibility are often overestimated. Additionally, the IKOB model rewards the destination's proximity by using the travel time decay curve, which can offer a more realistic estimation and overtake the limitation of border effects in the isochrone accessibility measure.

**IKOB Model: Limitations**

The IKOB model provides a more precise and realistic accessibility estimation by considering various factors, including transport, land use, and individual components. However, it has some limitations due to certain assumptions made about travel behaviour.

Firstly, the socioeconomic data used was from 2015, which may not represent the current situation in the case study area. Even though the infrastructure might not have changed significantly, the distribution of car ownership, mode preference, and income class might have changed considerably in some neighbourhoods over the past years. This could affect the distribution of population groups and the parameters of the travel decay function calibrated and validated by the data.

Secondly, the IKOB model assumes that individuals will choose the mode with the highest weight for each trip, which may not always be the case in reality. The relationship between this assumption in mode choice and actual travel behaviour has been questioned in the literature.

Thirdly, the IKOB model assumes that individuals will select the route with minimum travel time when modelling the transit-shared bike integration. However, people may not always realise the best route in reality.

Finally, there may be better options than the minimum travel time trip for commuters. For instance, people generally prefer to avoid riding a bike in the egress mode due to physical effort. Additionally, if there are multiple hubs, people may choose the closest one, even though there may be better options.

**Sufficientarian Approach: Advantages**
This thesis uses the sufficientarian approach to identify disadvantaged groups that face unfair accessibility. A coordinate system is employed, which includes the Potential Mobility Index (PMI), accessibility, and defined threshold lines of these two measures. This system visualises the groups whose accessibility falls below the threshold line. The level of accessibility deficiency is expressed by a measure called the Accessibility Fairness Index (AFI), which is weighted by the population. AFI can reflect not only how many people suffer from accessibility deficiency but also the severity of their suffering. Moreover, AFI is decomposable, providing insights at different disaggregate levels, ranging from a specific subgroup or neighbourhood to the whole system. It is also noteworthy that the contribution of each subgroup to the overall accessibility deficiency can be expressed in percentages, and the summation of contributions of all subgroups is precisely one hundred per cent.

**Sufficientarian Approach: Limitations**
In summary, the sufficientarian approach benefits policymakers aiming to prioritise disadvantaged groups with limited access to opportunities. However, several limitations were identified when applying this methodology in this thesis.

Firstly, the PMI value is calculated for each separate transport mode, which results in complexity when representing the PMI value for groups with multimodal options. Ideally, this issue could be resolved if the mode choice for each group for each origin-destination was known. However, this would result in a much larger computation time, especially for a broad case study area. For simplicity, this thesis takes the arithmetic average across all modes available to each group and weights it by the population of each subgroup in each neighbourhood. Although this solution cannot offer an accurate estimate, it can still reflect the difference between groups with and without cars.

Secondly, the value of the accessibility threshold might lose practicality as a strict value. This was particularly evident when assessing the impacts of transit-shared bikes. While some improvements in AFI reached 99.99%, the groups in the neighbourhoods were still regarded as having accessibility deficiency. The question here is: Does the negligible difference between the threshold lines and accessibility matter? Although this can be partially resolved by setting multiple threshold lines, a similar situation could arise again. Therefore, this thesis argues that it is possible to set the threshold line with a bandwidth rather than a fixed single value.

Thirdly, the population-weighted average accessibility of groups in the whole network broadly represents the accessibility in municipalities with large population sizes, for example, Amsterdam. Taking this threshold might result in difficulty in evaluating the impacts of intervention within some disadvantaged municipalities, where inhabitants can never be improved above the threshold. It is possible to take separate thresholds for each municipality to conduct a more detailed analysis.

**Other Limitations**
This thesis has a few other limitations that cannot be ignored apart from the two methodologies.

Firstly, the whole neighbourhood is used instead of precise coordinate data when determining the location of transit-shared bike integration. This could be problematic when the neighbourhood is large because different stations may be located in the same neighbourhood and have to be considered as one. Also, larger neighbourhoods will increase the uncertainty of transfer time from transit to shared bikes.

Secondly, the travel decay curve for the transit-shared bike integration mode is assumed to be the same as transit when calculating the weight in the IKOB model. This assumption is reasonable if we consider that travellers perceive transit and transit-shared bike integration almost equally, as transit is the main trip for the entire journey. However, this might underestimate the benefits of this intervention.

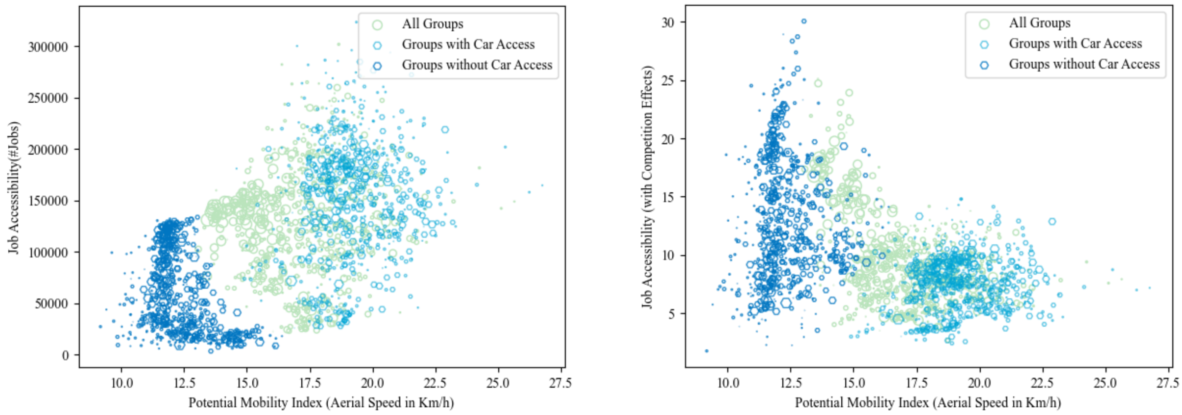
Thirdly, the station-based nature of shared bikes, such as ”OV-fiets” and ”Donkey Republic”, demands an ideal tour-based modelling approach to understand their impacts on job accessibility comprehensively. However, job accessibility calculations are inherently one-directional, limiting our ability to fully capture a holistic representation of the benefits of this bike-sharing system.

Finally, this thesis does not consider the competition effects when calculating job accessibility, which is essential for competitive opportunities like employment. Although the IKOB model has this functionality, it is not applied in this thesis to avoid introducing complexity in interpretation. Competition effects in the IKOB model are modelled by creating a supply-demand ratio, and the unit of the number of accessible jobs will be changed to a new scale. More importantly, the newly added variable will change the individuals' travel behaviour and thus change the results of accessibility and equity distribution. As this thesis aims to evaluate the impacts of transit-shared bike integration on accessibility and equity, it does not consider the competition effects.

