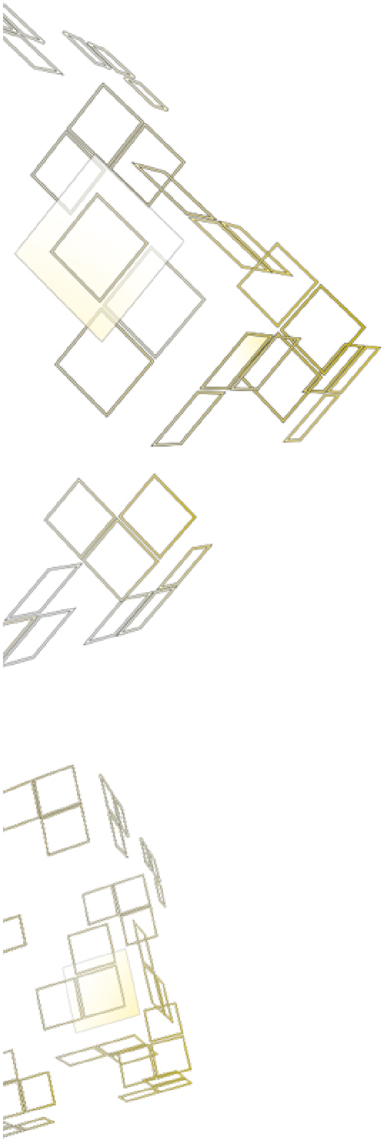

FINAL REPORT

INVESTIGATING ACCESSIBILITY AND RELATED INEQUALITIES USING A LOGSUM METRIC GROUNDED ON A MICROSCOPIC TRANSPORT DEMAND MODEL

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GLOSSARY

Term	Explanation	Further discussion in section:
Accessibility	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)	2.1
Mobility	The movement of people using various modalities in the transport network.	2.1
Microscopic transport model	The modelling approach in which a certain number of agents are created each having specific characteristics and corresponding behaviour in the transport system forming together a synthetic population.	3.1
Macroscopic transport model	A modelling approach to predict the average behaviour to model and analyse traffic flows as a whole.	3.1
Disaggregated transport modelling	Modelling approach in which the total population is divided into several groups of travellers that have identical characteristics. The behaviour of travellers belonging to the same group is subsequently predicted by the same models.	3.1
Aggregate transport modelling	Modelling approach in which the behaviour of individual travellers is combined to analyse the average behaviour of the complete population.	3.1
Inequalities	Refers to the distribution of a certain irrespective of moral judgment	2.2
Inequities	The moral judgment of whether the distribution of a certain good is considered fair	2.2
Integrale kijk of bereikbaarheid (IKOB)	Model to calculate accessibility by retrospectively disaggregating the general population into dozens of segments and finding the specific accessibility of each of them.	4.3.1
Octavius	An agent-based microscopic strategic transport demand model created by Goudappel. It aims to investigate travel patterns by modelling the behavioural choices of individual travellers.	4.3.2
Segment	A way of modeling the behaviour of various groups in the population. People belonging to the same segment have identical characteristics whilst people from two different segments vary in at least one matter.	3.1

ABSTRACT

Many accessibility analyses practically applied in the Netherlands only model the behaviour of the average population. As a result, more specific questions like does a measure increase disparities between people cannot be addressed. Therefore, there is a demand for more detailed approaches. One such approach is the emerging “Integrale kijk op bereikbaarheid” (IKOB) model. Moreover, the microscopic strategic transport demand model Octavius has just been completed by Goudappel. This model contains valuable information since it is one of the most detailed models to predict travel behaviour in the Netherlands. In this study, an approach is introduced to apply the information from the Octavius model to calculate accessibility with the so-called logsum approach as proposed by Ben-Akiva & Lerman (1985). This study therefore contributes to the current literature by introducing one of the most detailed accessibility analyses based on the logsum approach. Subsequently, the extent of application and the additional benefits in assessing accessibility to work and related inequalities using the devised metric is compared to the IKOB approach. This is achieved by applying both in a practical situation for the Municipality of Zwolle. For the comparison, an assessment framework is designed in which criteria are included that outline how a suitable accessibility measure should function. Both accessibility analyses are subsequently assessed with the framework by introducing five scenarios. This study concludes that results from the created logsum approach are more reliable to IKOB since all parameters are estimated with statistical procedures whilst the latter one considers expert judgment in several stages. Nevertheless, the model is less easy to work with than the IKOB approach. Furthermore, the assessment framework shows that the IKOB is a more extensive model as it considers more aspects of accessibility such as competition and relates available jobs to income. Therefore, a valuable first step is taken to establish a new accessibility approach in this study. Following this, the approach should be further developed to be more appropriate.

SUMMARY

An important concept to describe the extent to which land-use and transport systems enable individuals to reach activities or destinations by means of transport modes is called accessibility. Accessibility as considered in this study is not solely based on mobility and activities, but also the population composition of an area. Many past and current accessibility analyses only model the average behaviour of the population. Consequently, several questions that arise nowadays cannot be adequately addressed. For instance, which specific population groups will be the most affected by a policy measure, if a policy measure benefits the targeted people, whether it increases disparities in accessibility and more. To overcome this, accessibility approaches are required that not only consider the average person but also take into account the specific characteristics of multiple population groups. Several of these models have been introduced in the past. An important and emerging one in the Netherlands is called the "Integrale kijk of bereikbaarheid", or IKOB approach. This approach introduces a way to divide the general population into several groups and calculate the accessibility of each of them. To do so, the well-known potential accessibility measure is applied. The created model is a considerable improvement compared to past ones increasing its popularity. For instance, a resolution was passed in Dutch parliament that called for current policy to be adapted to IKOB's insights.

Another possibility to contribute to the stated demand for more detailed analyses is to evaluate accessibility based on microscopic transport demand models. These kinds of models are constructed by deploying data at the household or individual level. The premise of microscopic models is to predict where an individual will perform specific activities, given temporal, monetary and spatial constraints. The company Goudappel have just released such a model called Octavius. This model contains valuable information since it is one of the most detailed models to predict travel behaviour in the Netherlands. The specified information can be applied to calculate accessibility with the so-called logsum approach as proposed by Ben-Akiva & Lerman (1985).