**Impacts of Competition Effects**

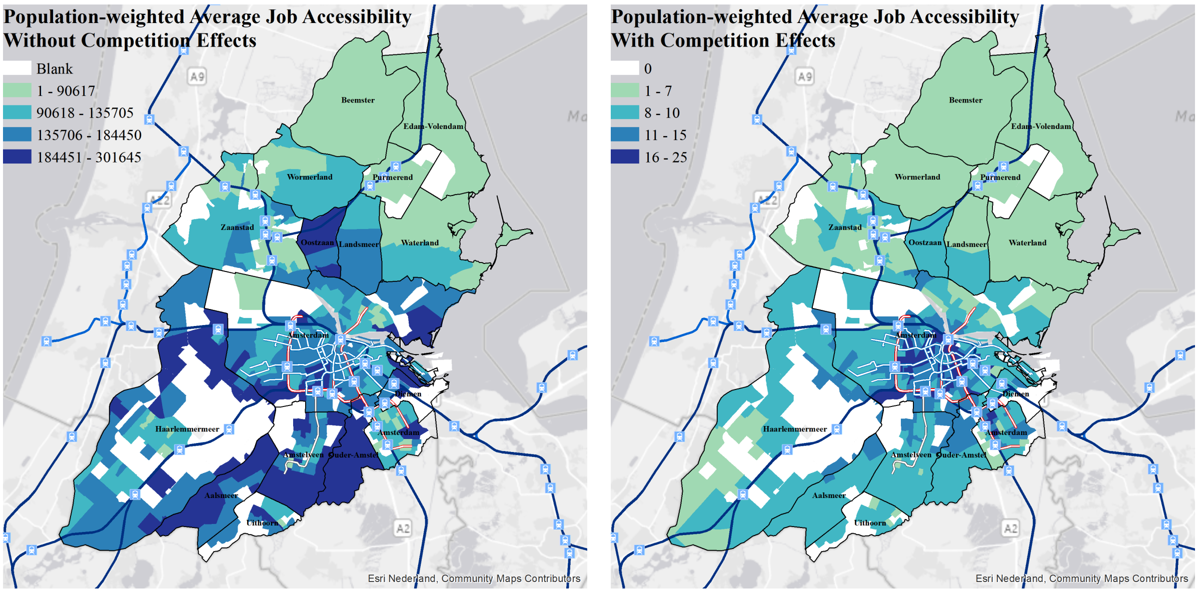
Even though this thesis does not take into account the competition effects, Figure 6.1 and Figure 6.2 are illustrated to show the potential impacts of introducing competition effects on job accessibility distribution by using the supply-demand ratio measure in the IKOB model.

Figure 6.1 shows that the situation of groups with car access and groups without car access almost reversed after taking into account the competition effects; the groups with car access now are the disadvantaged groups in the case study area. Additionally, Figure 6.1 presents a different pattern between job accessibility distribution with and without competition effects. Considering competition effects, the closer to Amsterdam's central area, the lower the competition among commuters. In contrast, Amsterdam is not the best municipality with the highest average job accessibility if competition effects are not included. To understand the reasons behind these differences, a more detailed analysis should be carried out from both the supply and demand side, which is highly recommended in future studies.




(a) (b)

**Figure 6.1:** PMI and Accessibility Coordinate System: without Competition Effects (a); with Competition Effects (b)




(a) (b)

**Figure 6.2:** Population-weighted Average Job Accessibility: without Competition Effects (a); with Competition Effects (b)

# 7
# Conclusion

To conclude, this thesis examined the benefits of transit-shared bike integration in the case study area, Amsterdam Transport Region, showing the significant impact it can make in enhancing accessibility for groups without cars and promoting the equity level of the whole transportation system.

Section 7.1 will answer the research questions, while section 7.2 will discuss this thesis's academic and practical implications. Finally, section 7.3 will present recommendations for the IKOB model, Amsterdam municipality, and future academic research.

## 7.1. Answers to the Research Questions

**Main Research Question:**
*What would be the impacts on job accessibility for commuters without car access and the equity of the whole transportation system in the Amsterdam Transport Region if shared bikes were provided at transit stations as an egress mode?*

Based on the analysis work of this thesis, we found that commuters living near transit stations are more likely to access insufficient jobs and contribute significantly to the overall severity of accessibility deficiency. It can be explained by the fact that groups without car access and groups from the low-income class are concentrated at these locations, but the share of jobs matching their ability is low. Therefore, they face challenges in access to employment even though they have convenient first-mile to transit stations. This implies that transit-shared bike integration would be a promising intervention to enhance their accessibility by facilitating their last mile to destinations and thus make the whole trip more seamless.

After providing shared bikes at transit stations as an egress mode, groups without car access can benefit more than groups with car access. However, benefits tend to favour high-income groups. This phenomenon can be explained by the cost structure, which includes transit and shared bike costs. Although the cost of shared bikes plays a vital role in affecting the impacts of this intervention, transit cost dominates the overall expense for a journey, making the benefits of transit-shared bike integration less effective in alleviating the economic burden and potentially diminishing its attractiveness to commuters on longer trips. Therefore, high-income groups are willing to pay more for travel with longer distances and shorter time. Consequently, although both groups lack car access, high-income commuters are more likely to utilise the potential benefits of transit-shared bike integration than low-income commuters. Geographically, the accessibility improvements are mainly distributed to commuters living next to transit stations, while equity improvements are mainly distributed to areas with dense and developed public transport systems.

**Sub Research Questions:**

**1. What is the most suitable principle to define an equitable distribution in the context of job accessibility?**

Sufficientarianism is argued as a more appropriate theory than utilitarianism and egalitarianism to evaluate social equity. As this study focuses on equity in job accessibility between groups with/without car access, it is essential to identify the group experiencing accessibility inequity and how this group contributes to the overall severity of accessibility inequity. However, utilitarianism assumes everyone is the same and does not consider the distribution effects, and the egalitarian indies only measure the level of equity and fail to identify the groups at risk of social exclusion (Lucas et al., 2016). Additionally, egalitarianism often neglects the heterogeneity within the aggregated groups. Simply minimising disparities does not guarantee that everyone receives a basic level of accessibility. This might result in a transport system that might be regarded as equitable using an egalitarian approach, but most people in that area still have insufficient accessibility (Martens et al., 2022). Therefore, a sufficientarianism approach is more suitable, which ensures that everyone is provided with a basic level of accessibility to reach their key activities.

**2. What influencing factors are relevant in individuals' perceptions of job accessibility?**

The influencing factors that relate to individuals' perceptions of job accessibility are classified into transport, land use, and individual and temporal components. Regarding transport components, factors such as travel resistance (cost, safety, comfort), the functionality and service quality of public transport systems, and the feeling of safety while travelling all affect one's perception of accessibility. For land-use-related factors, the distribution pattern of employment and the effects of competition among scarce resources can affect the individuals' perception of accessibility. The individual component is influenced by socioeconomic and demographic characteristics and a person's capabilities and preferences. Finally, the temporal component considers the time constraints of activity locations and the time availability for individuals.

**3. Which accessibility measure will be applied to incorporate individuals' perceptions to make a more realistic estimate of equity in job accessibility?**

Selecting the most appropriate measure based on the research objectives is important. As this study aims at analysing equity for population groups rather than locations, it is ideal to take individuals' perceptions of accessibility into account as much as possible to make a more realistic and accurate estimate of accessibility, resulting in a better impact evaluation of transport interventions on equity.

Utility-based measures are argued to be more suitable than other measures to estimate accessibility as they can directly reflect an individual's travel behaviour, and there is no need to make prior estimations. However, this measure cannot be easily interpreted and implemented without detailed data. Therefore, this thesis will apply gravity-based accessibility in the IKOB model to calculate accessibility. Firstly, perceptions of employment are represented in a travel time decay curve, which gives less weight to the further away locations. Additionally, the type of employment links to income class, which determines whether individuals can match them. Moreover, travel decay curves are constructed based on differences of individuals in income class, car ownership and mode preference to reflect their behaviour. Even though some other important factors are not included in this model, it can offer a more realistic estimation than other location-based measures that have been applied in the literature.

**4. How can the impacts of providing shared bikes as an egress mode at transit stations on equity in job accessibility be evaluated based on the selected accessibility measure and equity principle?**
To assess the impacts of transit-shared bike integration on equity in job accessibility, the approach proposed by Martens (2016) will be applied as the guideline for equity evaluation. Additionally, the IKOB model proposed by Voerknecht (2021) will be adapted to the context of transit-shared bike integration and calculate the perceived accessibility for different subgroups. Results in the distribution of job accessibility and level of equity within the four scenarios will be compared and analysed visually and statistically.

Considering varied renting costs of shared bikes due to different operating systems and price strategies of different companies, the impacts of transit-shared bike integration on equity in job accessibility are investigated by comparing four scenarios, including a base scenario and three intervention scenarios with varying renting prices (0, 1 and 2 euro per trip). The methodology for this study is structured into three main steps: (1) Impacts Modelling, (2) Accessibility Calculation, and (3) Equity Evaluation.

Firstly, the impacts of locations where commuters can shift from transit to shared bikes are modelled in the IKOB model Voerknecht (2021). A total of 103 locations for transit-shared bike integration are considered in this thesis, combined from several sources, including the NS train stations and P+R facilities in the Amsterdam Metropolitan Area, and service points for shared bikes in the municipality of Amsterdam. In order to incorporate the impacts of transit-shared bike integration, this step involves several assumptions. The first assumption is that the travel decay curve of groups using transit-shared bike integration is assumed to be equal to the transit curve as the transit is the main trip due to calibration and validation difficulties without empirical data. The second assumption is that all commuters will choose the transit stations that provide minimum travel time between each origin and destination. The third assumption is that commuters take the mode that provides maximum weight across their available mode options.

Secondly, as the IKOB model distinguishes 60 subgroups based on preferences, car ownership and income class, the accessibility for each subgroup is calculated first. Afterwards, population-weighted average accessibility for four groups of commuters (low/high-income groups with/without car access) is calculated in four scenarios. In addition, the population-weighted average accessibility for each neighbourhood and the whole Amsterdam Transport Region is also calculated.

Thirdly, a coordinate system integrating the ”Potential Mobility Index” (PMI) and accessibility, along with ”Accessibility Fairness Index” (AFI) in sufficientarian approach (Martens, 2016) will be applied for equity evaluation in all scenarios. The PMI for each subgroup is assumed to be the arithmetic average of their available mode options. The coordinate system will visualise the commuters experiencing accessibility deficiency in neighbourhoods. AFI will represent the severity of deficiency for different commuters or neighbourhoods. Additionally, the contribution to the overall level of accessibility deficiency for different commuters/neighbourhoods will be determined.

**5. What are the potential implications of the outcomes of creating a more equitable transportation system in the Amsterdam Transport Region?**
Firstly, introducing the transit-shared bike may favour high-income groups. Policymakers could propose targeted interventions to protect low-income groups. For example, provide them with an allowance or discount plan for public transport fees to reduce accessibility inequity between different income levels. Secondly, peripheral municipalities, especially those without highway networks and train lines, are also concerned. People there have to rely heavily on buses or private cars, thus having lower accessibility than central and southern municipalities, where public transport systems are more densely distributed. Therefore, policymakers should ensure high-quality bus service to help groups without car access and low income in these neighbourhoods with poor public transport systems. Thirdly, as accessibility results from interaction between transport, land use, individual and temporal components, it is better to carry out combined interventions rather than focusing on one component. Finally, accessibility improvements are mainly distributed in neighbourhoods near transit stations. Improving their first-mile segment to transit stations could benefit other commuters living far away from them. Improving the public transport service or implementing shared bikes at locations where low-income jobs are concentrated could also help this disadvantaged group. In summary, policymakers from the Amsterdam Transport Region could analyse equity in job accessibility in a disaggregate manner to identify the groups suffering from accessibility inequity, understand the reasons behind them, and then prioritise the policies. Analysing accessibility and equity distribution is beneficial to creating a more equitable transportation system in the Amsterdam Transport Region.

## 7.2. Implications

### 7.2.1. Academic Implications

The thesis fills the research gap that no literature evaluates the impacts of transit-shared bike integration based on sufficientarianism. It introduces the effects of the location, which allows travellers to shift from transit to shared bikes rather than a simple assumption that transfer can happen in all areas. Furthermore, this thesis utilised the IKOB model to provide a more realistic representation of individuals' accessibility by incorporating the influencing factors of perceptions in transport, land use and individual components. The final results in the thesis reveal the promising potential of providing shared bikes at transit stations as an egress mode in improving the accessibility for groups without car access, as well as promoting the equity level of the whole transport system.

### 7.2.2. Practical Implications

This thesis is the first literature combining the IKOB model and the sufficientarian approach to comprehensively analyse accessibility and equity from aggregated regions to disaggregated subgroups. Aggregate results align better with broad transportation policy decisions, allowing policymakers to focus on overall trends. When the policy aims to identify and address specific equity issues among different subgroups, a disaggregate analysis can offer more appropriate guidance to avoid ignorance of people more likely to experience accessibility deficiency.

Secondly, this thesis emphasises the importance of taking into account the heterogeneity of individuals' perceptions of accessibility when analysing equity in accessibility. By incorporating the critical influencing factors that shape perceived accessibility for different individuals in land use, individuals, transport and temporal components, it helps understand who is experiencing unfair accessibility and to what extent they are suffering and advance the targeted transport policy to create a more equitable transportation system.

Thirdly, some observations can be implied for the Amsterdam Transport Region or a broader context. For example, introducing the transit-shared bike may favour high-income groups. Also, when considering factors related to perception, such as travel costs, the employment competence of individuals, and mode preference, the disadvantaged group experiencing accessibility deficiency is concentrated near transit stations, even though people could benefit from the high connectivity of the first mile to access the public transport systems.

## 7.3. Recommendations

### 7.3.1. Recommendations for the IKOB Model

**The Synergy of the IKOB Model and Sufficientarian Approach**
It is highly recommended that the IKOB model and the sufficientarian approach be integrated and operationalised to offer a more comprehensive approach to equity assessment. These two methodologies are all designed for analysis from different disaggregate perspectives by distinguishing groups and weighting their population. The IKOB model has high adaptability to accommodate most transport scenarios because of its general framework of accessibility calculation, which is not included in the sufficientarian approach. However, the IKOB model needs a framework for equity assessment, which the sufficientarian approach can complement. The synergy between these two methodologies can be beneficial for research about equity and accessibility.

**Parameters of Travel Time Decay Curve**
It is essential to update the functions and parameters of the travel time decay function periodically to keep them in line with changing travel behaviours. The socioeconomic data derived from 2015 needs to be updated to represent the current situation in the case study area accurately. Although the infrastructure might not have undergone significant changes, the distribution of car ownership, mode preference, and income class may have changed significantly in some neighbourhoods over the past years. As a result, the distribution of population groups and the parameters of the travel decay function, which were calibrated and validated based on

the data, would be affected. Therefore, it is recommended that data be updated regularly to obtain the most realistic current situation.