Interestingly, it has been proved that the logsum and potential accessibility measure are related and predict the same ordering of accessibilities when equivalently specified. In other words, when ranking individual accessibilities or zonal averages, both would predict the same ranking. It is however unclear how an accessibility approach with a devised logsum-metric based on Octavius would relate to the introduced IKOB model with the potential accessibility in a practical situation. This study investigates this by examining the ability of the models to assess accessibility and related inequality to employment opportunities. This is first achieved by using the logsum approach to create a measure to calculate accessibility based on Octavius. Because Octavius is an extensive model, this study contributes to the current literature by introducing one of the most detailed accessibility analyses based on the logsum approach. Then, both accessibility approaches are implemented for the municipality of Zwolle using current data. The found accessibilities in Zwolle using the standard input data is called the baseline situation. Hereafter, an assessment framework is designed in which criteria are included that outline how a suitable accessibility measure should function. Both accessibility analyses are assessed with the criteria by introducing five scenarios. Some input data has been altered in each of these scenarios causing variations from the baseline situation.

In the first scenario, the cost of using the car is increased by 30%. Several conclusions could be made considering the results of this scenario. First of all, both accessibility approaches predict that the accessibility by car as well as the total accessibility (accessibility considering all modalities) will decrease when the measure is implemented. Next, it was found that the measure has a more substantial effect on the accessibility in the IKOB approach compared to the logsum one. It can

therefore be concluded that travel costs have a more considerable influence on accessibility in said IKOB approach. Further, it has been found that IKOB predicts that increasing the cost of travelling will reduce the accessibility of those with less to spend to a greater extent compared to those with more to spend. As a result, inequalities will increase when the cost of using the car rises. On the contrary, the accessibility approach based on Octavius predicts that everyone will be affected the same keeping inequalities constant. The reason is that the cost of travelling is not related to individual characteristics in the model. Therefore, everyone perceives the initial travel costs as well as the increased costs the same. Based on this scenario, it is concluded with the framework that the IKOB approach incorporates travel costs more appropriately than the logsum approach founded on Octavius.

In the second scenario, two important bridges over the IJssel river have been closed. This has created some kind of imaginary barrier in the west of the municipality of Zwolle. As a result, travel times to locations in the Randstad area and cities like Arnhem and Apeldoorn have increased by around 10 to 15 minutes on average. The accessibility in Zwolle has been recalculated by both approaches with the modified network. Subsequent results show that the people with the highest accessibility in the baseline situation will be affected relatively the most. According to IKOB, these are people with a high income who have a car. The logsum approach predicts middle-aged men with a car to be the most impacted. The reason that those with the highest accessibility will be the most affected is because their advantage arises from reaching job opportunities in the cited areas. Increasing travel times to these areas will weaken their advantage. The accessibility of most people does not depend that much on job opportunities in the Randstad. Extending travel times to those locations will therefore not have a big effect. The discussed factors cause inequalities in accessibility to decrease. Furthermore, the accessibility approaches show that the province of Gelderland has become more difficult to reach for everyone. The primary reason is that the IJssel river forms the border between Overijssel and Gelderland. So, the closures take place right on this border causing the found results.

In the third scenario, car ownership in the study area has been reduced by 30%. Consequently, fewer people can make use of the car modality, which is the most important modality for accessibility in Zwolle. The subsequent results of the third scenario reveal interesting behaviour from both models. First of all, both approaches predict that the accessibility by car will reduce on average. This is because the number of people who do not have a car whose accessibility is (almost) zero will rise. Increasing the frequency of such segments brings down the total weighted average. Furthermore, the accessibility by bicycle and public transport has not changed according to the logsum approach. On the contrary, the IKOB approach predicts that the accessibility of these modalities will increase when car ownership is reduced. The reason is that IKOB assumes that people who do not have a car are willing to make longer trips with public transport and cycling on average compared to those who have a car, increasing accessibility. Reducing the number of people without a car will increase the number of people with higher accessibility with the two mentioned modalities.

The number of available job opportunities has been increased in one zone by 10,000 in the fourth scenario. The zone that is chosen is located in a relatively poor neighbourhood in the north of the municipality. The logsum approach predicts that accessibility in the zones surrounding the chosen location has relatively increased the most. After that, the effect declines steadily as the travel time to the new jobs increases. The pattern predicted by the IKOB approach is less distinctive. Essentially, a similar pattern as predicted by Octavius can be observed. That is, the longer the distance to the targeted zone becomes, the lower the effect. However, it is also shown that the effect is more apparent in neighbouring areas where people have a higher income than average. The reason is that more people will have a car in these zones (and some can use it for free) allowing them to reach the added jobs more easily, increasing accessibility. Nevertheless, both models predict that inequalities in accessibility will decrease because of the introduced measure. Primarily because the jobs were added in an area where people generally have poorer accessibility in the baseline situation compared to the rest of the municipality. Their disadvantage has been partially resolved, which has a positive effect on inequalities.

In the fifth scenario, it is modelled that additional public transport services are provided to those who neither have a car nor a driver's license. The idea of this measure is to help the people who have on average the lowest accessibility. It is assumed that travel times by PT have been decreased for the targeted segment by 40% as a result. The subsequent results show first that the accessibility by public transport has increased significantly for the targeted segment. According to both approaches they now have on average the best accessibility with PT in Zwolle. According to the logsum approach, the accessibility is improved so much that inequalities in accessibility by PT considering the entire population have actually increased. Further, IKOB predicts that the impact of the measure on the total accessibility (considering all modalities) is not significant. Primarily, because the IKOB model considers cycling and using the car to be much more important for accessibility than public transport. So, improving public transportation does little to improve people's overall accessibility. In contrast, Octavius predicts a significant effect of the measure on overall accessibility. The main reason for this is that the Octavius model considers public transport as a more important modality. Therefore, improving public transport will have a strong impact on the total accessibility.