### 7.3.2. Recommendations for Amsterdam Transport Region

**Disaggregate Analysis for Targeted Policies**

Instead of analysis from the aggregate level, it is better to conduct a disaggregate analysis for equity issues. Factors in transport, land use, and individual and temporal components should be considered when understanding their difficulty in accessing opportunities. It can help understand groups suffering from accessibility deficiency and thus help propose prioritised policies.

For instance, although this thesis indicates promising benefits of transit-shared bike integration on job accessibility and equity, realising these promising benefits involves challenges and essential efforts, such as infrastructure development and maintenance, transit service quality, and convenience and ease of payment. Meanwhile, the benefits tend to favour high-income groups. Therefore, it is recommended that low-income groups be protected by offering targeted policies. In addition, the locations of transit-shared bikes are selected at the transit stations in this thesis. However, low-income jobs account for less than high-income jobs in these places, which indicates this intervention might not help low-income groups whose workplace locations relative to the transit station are far away. Therefore, it is more effective to introduce this intervention where low-income jobs are concentrated to improve their accessibility. Finally, several northern municipalities (Oostzaan, Landsmeer, Waterland, Edam-Volendam) are observed to provide insufficient accessibility for most commuters, particularly municipalities without highway networks and train lines, forcing people to rely on buses or private cars. Therefore, high-quality bus service or allowance for public transport is recommended to help groups without car access and low income.

### 7.3.3. Recommendations for Future Academic Research

**Travel Behaviour Representation**

Several assumptions were made in this thesis that are primarily related to the travel behaviour of the individuals. These limitations can be improved in future research to generate more accurate results. Firstly, as utility-based accessibility measures do not need to make a priori assumptions given they are derived from travel behaviour theory, this measure could be applied to link the accessibility and actual travel behaviour. Secondly, one unexploited research direction is constructing the travel time decay curve for multimodal chain trips to better incorporate its impacts. Thirdly, the individuals' perception of safety and service quality of transport service also shapes how they value the opportunities. These subjective terms can be incorporated into calculating the experienced travel time.

**Competition effects**

Employment is often a scarce resource, which means it has competition effects. Even though one region has a dense distribution of employment, job accessibility might still be low as more people are going to this region, which may reduce the possibility of being employed and tends to overestimate the number of jobs people can access. Therefore, it is recommended that competition effects are incorporated when analysing job accessibility. However, it is also important to note that introducing competition effects will increase the complexity and difficulty in interpretation.

**Impacts of Multimodal Hubs**

The final recommendation is to investigate the impacts of multimodal hubs on accessibility and equity as some other promising modes can also be integrated with transit to enhance accessibility, especially e-mobilities, which could provide more benefits than traditional modes. Additionally, the capacity problem of shared bikes at each station can help balance the demand and supply and optimise the service to attract more users. Last but not least, when implementing the hubs into the transportation networks, it is also interesting to investigate to what extent each hub could benefit people, which can help in understanding the possible reasons for the improvements.

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# A

# Appendix: Socio-economic Data in the IKOB Algorithm

### Determine car ownership

**Table A.1:** Percentage of Car Ownership per Urbanisation Degree and Income Class (source: CBS)

| Urbanisation degree | Low | Middle low | Middle high | High |
|---|---|---|---|---|
| 1 | 33 | 59 | 78 | 94 |
| 2 | 49 | 74 | 91 | 97 |
| 3 | 60 | 80 | 94 | 97 |
| 4 | 66 | 84 | 95 | 98 |
| 5 | 70 | 86 | 96 | 97 |

**Table A.2:** Percentage of People without a Car with a Driving License per Income Class and Urbanisation Degree (source: CBS)

| Urbanisation degree | Low | Middle low | Middle high | High |
|---|---|---|---|---|
| 1 | 29 | 20 | 14 | 4 |
| 2 | 21 | 12 | 5 | 2 |
| 3 | 15 | 8 | 3 | 1 |
| 4 | 12 | 6 | 2 | 0 |
| 5 | 10 | 5 | 2 | 1 |

**Table A.3:** Percentage without a Driving License per Urbanisation Degree and Income Class (source: CBS)

| Urbanisation degree | Low | Middle low | Middle high | High |
|---|---|---|---|---|
| 1 | 38 | 21 | 9 | 2 |
| 2 | 29 | 14 | 4 | 1 |
| 3 | 25 | 12 | 3 | 2 |
| 4 | 22 | 10 | 2 | 2 |
| 5 | 20 | 9 | 2 | 2 |

## Determine free car and free public transport

**Table A.4:** Percentage of Company Cars per Income Class (source: VZR)

| Income class | Percentage of company cars |
|---|---|
| High | 27.5% |
| Middle high | 17.5% |
| Middle low | 2.0% |
| Low | 0% |

**Table A.5:** Percentage of People with Free Public Transport per Urbanisation Degree (estimate based on NS data)

| Income class | Percentage of Free Transit |
|---|---|
| High | 4.0% |
| Middle high | 2,5% |
| Middle low | 1.0% |
| Low | 0.% |

## Determine Preferences

**Table A.6:** Percentages of Preferences for Transport Modes per Urbanisation Degree (source: OVIN and survey by the municipality of Amsterdam)

| Urbanisation degree | Car | Neutral | Bike | Transit |
|---|---|---|---|---|
| 1 | 25 | 25 | 30 | 20 |
| 2 | 35 | 25 | 30 | 10 |
| 3 | 50 | 20 | 25 | 5 |
| 4 | 70 | 10 | 15 | 5 |
| 5 | 85 | 5 | 10 | 0 |

**Table A.7:** Percentages of Preferences for Transport Modes per Urbanisation Degree for Who Do Not Own a Car (source: OVIN and survey by the municipality of Amsterdam)

| Urbanisation degree | Neutral | Bike | Transit |
|---|---|---|---|
| 1 | 33 | 40 | 27 |
| 2 | 38 | 46 | 15 |
| 3 | 40 | 50 | 10 |
| 4 | 33 | 50 | 17 |
| 5 | 33 | 67 | 0 |

**Table A.8:** Distribution of Income levels based on Education Levels (source: CBS data and analyses by the municipality of Amsterdam)

| Income | Low and allowance | Middle | High | Total |
|---|---|---|---|---|
| Low | 20% | 4% | 1% | 25% |
| Middle Low | 6% | 16% | 3% | 25% |
| Middle High | 2% | 12% | 11% | 25% |
| High | 1% | 4% | 20% | 25% |
| Total | 29% | 36% | 35% | 100% |

## Calculation of experienced travel time

**Table A.9:** Parking Searching Time in Minute by Urbanisation Degree (source: OVIN and survey by the municipality of Amsterdam)

| Urbanisation degree | Arrival search time | Departure search time |
|---|---|---|
| 1 | 12.5 | 5 |
| 2 | 7.5 | 2.5 |
| 3 | 4 | 2 |
| 4 | 0 | 0 |
| 5 | 0 | 0 |

**Table A.10:** Value of Costs in Experienced Travel Time per Income Class with Commuting Motive

| Income class | Value of Costs |
|---|---|
| High | 4 Min/Euro |
| Middle high | 6 Min/Euro |
| Middle low | 9 Min/Euro |
| Low | 12 Min/Euro |