It has been concluded with the assessment framework that the IKOB method predicts the general effect of a particular measure. For instance, when will accessibility increase, which people will be the most affected and more. Whether the quantitative results from the model are accurate is more questionable as several parameters are (partly) estimated using expert judgment. The IKOB approach is therefore an appropriate method to get an *initial* estimation of what a policy measure will do. However, to base actual policy decisions on IKOB does not seem appropriate. It would therefore be recommended to primarily use the IKOB in the initial research phase of a measure. After that, more research on the precise effects should be conducted using other approaches and models.

Next, the distinction between the method to calculate accessibility based on Octavius to IKOB is that each behavioural parameter is estimated from statistical information about the daily mobility of the Dutch population. One should therefore expect that the calculated accessibilities will be more reliable. Next, being able to collectively offer a traffic model and an accessibility study together may also increase the market opportunity of the Octavius model. There are however a few elements to consider. For instance, it has been concluded that the cost of travelling is perceived the same by every agent in Octavius as found with the first scenario, which is not entirely realistic. It is therefore recommended to explore an implementation where the travel costs are connected to characteristics like age and household composition for instance to model individual responses. Secondly, the logsum approach based on Octavius predicts fewer inequalities in accessibility compared to the IKOB approach. The considered scenarios in this study have subsequently a small influence on inequalities according to the logsum approach. Because of these small deviations, it is difficult to confidently conclude whether a situation has in fact improved or not. The created logsum measure is therefore less appropriate to investigate inequalities. Lastly, the availability of remote working is increasing, which decreases the importance of physical travel. Both models do not consider the effect of remote working on accessibility. They therefore assume an outdated worldview which means they cannot fully reflect current behavior. It is therefore worthwhile for the creators of both approaches to investigate creating an online component.

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1. Introduction

1.1. Background

Facilitating mobility in itself has been a dominant premise in Dutch accessibility policy (Raad voor de leefomgeving en infrastructuur (Rli), 2021). An important factor is that current policy approaches that determine the prioritization of infrastructure solutions for mobility problems primarily concentrate on one aspect of accessibility. Namely, solving expected bottlenecks. For example, by resolving a busy intersection, traffic jams or capacity problems in public transport. The prevailing approach suffers from several drawbacks. First, aggregated measures for the complete population are considered most of the time (Hoen et al., 2019). As a result, introduced policy measures may increase inequalities or negatively affect specific groups despite an overall improvement. Recent research shows that often more wealthy people or those who already have sufficient accessibility benefit from policy measures (Hoen et al., 2019; Voerknecht, 2021). As a result, there is a need to balance the discussed factors within a more integrated approach during decision-making processes. In essence, current policy approaches should be suitable for this. However, in practice a limited number of parameters are often included in the analyses. Other important considerations, as discussed above, are not taken into account, so solutions with a broader perspective are likely to be discarded early in the decision-making process. (Rli, 2021). This ultimately leads to the decision to apply conventional solutions.

To challenge this approach, the Council for the Environment and Infrastructure (Rli) recommends aiming for “wellbeing” (Rli, 2021). The concept of wellbeing has been introduced in the Netherlands over the last few years (Snellen et al., 2022). It aims to measure welfare in the country more appropriately compared to the original measures which mostly focused on the Gross Domestic Product. This concept is highly connected to the more internationally focused Sustainable Development Goals (SDGs). For instance, SDG target 10.2 aims for “social, economic and political inclusion for all irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status” (United Nations, 2023). It could be argued that accessibility is an important condition to achieve inclusion because great disparities can be generated by the extent to which everyone is able to reach destinations such as schools, jobs, leisure and other opportunities. Next, wellbeing covers everything people value, such as how they are doing as an individual, how other people are doing and the state of their physical living environment (Snellen et al., 2022). As advised by the Rli (2021), the approach should be applied more often in the transport domain. Snellen et al. (2022) differentiate between four main dimensions related to transport as shown in Figure 1. Accessibility is the first dimension; it relates to how the land-use and transport system enables people to reach destinations and opportunities (Geurs & Van Wee 2004). In the new approach, mobility should not be seen as the objective in itself, but as a way for everyone to reach sufficient destinations in a reasonable time (Hoen et al., 2019). The emphasis is on "everyone" to ensure that each person has adequate opportunities to develop themselves, regardless of the type of demographic segment they belong to or the type of area they live (Snellen et al., 2022). Other dimensions generally cover the negative impacts of transport on health, safety and the environment. These are out of the scope for this report. In the proposed approach, all impacts should be fairly weighed throughout a project's decision-making process.

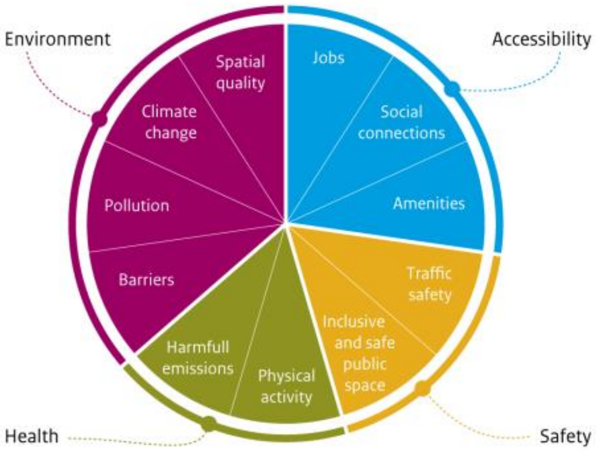

Figure 1: The four dimensions of wellbeing in transport (Snellen et al., 2021)