### Weights

**Table A.11:** Values of the Constants in the Travel Time Decay Curve for the Commuting Motive

| Modes | $\alpha$ | $\omega$ | $W$ |
|---|---|---|---|
| | | Preferred car | |
| Car | 0.125 | 50 | 1 |
| Transit | 0.125 | 30 | 0.95 |
| Bicycle | 0.225 | 25 | 1 |
| | | Preferred neutral | |
| Car | 0.125 | 45 | 1 |
| Transit | 0.125 | 45 | 1 |
| Bicycle | 0.225 | 25 | 1 |
| | | Preferred transit | |
| Car | 0.125 | 45 | 0.96 |
| Transit | 0.12 | 60 | 1 |
| Bicycle | 0.225 | 35 | 1 |
| | | Preferred bikes | |
| Car | 0.125 | 45 | 0.75 |
| Transit | 0.125 | 45 | 1 |
| Bicycle | 0.175 | 35 | 1 |

# B

# Appendix: Locations of Transit-Shared Integration

### Locations of P+R Facilities

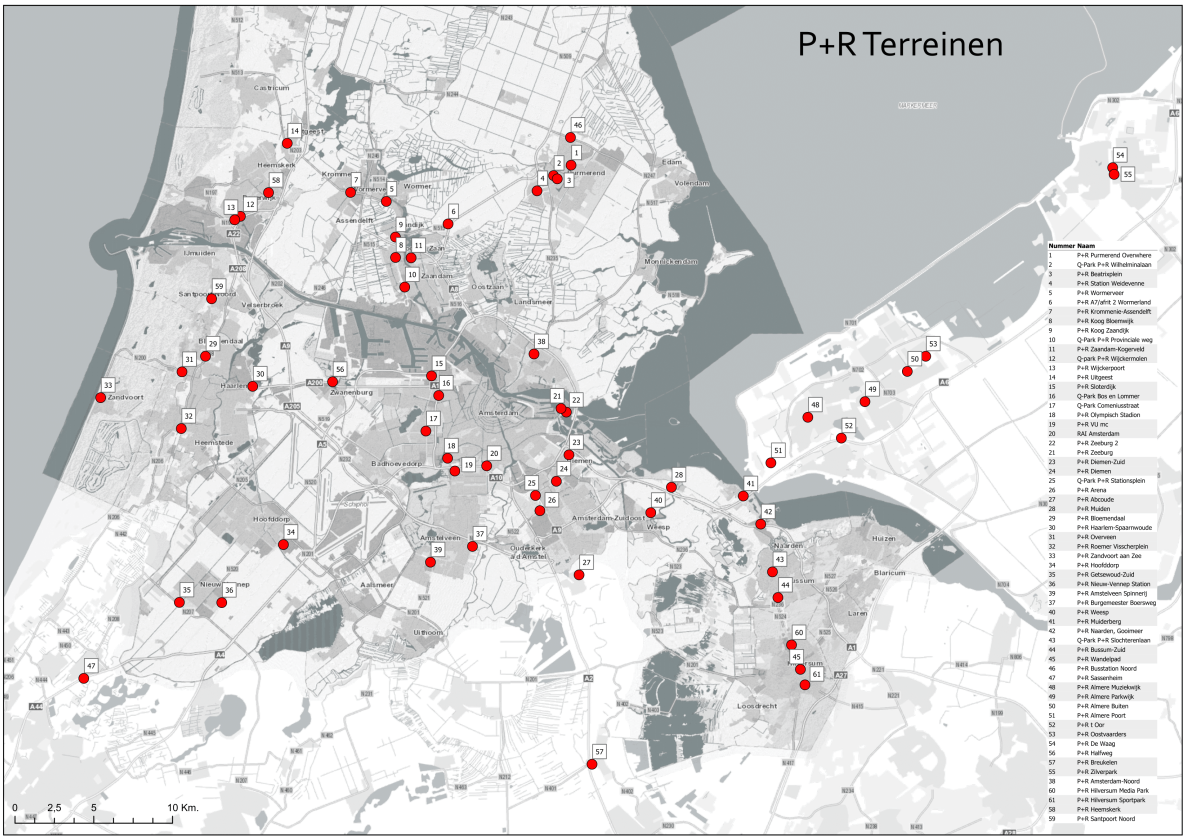


**Figure B.1:** Locations of P+R Facilities in the Amsterdam Metropolitan Area: From Mobility (2023)

**Table B.1:** Locations of P+R Facilities in the Amsterdam Transport Region

| P+R Name | Mode(s) |
|---|---|
| **Municipality of Aalsmeer** | |
| **Municipality of Amstelveen** | |
| P+R Burgemeester Boersweg | Bus + Tram (Ouderkerkerlaan) |
| P+R Amstelveen Spinnerij | Bus + Tram |
| **Municipality of Amsterdam** | |
| P+R Sloterdijk | Train + BTM |
| Q-Park Bos en Lommer | Bus + Tram (Bos en Lommerplein) |
| Q-Park Comeniusstraat | Train + BTM (Lelylaan) |
| P+R Olympisch Stadion | Bus + Tram (Olympisch Stadion) |
| P+R VU mc | BTM (Amstelveenseweg) |
| RAI Amsterdam | Train + BTM (RAI) |
| P+R Zeeburg | Bus + Tram (Zuiderzeeweg) |
| P+R Zeeburg 2 | Bus + Tram (Bob Haarmslaan) |
| Q-Park P+R Stationsplein | Train + Bus + Metro (Duivendrecht) |
| P+R Arena | Train + Bus + Metro (Bijlmer ArenA) |
| Amsterdam Noord | Bus + Metro (Noord) |
| **Municipality of Diemen** | |
| P+R Diemen-Zuid | Train + Tram + Bus (Diemen Zuid) |
| P+R Diemen | Train + Bus (Diemen) |
| **Municipality of Edam-Volendam** | |
| **Municipality of Haarlemmermeer** | |
| P+R Hoofddorp | Train + Bus (Hoofddorp) |
| P+R Getsewoud-Zuid | Bus (Getsewoud P+R) |
| P+R Nieuw-Vennep Station | Train + Bus (Nieuw-Vennep) |
| **Municipality of Landsmeer** | |
| **Municipality of Oostzaan** | |
| **Municipality of Ouder-Amstel** | |
| **Municipality of Purmerend** | |
| P+R Purmerend Overwhere | Train (Overwhere) + Bus |
| P+R Wilhelminalaan | Train + Bus (Purmerend) |
| P+R Beatrixplein | Train + Bus (Purmerend) |
| P+R Station Weidevenne | Train + Bus (Weidevenne) |
| P+R Busstation Noord | Bus (P+R N244) |
| **Municipality of Uithoorn** | |
| **Municipality of Waterland** | |
| **Municipality of Wormerland** | |
| P+R Wormerland | Bus (P+R Wormerland A7) |
| **Municipality of Zaanstad** | |
| P+R Wormerveer | Train + Bus (Wormerveer) |
| P+R Krommenie-Assendelft | Train + Bus (Krommenie-Assendelft) |
| P+R Koog Bloemwijk | Train + Bus (Koog aan de Zaan) |
| P+R Koog Zaandijk | Train + Bus (Zaandijk Zaanse Schans) |