In the Netherlands, accessibility analyses to support policy decisions are often based transport demand models that only consider the average behaviour of people. Such models have several limitations causing that differences in accessibility cannot be adequately investigated. To overcome this, the "Integrale kijk op bereikbaarheid", or IKOB has been devised by Voerknecht (2021). It employs a post-process approach to overcome the limitations of aggregate models by introducing a way to disaggregate the general population into several segments and calculate the accessibility of each of them. This is a considerable extension compared to traditional approaches. This extension is that the potential accessibility is not solely based on mobility and activities, but also on the population composition of an area and its characteristics (Hoen et al., 2019). For instance, an approach based purely on mobility shows that accessibility is the highest within city centres. However, people in these areas have fewer cars on average, which means that actual accessibility could be much lower (Voerknecht, 2021). While the IKOB is certainly an improvement compared to traditional approaches, it still has limitations. The IKOB approach and these limitations are discussed in more detail at a later stage in this report. In short, several parameters are not directly calculated with data, but estimated by experts which affects the accuracy of the approach. Also, the parameters considered in each case study differ. Consequently, it may be time-consuming to discuss which parameters to include and how to model them. Furthermore, there could be inconsistencies between assumptions on the aggregate (transport demand model) and the disaggregate scale (IKOB).

Another possibility would be to evaluate accessibility based on microscopic transport demand models. These kinds of models are constructed by modelling travellers at the household or individual level (Tye et al, 1982) and are deployed more often in practice. The main reason for the development of such models is to account for the differences in travel behaviour between diverse people, which increases the accuracy of prediction when accounted for. This contrasts with macroscopic (gravity) models that commonly use aggregated data such as zonal averages. The idea with microscopic models is to predict when and where an individual will perform specific activities, given temporal, monetary and spatial constraints (Puhe & Vortisch, 2019). The decisions each person makes, such as for which reason they will travel, by what modality and to which location can be modelled using a discrete choice modelling approach. The logsum measure is a way to calculate accessibility based on these choice models (Ben-Akiva & Lerman, 1985). The strength of this approach is that accessibility can be determined on the disaggregated individual or household level. Consequently, it should be possible to identify and compare differences in accessibility between different segments in the population. With this approach, disaggregation is incorporated from the start which eliminates the necessity of a post-processing approach such as IKOB. The earlier stated mismatch between assumptions on the aggregate and disaggregate scale for IKOB could therefore be eliminated. However, the segmentation used within this modelling approach is not necessarily the same as which is of interest to policymakers (i.e., in the modelling segmentation only characteristics are included which can be used and can be estimated to distinguish travel behaviour, while for the analyses policymakers can be interested in segmentations for which no data is available or travel behaviour was not significantly different). However, the advantage of this method is that the parameters used are estimated based on observed travel behaviour instead of expert judgments. Results should therefore be more reliable. Because of these reasons, estimating accessibility on a disaggregated scale has the potential to contribute to Dutch accessibility policy.

1.2. Research aim

Currently, IKOB is an upcoming way of determining accessibility in the Netherlands. For instance, a resolution was passed in Dutch parliament that called for current policy to be adapted to IKOB's insights[1]. It may also be conceivable to determine accessibility based on microscopic transport demand models with the logsum measure, as discussed earlier. However, it is unclear how the two methods relate to each other. In what situations will each one provide added value in a practical setting? Next, Goudappel is one of the most prominent developers of transport models in the Netherlands. Their macroscopic (gravity) models are still often applied for various goals. Additionally, the current demand for more disaggregated approaches has not gone unnoticed at Goudappel. Therefore, they have developed a microscopic strategic transport demand model called Octavius. The first version of this model is already utilized in practice for several regional applications. The availability of a microscopic transport demand model at Goudappel presents a unique opportunity to answer the stated questions. To do so, a practically applicable method to determine accessibility based on Octavius must first be determined. The goal of this research is to determine the extent of application and the additional benefits in assessing accessibility to work and related disparities using a devised logsum-metric grounded on the microscopic transport model Octavius compared to the IKOB approach.

1.3. Research questions

Various steps are going to be performed to achieve the stated goal. The envisioned process is visualized in the figure below. Each colour represents a research question, which are elaborated upon hereafter.

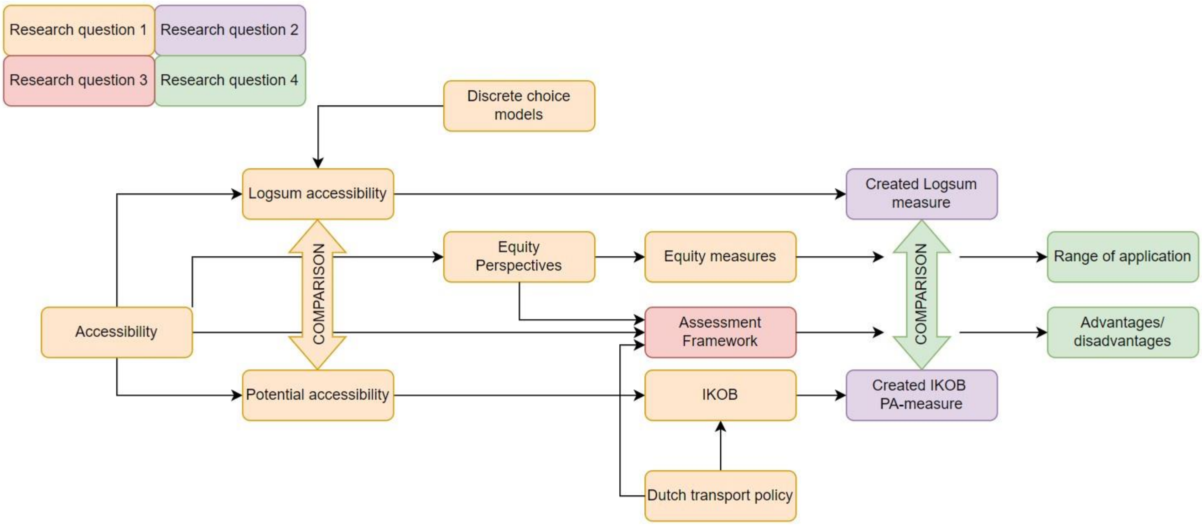

Figure 2: The envisioned process to reach the aim of this thesis.

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[1] Kamerstukken II 2022/23, 35925, nr. 59, p. 1.

1) **How can accessibility to work be determined with the logsum and potential accessibility measures and related inequalities quantified?**

The first research question aims to create a sound theoretical basis for this study. This is firstly achieved by investigating what accessibility represents by itself. Accessibility is a versatile concept, there exist many different perspectives on it. These are critically examined and compared. This study considers accessibility from the perspective of (groups of) individuals to work opportunities. Still, it may remain uncertain how accessibility based on some perception could be determined or quantified in a real-life situation. This can be remedied by using accessibility measures. Because accessibility is not a well-defined or agreed-upon concept, many different measures exist to define it. This study focuses on the logsum and potential accessibility measures. The mathematical basis of these is investigated and the implications for interpreting results are explored. The following information is then compared.

Next, there will be differences in accessibility between people. The current and upcoming demand in Dutch policy is to investigate these discrepancies. To do so, an essential part is to quantify how (un)equal the distribution of accessibility is. There are several philosophical perspectives on this matter. Relevant perspectives are discussed. Subsequently, each perspective could be operationalized with different measures, indicators or statistics. It is investigated which ones are appropriate for this study.

2) **How can accessibility to work be determined in practice for the municipality of Zwolle using the transport demand model Octavius with the logsum measure and the IKOB approach?**

The second research question aims to create a practical application of both measures for the municipality of Zwolle. This involves on the one hand preparing a suitable version of the IKOB approach which at its core makes use of the potential accessibility measure. Next, it is examined on the other hand how the logsum measure could be applied. By doing so, accessibility is determined based on information from the microscopic traffic model Octavius. Namely, the utility functions to model the attractiveness of each travel alternative. The created measures should be realistic. That is, they can be drafted with the available data and information. Furthermore, both should be defined in a similar matter so that the upcoming comparison will be as appropriate as possible.

3) **What criteria need to be taken into account in order to build a framework that formulates how a proper measure should behave when accessibility to work is considered?**

The third research question aims to create an assessment framework that is going to be applied to investigate the suitability of the two created accessibility approaches in the second research question. To achieve this, an assessment framework will be created based on which the comparison will be performed. The framework will consist of various criteria formulated with the literature collected in this report. These criteria specify how a proper accessibility measure should behave in certain conditions. The criteria will be established in accordance with the components of accessibility according to Geurs & van Wee (2004). Next, the four components will also be examined in a Dutch context.

4) **What is the extent of application and the additional benefits in assessing accessibility to work and related inequalities using the devised logsum-metric grounded on the microscopic transport model Octavius compared to the IKOB approach?**

An IKOB and a logsum application based on an Octavius application have been created by answering the second research question. Subsequently, an assessment framework is designed in which criteria are included that outline how a suitable accessibility measure should function. The criteria are assessed by creating several scenarios. In each one of these scenarios, some parameter(s) are altered. The created situations do not have to be realistic; they can be an exaggeration. In these scenarios, the accessibility to essential services such as doctors, dentists and suchlike are out of scope. Instead, accessibility for work is considered. Next, it is expected that it is not possible to calculate the most complex situations. Only the situations that can be performed with the available models are considered. Situations that require modifying the coding itself in the models are outside the scope of this project. Lastly, the subsequent results from the scenarios is applied to answer the final research question. The discussed steps for the last research question are visualized in the schema below. The shown schema is an expansion of Figure 2. It is found by extending the green 'comparison' arrow and the parts around it.

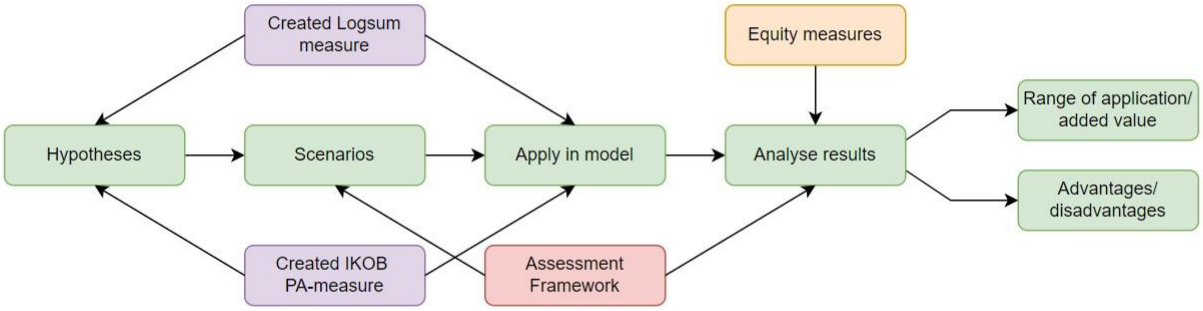

Figure 3: The required steps to answer the third research question.

1.4. The scope of the accessibility analyses.

Accessibility analyses can be wide-ranging. This study will set some boundaries to keep the scope manageable. Firstly, it has been stated before that only accessibility to work locations will be considered. Because of this, accessibility to opportunities such as schools, shops, hospitals and more are out of scope. Furthermore, employees are increasingly able to work from a remote location outside of corporate facilities (Pokojski et al., 2022). This involves both completely working remotely or a hybrid approach where physical presence is only required on certain days. The prevalence of remote working has accelerated during the Covid-19 pandemic. Because of the discussed reasons, ICT provides virtual access to opportunities that are normally located in space. The accessibility to physical spaces could therefore become less important. Determining accessibility to work nowadays would consist of an online and physical component. For instance, such an approach is proposed by Cavallaro & Dianin (2022). However, the online part will not be included in this study because the considered models do not yet incorporate it. This will therefore have to be reflected in the conclusion. Due to the scope chosen, conclusions can only be drawn related to the suitability of the accessibility models about the parts that are considered.