Table B.1 – continued from previous page

| **P+R Name** | **Mode(s)** |
|---|---|
| Q-Park P+R Provinciale weg | Train + Bus (Koog aan de Zaan) |
| P+R Zaandam Kogerveld | Train + Bus (Zaandam Kogerveld) |
| **Outside of Amsterdam Transport Region** | |
| Q-park P+R Wijckermole | Train + Bus (Beverwijk) |
| P+R Wijckerpoort | Train + Bus (Beverwijk) |
| P+R Uitgeest | Train + Bus (Uitgeest) |
| P+R Abcoude | Train + Bus (Abcoude) |
| P+R Muiden | Bus (Muiden) |
| P+R Bloemendaa | Train + Bus (Bloemendaal) |
| P+R Haarlem Spaarnwoude | Train + Bus (Spaarnwoude) |
| P+R Overvee | Train + Bus (Overveen) |
| P+R Roemer Visscherple | Train + Bus (Heemstede-Aerdenhout) |
| P+R Zandvoort aan Zee | Train + Bus (Zandvoort aan Zee) |
| P+R Weesp | Train + Bus (Weesp) |
| P+R Muiderberg | Bus (Muiderberg) |
| P+R Naarden, Gooimeer | Bus (Gooimeer) |
| Q-Park P+R Slochterenlaa | Train + Bus (Naarden-Bussum) |
| P+R Bussum-Zuid | Train + Bus (Bussum Zuid) |
| P+R Wandelpad | Train + Bus (Hilversum) |
| P+R Sassenheim | Train + Bus (Sassenheim) |
| P+R Almere Muziekwijk | Train + Bus (Muziekwijk) |
| P+R Almere Parkwijk | Train + Bus (Almere Parkwijk) |
| P+R Almere Buiten | Train + Bus (Almere Buiten) |
| P+R Almere Poort | Train + Bus (Almere Poort) |
| P+R t Oo | Bus (Busstation ’t Oor) |
| P+R Oostvaarders | Train + Bus (Almere Oostvaarders) |
| P+R De Waag | Train + Bus (Lelystad Centrum) |
| P+R Zilverpark | Train + Bus (Lelystad Centrum) |
| P+R Halfweg | Train + Bus (Halfweg-Zwanenburg) |
| P+R Breukelen | Train + Bus (Breukelen) |
| P+R Heemskerk | Train + Bus (Heemskerk) |
| P+R Santpoort Noord | Train + Bus (Santpoort Noord) |
| P+R Hilversum Media Park | Train + Bus (Hilversum Media Park) |
| P+R Hilversum Sportpark | Train + Bus (Hilversum Sportpark) |

### Locations of Hubs and Transit-Shared Bike Integration in Amsterdam

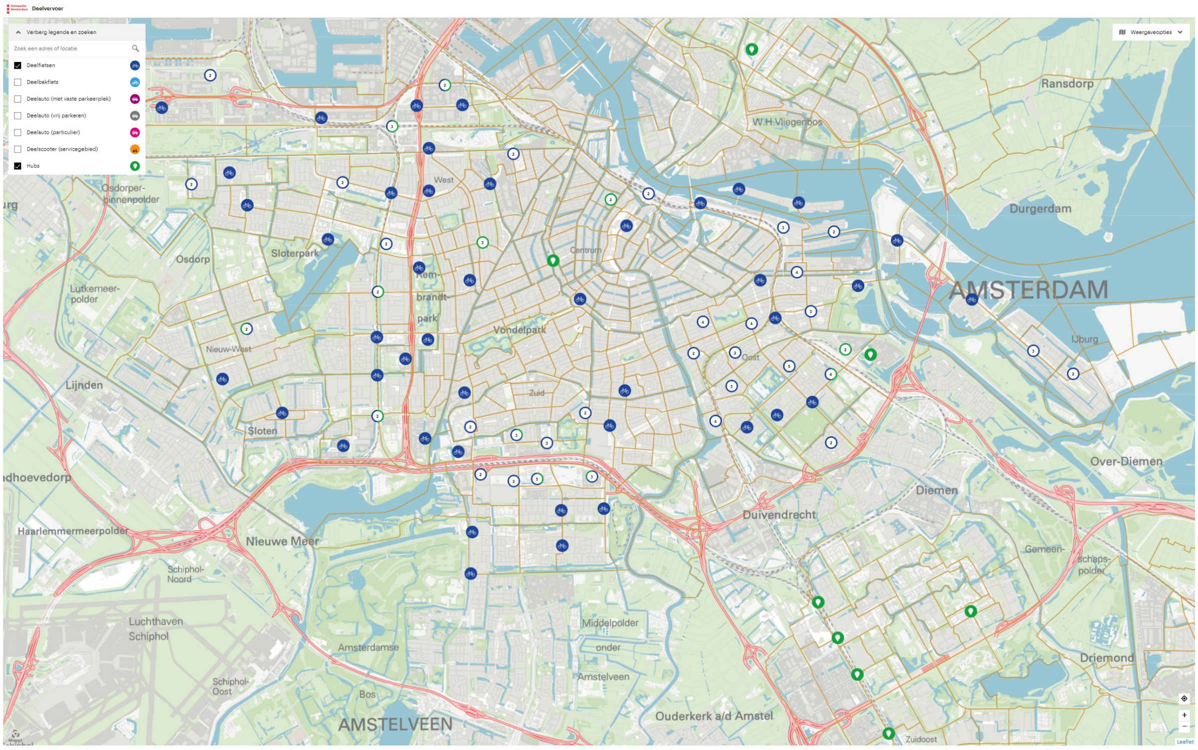


**Figure B.2:** Locations of Transit-Shared Bike Integration in Amsterdam: From Amsterdam (2023)

**Table B.2:** Locations of Hubs and Transit-Shared Bike Integration in the Amsterdam

| Station Name | Mode(s) |
|---|---|
| **Hubs** | |
| Elandsgracht | Bus+Tram |
| Isolatorweg | Metro |
| Sloterdijk | Train + Bus + Metro |
| Postjesweg | Bus + Metro |
| Hoekenes | Bus + Tram |
| Henk Sneevlietweg | Bus + Metro |
| Amsterdam Zuid | Train + Metro |
| Science Park A'dam | Bus |
| Science Park | Train + Bus |
| Strandvliet | Metro |
| Bijlmer ArenA | Train +Bus +Metro |
| Bullewijk | Metro |
| Holendrecht | Train + Bus + Metro |
| Kraaiennest | Metro + Bus |
| **Transit-Shared Bike Integration** | |
| Oderweg | Bus |
| Plein '40-45 | Bus + Tram |