2. Accessibility

One of the main foundations of society is the movement of goods and people. For this study, commuting to work is considered. Such movements are established by the function of both the performance of the transport network and land-use patterns (Morris et al., 1979). The network is the outcome of a trade-off between the desire to connect as many locations as possible and several constraints such as cost, space and time (Rodrigue & Ducruet, 2022). Because of these constraints, it is not possible to establish the perfect network. It will have weaknesses and vulnerabilities in some areas. This creates differences between people based on where they live and their characteristics, capabilities and desires. It is essential to evaluate the system to locate weaknesses so that everyone has a fair chance to participate in society. One way of doing so is by investigating accessibility. In this first chapter, it will initially be discussed what the concept of accessibility is about and how it can be defined. However, there is not a general consensus on what accessibility is. Instead, many different perspectives exist on it which will be elaborated upon in Section 2.1. With this information, the most appropriate definition of accessibility is selected for this research. Moreover, accessibility will not only be assessed in this research by itself but variations among it will also be investigated. This is where the concept of equity comes into play to identify those differences. The necessary information to appropriately discuss the concept of equity in relation to accessibility will be elaborated upon in the last part of this chapter.

2.1 Perspectives on accessibility

First of all, accessibility is not a well-defined or agreed-upon construct (Geurs & van Wee, 2004). Instead, many different definitions and methods to determine it have been established during the last decades. First, Hansen (1959) defined accessibility as “the potential of opportunities for interaction”. He considers both the performance of the transport system and land use characteristics. Other perspectives have also emerged. For instance, Hägerstrand (1970) proposed a space-time approach that measures the limitations on the actions of individuals in the built environment. In this way, the level of accessibility is not considered equal for individuals from the same zone. Temporal constraints of people to participate in certain activities are also considered by several authors (H. J. Miller, 1999). Already, Dalvi & Martin (1976) argued that there is a need for a clear and unambiguous definition of the term accessibility. Instead, studies often consider their balance between the discussed transport, land use, individual and temporal dimensions. Accessibility is then operationalized depending on the problem (Kwan, 1998). For instance, Neutens et al. (2010) make the distinction between place-based and people-based accessibility. Place-based accessibility describes the proximity to desired locations while people-based accessibility describes an individual’s travel behaviour in a space-time environment (Neutens et al., 2010). This report should consistently deploy a particular definition of accessibility. It has been decided to use the definition by Geurs & van Wee (2004) since it is an all-encompassing definition that considers all relevant components of accessibility. They define accessibility as:

“The extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of (a combination of) transport mode(s)” (p. 128).

In the next sections, each component will be elaborated upon in further detail. In addition, the components interact, as will be discussed thereafter.

2.1.1 The transport component

The first one is the transport component which is about overcoming some sort of spatially operating source of friction. Put more clearly, it describes the disutility of the transport system to travel between a given origin and destination (Geurs & van Wee, 2004). In this way, it is ensured that an activity that is located ten kilometres away does not provide the same accessibility as a similar one on the other side of the country. Changes in the transport system affect the accessibility of any area, altering the desirability of activities (Dalvi & Martin, 1976). Several factors could be considered to define the disutility of travelling through the network. The most straightforward way is by including the geographical distance. The Euclidean, Manhattan or distance through the network could be used for this (Apparicio et al., 2008; E. Miller, 2020). Conversely, most studies consider travel times (e.g. Farber et al., 2014; Haynes et al., 2003; Tillema et al., 2011). In this way, the speed of modalities, congestion and other obstacles in the network can be taken into account. In general, this approach is more accurate compared to taking the distance (Apparicio et al., 2008). Furthermore, other factors such as comfort, safety and quality could be considered as part of the disutility to travel.

2.1.2 The land use component

The next component refers to the land use system. It considers both the supply and demand for opportunities. On the one side, the supply is about the number, quality and (spatial) distribution of activities at certain destinations (Geurs & van Wee, 2004). This could be about jobs, schools, shopping, leisure and more. On the other hand, there is a demand for these opportunities that has to originate from somewhere. This mostly includes individuals travelling from residential locations, but other alternatives could also be considered. For instance, someone who goes to a supermarket during their lunch break. The disutility to travel between the supply and demand is indicated by the transport component, as discussed in the previous section. The land use and transport components are often combined to establish location-based measures, which will be elaborated upon in more detail in Section 3.2. Furthermore, most opportunities like the discussed number of jobs, schools and healthcare institutions can only accommodate a certain number of people. The situation in which individuals compete for a limited number of opportunities is called competition. Shen (1998) states that not considering competition could lead to unrealistic or even misleading results. For instance, by concluding that accessibility is higher in cities, since more jobs are available here. However, the number of people competing for these jobs is also higher which reduces the ‘actual’ accessibility. Shen therefore states that most accessibility measures only consider the supply side whilst the demand side is ignored. Following that, he discusses that this is only valid if the demand for opportunities is uniformly distributed across space and when there are no capacity limitations. The first condition is rarely met since cities and regions are characterized by uneven distributions of people. The second condition is especially questionable when analysing accessibility to jobs, as one job can only be filled by one (qualified) person.

2.1.3 The individual component

Accessibility is not the same for everyone, even when they live in the same area, street or household. This is however ignored when only the land use and transport components are considered (E. Miller, 2020). As a consequence of this, significant differences in accessibility may be overlooked (Dixit & Sivakumar, 2020; Kwan, 1998). This could be rectified by also taking the individual component into account. In this way, the needs, abilities and opportunities to shape the accessibility of individuals are considered. (Geurs & van Wee, 2004). Several elements are relevant to this. First, the reason people travel depends on their situation. It seems logical that a student would seek different opportunities compared to a retired person. Next, not everyone has the same modalities at their disposal. For example, someone without a driver's license cannot use a car, while those who receive compensation for using public transportation may take the train more often (Hoen et al., 2019). In addition, the accessibility could differ between individuals depending on personal and household features. For instance, Billaudeau et al. (2011) found that income affected the accessibility to sports facilities in the Paris region. Likewise, Dixit & Sivakumar (2020) investigated accessibility in greater London to job opportunities based on gender, age and income. Next, the individual component is especially important when more disaggregated analyses are required or when the degree of accessibility between groups needs to be compared (Kwan, 2013). By doing so, equitable situations could be established in which no segments of the population are unjustly disadvantaged (Neutens, 2015).