Table B.2 – continued from previous page

| **Station Name** | **Mode(s)** |
|---|---|
| Burg. Eliasstraat | Bus + Tram |
| Molenwerf | Tram |
| Contactweg | Bus |
| Amsterdam Centraal | Train + Bus + Tram + Metro |
| Piet Heinkade | Bus + Tram |
| Rietlandpark | Tram |
| C. van Eesterenlaan | Tram |
| Borneolaan | Bus |
| Zuiderzeeweg | Bus + Tram |
| Steigereiland | Bus + Tram |
| Vennepluimstraat | Bus + Tram |
| Diemerparklaan | Bus + Tram |
| Lumierestraat | Bus + Tram |
| Ijburg | Tram |
| Lelylaan | Train + Bus + Tram + Metro |
| Burg.de Vlugtlaan | Bus + Tram + Metro |
| Jan van Galenstraat | Bus + Metro |
| Leidseplein | Tram |
| Wibautstraat | Bus + Metro |
| Amstel | Train + Bus + Tram + Metro |
| Prins Bernhardplein | Bus |
| James Wattstraat | Bus |
| Flevopark | Tram |
| Kruislaan | Bus + Tram |
| Brinkstraat | Bus + Tram |
| Hogeweg | Bus + Tram |
| Oostpoort | Bus + Tram |
| Veelaan | Bus |
| Muiderpoort | Train + Bus + Tram |
| Linnaeusstraat | Bus + Tram |
| Pontanusstraat | Tram |
| Javaplein | Bus |
| Molukkenstraat | Bus + Tram |
| Baden Powellweg | Bus + Tram |
| Centrum Nieuw Sloten | Tram |
| Heemstedestraat | Tram |
| Kalfjeslaan | Bus |
| RAI | Train + Tram + Metro |
| Scheldeplein | Bus |
| Olympisch Stadion | Bus + Tram |
| Prinses Irenestraat | Bus + Tram |
| Amstelveenseweg | Bus + Tram + Metro |
| Vumc | Bus + Tram |

Table B.2 – continued from previous page

| Station Name | Mode(s) |
|---|---|
| De Boelelaan/VU Tram Bus | Bus + Tram |

### Locations of NS Stations in the Amsterdam Metropolitan Area

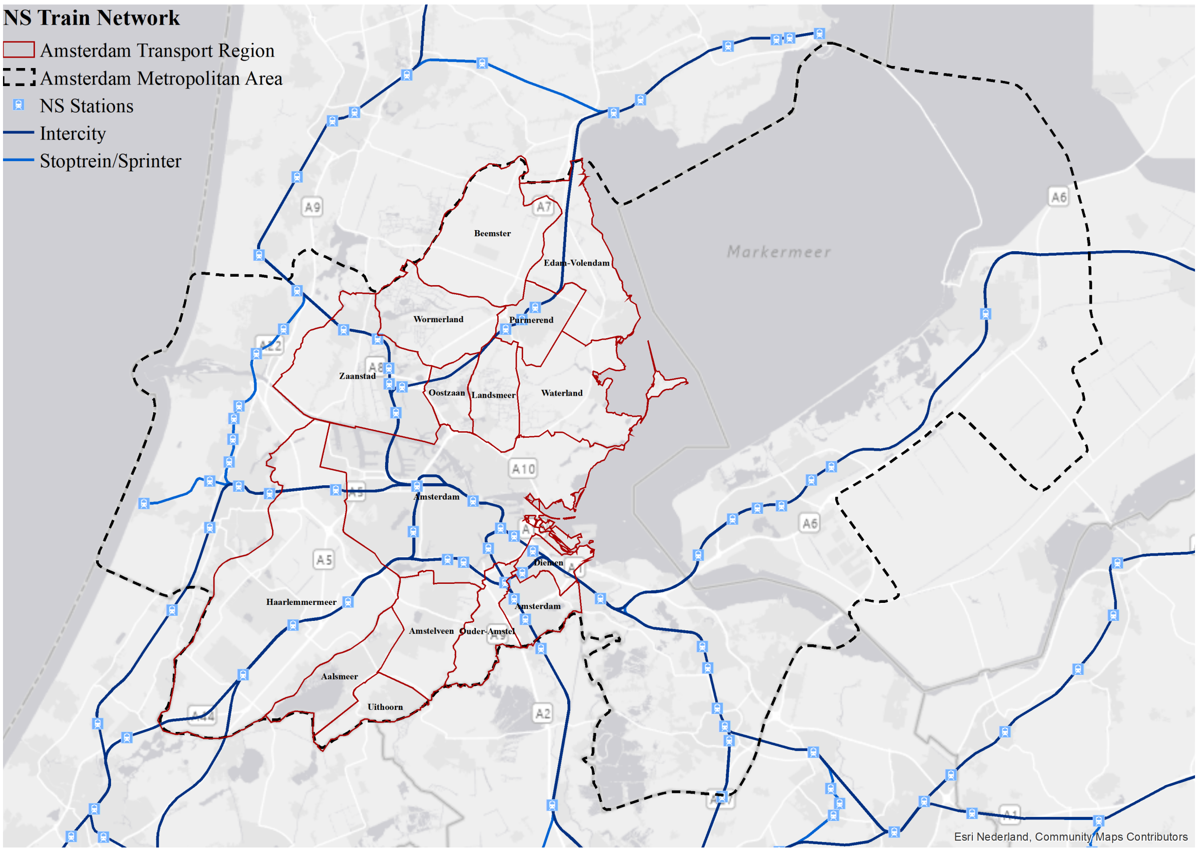


**Figure B.3:** Distribution of NS Stations in the Amsterdam Metropolitan Area

**Table B.3:** NS Stations in the Amsterdam Metropolitan Area

| Number | Station Name | Number | Station Name |
|---|---|---|---|
| **Within the Amsterdam Transport Region** | | | |
| 1 | Amsterdam Centraal | 14 | Nieuw-Vennep |
| 2 | Amsterdam Sloterdijk | 15 | Hoofddorp |
| 3 | Amsterdam Lelylaan | 16 | Schiphol Airport |
| 4 | Amsterdam Zuid | 17 | Halfweg-Zwanenburg |
| 5 | Amsterdam RAI | 18 | Purmerend Overwhere |
| 6 | Amsterdam Amstel | 19 | Purmerend |
| 7 | Amsterdam Science Park | 20 | Purmerend Weidevenne |
| 8 | Amsterdam Muiderpoort | 21 | Krommenie-Assendelft |
| 9 | Duivendrecht | 22 | Wormerveer |

Table B.3 – continued from previous page

| Number | Station Name | Number | Station Name |
|---|---|---|---|
| 10 | Amsterdam Bijlmer ArenA | 23 | Zaandijk Zaanse Schans |
| 11 | Amsterdam Holendrecht | 24 | Koog aan de Zaan |
| 12 | Diemen Zuid | 25 | Zaandam Kogerveld |
| 13 | Diemen | 26 | Zaandam |
| **With the Amsterdam Metropolitan Area** | | | |
| 27 | Spaarnwoude | 39 | Weesp |
| 28 | Uitgeest | 40 | Almere Poort |
| 29 | Heemskerk | 41 | Muziekwijk |
| 30 | Beverwijk | 42 | Almere Centrum |
| 31 | Driehuis | 43 | Almere Parkwijk |
| 32 | Santpoort Noord | 44 | Almere Buiten |
| 33 | Santpoort Zuid | 45 | Almere Oostvaarders |
| 34 | Bloemendaal | 46 | Lelystad Centrum |
| 35 | Overveen | 47 | Naarden-Bussum |
| 36 | Haarlem | 48 | Bussum Zuid |
| 37 | Zandvoort aan Zee | 49 | Hilversum Media Park |
| 38 | Heemstede-Aerdenhout | 50 | Hilversum |
| | | 51 | Hilversum Sportpark |

# C

# Appendix: Accessibility Deficiency Information

**Table C.1:** Sufficiency and Insufficiency at Neighbourhood-level and Group-level in Price = 0

| Disaggregate Level | Weighted Average Job Accessibility | Sufficiency in Neighbourhoods | Deficiency in Neighbourhoods |
|---|---|---|---|
| **Group Level-1** | 132807 | 567 | 100 |
| **Group Level-2** | | | |
| Groups with Car Access | 152201 | 651 | 16 |
| Groups without Car Access | 102528 | 75 | 592 |
| **Group Level-3** | | | |
| Group_1 ($With\_car\_low$) | 93113 | 644 | 23 |
| Group_2 ($With\_car\_high$) | 196606 | 654 | 9 |
| Group_3 ($Without\_car\_low$) | 94560 | 47 | 620 |
| Group_4 ($Without\_car\_high$) | 134683 | 144 | 519 |

**Table C.2:** Sufficiency and Insufficiency at Neighbourhood-level and Group-level in Price =1

| Disaggregate Level | Weighted Average Job Accessibility | Sufficiency in Neighbourhoods | Deficiency in Neighbourhoods |
|---|---|---|---|
| **Group Level-1** | 128200 | 562 | 105 |
| **Group Level-2** | | | |
| Groups with Car Access | 150121 | 651 | 16 |
| Groups without Car Access | 93999 | 44 | 623 |
| **Group Level-3** | | | |
| Group_1 ($With\_car\_low$) | 90427 | 644 | 23 |
| Group_2 ($With\_car\_high$) | 194980 | 651 | 12 |
| Group_3 ($Without\_car\_low$) | 86541 | 0 | 667 |
| Group_4 ($Without\_car\_high$) | 124096 | 124 | 539 |

**Table C.3:** Sufficiency and Insufficiency at Neighbourhood-level and Group-level in Price =2

| Disaggregate Level | Weighted Average Job Accessibility | Sufficiency in Neighbourhoods | Deficiency in Neighbourhoods |
|---|---|---|---|
| **Group Level-1** | 126973 | 561 | 106 |
| **Group Level-2** | | | |
| Groups with Car Access | 149566 | 651 | 16 |
| Groups without Car Access | 91728 | 24 | 643 |
| **Group Level-3** | | | |
| Group_1 ($With\_car\_low$) | 90055 | 644 | 23 |
| Group_2 ($With\_car\_high$) | 194287 | 651 | 12 |
| Group_3 ($Without\_car\_low$) | 85103 | 0 | 667 |
| Group_4 ($Without\_car\_high$) | 118467 | 110 | 553 |

**Table C.4:** Overview of Groups with Accessibility Deficiency in Price = 0

| Disaggregate Level | Population Share | Share of Deficiency in Group | Share of Deficiency in Total Population | Contribution to the Overall Deficiency |
|---|---|---|---|---|
| **Group Level-1** | 100% | 15.18% | 15.18% | 100% |
| **Group Level-2** | | | | |
| Groups with Car Access | 60.8% | 1.31% | 0.80% | 1.13% |
| Groups without Car Access | 39.2% | 58.52% | 22.92% | 98.87% |
| **Group Level-3** | | | | |
| Group_1 ($With\_car\_low$) | 26.1% | 1.44% | 0.38% | 2.18% |
| Group_2 ($With\_car\_high$) | 34.8% | 1.02% | 0.35% | 0.17% |
| Group_3 ($Without\_car\_low$) | 31.4% | 73.85% | 23.18% | 86.41% |
| Group_4 ($Without\_car\_high$) | 7.8% | 29.35% | 2.28% | 11.22% |

**Table C.5:** Overview of Groups with Accessibility Deficiency in Price = 1

| Disaggregate Level | Population Share | Share of Deficiency in Group | Share of Deficiency in Total Population | Contribution to the Overall Deficiency |
|---|---|---|---|---|
| **Group Level-1** | 100% | 16.55% | 16.55% | 100% |
| **Group Level-2** | | | | |
| Groups with Car Access | 60.8% | 1.31% | 0.80% | 1.19% |
| Groups without Car Access | 39.2% | 75.92% | 29.73% | 98.81% |
| **Group Level-3** | | | | |
| Group_1 ($With\_car\_low$) | 26.1% | 1.44% | 0.38% | 2.05% |
| Group_2 ($With\_car\_high$) | 34.8% | 1.34% | 0.46% | 0.20% |
| Group_3 ($Without\_car\_low$) | 31.4% | 100% | 31.39% | 86.44% |
| Group_4 ($Without\_car\_high$) | 7.8% | 33.46% | 2.60% | 11.31% |

**Table C.6:** Overview of Groups with Accessibility Deficiency in Price =2

| Disaggregate Level | Population Share | Share of Deficiency in Group | Share of Deficiency in Total Population | Contribution to the Overall Deficiency |
|---|---|---|---|---|
| **Group Level-1** | 100% | 17.04% | 17.04% | 100% |
| **Group Level-2** | | | | |
| Groups with Car Access | 60.8% | 1.31% | 0.80% | 1.21% |
| Groups without Car Access | 39.2% | 89.90% | 35.21% | 98.79% |
| **Group Level-3** | | | | |
| Group_1 ($With\_car\_low$) | 26.1% | 1.44% | 0.38% | 2.01% |
| Group_2 ($With\_car\_high$) | 34.8% | 1.34% | 0.46% | 0.22% |
| Group_3 ($Without\_car\_low$) | 31.4% | 100% | 31.39% | 86.09% |
| Group_4 ($Without\_car\_high$) | 7.8% | 35.784% | 2.78% | 11.68% |

**Table C.7:** Improvements in Number of Average Job Accessibility in the Three Pricing Scenarios

| Disaggregate Level | Scenario_Price_0 | Scenario_Price_1 | Scenario_Price_2 |
|---|---|---|---|
| **Group Level-1** | 6290 | 1683 | 456 |
| **Group Level-2** | | | |
| Groups with Car Access | 2832 | 752 | 197 |
| Groups without Car Access | 11659 | 3130 | 859 |
| **Group Level-3** | | | |
| Group_1 ($With\_car\_low$) | 3076 | 390 | 18 |
| Group_2 ($With\_car\_high$) | 2650 | 1024 | 331 |
| Group_3 ($Without\_car\_low$) | 9585 | 1566 | 128 |
| Group_4 ($Without\_car\_high$) | 20030 | 9443 | 3814 |

**Table C.8:** Overview of Groups with Accessibility Deficiency

| Disaggregate Level | Scneario_Price_0 | | Scenario_Price_1 | | Scenario_Price_2 | |
|---|---|---|---|---|---|---|
| | Population | Percentage | Population | Percentage | Population | Percentage |
| **Group Level-1** | 99.88% | 4.97% | 99.14% | 1.33% | 97.72% | 0.36% |
| **Group Level-2** | | | | | | |
| Groups with Car Access | 90.37% | 1.90% | 84.27% | 0.50% | 73.26% | 0.13% |
| Groups without Car Access | 99.97% | 12.83% | 99.79% | 3.44% | 99.26% | 0.95% |
| **Group Level-3** | | | | | | |
| Group_1 ($With\_car\_low$) | 90.62% | 3.42% | 81.78% | 0.43% | 44.91% | 0.02% |
| Group_2 ($With\_car\_high$) | 86.93% | 1.37% | 81.56% | 0.53% | 70.42% | 0.17% |
| Group_3 ($Without\_car\_low$) | 99.68% | 11.28% | 97.79% | 1.84% | 89.86% | 0.15% |
| Group_4 ($Without\_car\_high$) | 99.97% | 17.47% | 99.75% | 8.24% | 99.35% | 3.33% |

*Population represents the share of population group who benefits from the interventions.
*Percentage represents the percentage of improvements in average job accessibility.