2.1.4 The temporal component

The last component is the temporal one. It takes into account that accessibility is not the same for everyone over time. First, more realistic travel times could be found by establishing a better representation of the transportation network (Kim & Kwan, 2003). This could involve identifying how travel times are affected by demand, which is especially relevant during rush hours. A similar approach is considered by Farber et al. (2014) who investigate how accessibility to supermarkets fluctuates throughout the day. One could also consider different scheduling and transfer times for public transport. For instance, less service could be provided during off-peak hours. Another important temporal component is the availability of opportunities at various times throughout the day. Some activities have specific schedules that make them unavailable at certain moments (Kwan, 1998). Logically, one can only participate in a particular activity in the urban environment during business hours. For instance, most supermarkets are closed at night. Furthermore, certain opportunities could also be unreachable due to the time constraints of an individual (Kwan, 1998). This on the one hand includes the need for people to reach locations at a particular time of the day (H. J. Miller, 1999). On the other hand, the time required to participate meaningfully. Both must be compatible with the time-based timetables of the locations themselves as discussed earlier to facilitate the action of interest (Kwan, 2013). It will otherwise not enhance the accessibility. In addition, these temporal constraints differ depending on the characteristics of individuals or households, which are discussed in the previous section. The temporal component is therefore often combined with the individual one. A similar approach is proposed by Dong et al. (2004) who include individual constraints, scheduling and trip changing in an activity-based accessibility measure. In conclusion, Kwan (2013) states that considering accessibility the same for everyone during the day will lead to serious overestimation because of the reasons discussed.

2.1.5 Interaction effects.

The four discussed components have each a direct influence on the accessibility to opportunities (Geurs & van Wee, 2004). Moreover, the components also interact with each other as shown in Figure 4. The figure shows for instance that the individual component has an indirect relationship with all the other ones, due to the factors discussed in Section 2.1.3. The land-use component is an important factor in travel demand, as there is a need to travel between supply and demand.

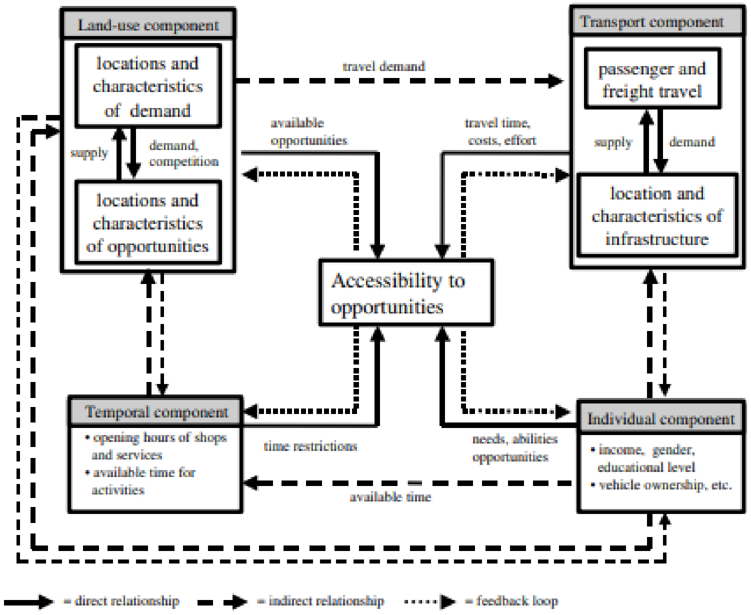

Figure 4: Relationships between components of accessibility (Geurs & van Wee, 2004)

2.2 Equity and accessibility

Accessibility is not only assessed in this research by itself but variations among it will also be investigated. This is where the concepts of equality and equity come into play. First of all, equality refers to the distribution of a certain good, irrespective of moral judgment (González et al., 2022). The concept of equity could be referred to as “fairness” or “Justice”. It involves moral judgment of whether the distribution of benefits and costs is considered fair (Litman, 2022). A situation can be unequal, but equitable (van Wee & Geurs, 2011). Like in many fields, equity in transportation is an essential element. Transport equity refers according to Dixit & Sivakumar (2020) to a fair distribution of transport projects and their impact. But what “fair” entails varies, depending on which ethical framework is considered. Three relevant frameworks are discussed in the upcoming sections. In doing so, each framework is introduced and related to the concept of accessibility.

2.2.1 Utilitarianism

A traditional family in normative ethics is utilitarianism. A general doctrine of this perspective is that actions should be evaluated based on their consequences (West, 2022). A utilitarian includes all good and bad produced by an action. It is possible to sum up units of “good” and “bad”. Acts are morally right if the total sum of “good” outweighs the sum of “bad” (West, 2022). The aim of policies is thus to maximize the aggregated welfare for the greatest number of people (González et al., 2022). Equity is considered by giving the same weight to everyone’s welfare (Pereira et al., 2017). Utilitarianism is the ethical foundation of the cost-benefit analysis, in which the total benefit is balanced with the total costs (Hausman & McPherson, 2006). The utilitarian theory has however several limitations and problems. First, it is difficult to predict what the exact consequences of an action are in the future (McCombs School of Business, 2022). Second, it is perfectly acceptable according to utilitarianism to increase welfare at the expense of those less well-off. It may therefore prioritize accessibility improvements to more profitable activities and for people with greater resources (Pereira et al., 2017). Moreover, total welfare-increasing actions could conflict with or violate the rights of others. Because utilitarianism ignores distributional effects, it is questionable whether it is a sound perspective on equity (González et al., 2022).

2.2.2 Egalitarianism

Another perspective on equity is egalitarianism, where the fundamental idea is that people should be seen as equals and treated the same (Arneson, 2013). Everyone should essentially enjoy the same welfare. Technically, disparities could also be reduced by worsening the situation of the well-off. This is called extreme egalitarianism, which is not really something to strive for (González et al., 2022). Instead, a moderate form of egalitarianism will be considered in this report. For this, the primary aim should be to reduce inequality of opportunities. To achieve this, differences in accessibility are primarily examined. Policy measures are beneficial if these differences are reduced. To do so, Litman (2022) makes the distinction between horizontal and vertical equity. Horizontal equity implies that people with similar needs and abilities are treated similarly. This means that each person should receive a similar share of resources and bear similar costs. Vertical implies that disadvantaged people should receive preferential treatment so that the gap to the well-off is reduced. Additionally, people do not often rate the degree of their accessibility, but rather compare it to that of others (van Wee & Mouter, 2021). What people therefore perceive as adequate accessibility depends on their circumstances.

2.2.3 Sufficientarianism

The last theory that is considered in this report is sufficientarianism. Sufficientarians believe that it is important to ensure that each individual has enough (Casal, 2007). So, not focus on people who have “less”, but on those who have “too little” (Frankfurt, 1987). Martens (2016) states that the transport- and land-use system is only fair if it provides a sufficient level of accessibility. The theory suggests some kind of threshold to define what is acceptable and what is not (Casal, 2007). Where a threshold is located in relation to accessibility may be arbitrary and difficult to define because of multiple reasons. First, accessibility is defined in many different ways and could be quantified using a wide variety of measures (Geurs & van Wee, 2004; van Wee & Geurs, 2011). Second, the threshold may vary according to the context and the individual. (Lucas, 2012). Third, there is much debate about what constitutes "sufficient" accessibility. This is essentially a political choice (González et al., 2022; Lucas et al., 2016). The consequence of having poor accessibility may be a lack of access to life-enhancing opportunities compared to the majority of people, which could lead to social exclusion (Lucas, 2012; Martens, 2016). The threshold should be defined in such a way that social exclusion is eliminated, or at least reduced. The problem is again, at what level that is. At last, inequalities above the established threshold are of less importance, which could be problematic.

2.2.4 Equity in transport

Assessing equity in transport is complicated because many factors play a role. In essence, accessibility is unequal, for instance between different locations (van Wee & Geurs, 2011). The main challenge is what to consider unfair. Besides, the same service level might not provide the same benefits to everyone because of differing abilities, needs or tastes (Dixit & Sivakumar, 2020). Moreover, inequity could appear in two main dimensions in accessibility. Namely, social and spatial equity. This could become problematic as one situation may seem equitable from one perspective but not from the other (Litman, 2022). One can also distinguish between intended and unintended equity impacts (Rietveld et al., 2007). For instance, a project to build a metro line through a poor neighbourhood could have a direct intended impact to reduce inequality. A policy like road pricing can have unintended effects. In general, if policies aim to reduce inequity, they should report on the targets beforehand (van Wee & Geurs, 2011).

3. Operationalizing Accessibility

Accessibility and its connection to several equity perspectives were discussed in the previous chapter. This chapter aims to turn these abstract concepts into measurable observations. Several steps are going to be undertaken to do so. First of all, measures to operationalize accessibility are generally based on transport demand models. The decisions taken to create these transport models have ramifications for subsequent accessibility measures. Therefore, transport demand models are introduced first (Section 3.1). Here, a distinction will be made between 'microscopic' and 'macroscopic' models. Next, the measures to turn the abstract concepts of accessibility into measurable observations are elaborated upon in the following sections. To do so, it will first be explained what kinds of measures exist (Section 3.2). Hereafter, two measures that are central to this study are further elaborated upon and compared. This includes the logsum (Section 3.3) and potential accessibility (Section 3.4) measures. Lastly, how the equity could be operationalized to analyse accessibility in a real-life situation is elaborated upon in Section 3.6.

3.1 Transport demand models

Transport models are deployed to predict travel conditions such as intensities on roads under various configurations (Bhat & Koppelman, 2003). Many different approaches to do so could be distinguished. Each one generally consists of four steps (Chu et al., 2012). The first step is trip attraction and generation in which it is estimated how many trips are produced in and attracted to a certain area. The next step is to link attraction and generation to create potential movements. So, people will have a reason to travel. The third step is to determine which modalities are selected to perform the generated movements. For instance, will a person take a car, public transport, the bicycle or a combination of them? The last step is called the traffic assignment, for which the chosen movements are put through the (multi-modal) network. The main goal of the last step is generally to mimic observed intensities on the road as accurately as possible (Tye et al., 1982). With this, and often part of the assignment, is to calculate the travel times between any two zones. This information can be applied in accessibility measures. Besides, the first three steps, without the traffic assignment, are referred to as demand models. The discussed steps are visualized in Figure 5. How these steps are performed widely differs depending on the chosen approach. In this section, the distinction between ‘macroscopic’ and ‘microscopic’ models is made. This is achieved by first describing the models by themselves in Sections 3.1.1 and 3.1.2. Then, a comparison between the two is provided in Section 3.1.3.

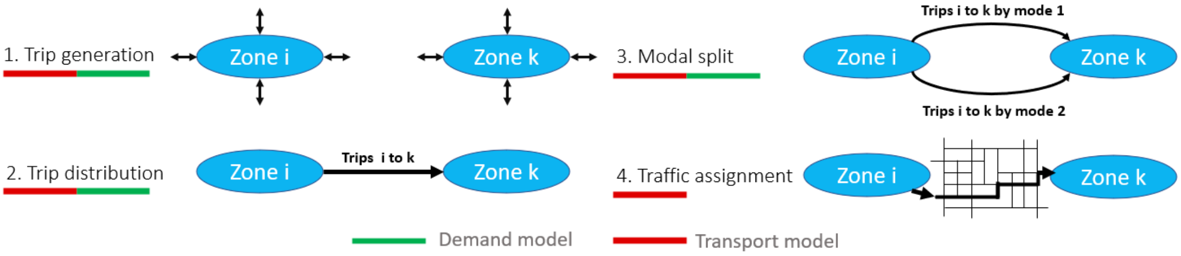

Figure 5: The four steps of transport models

3.1.1 Macroscopic models

First of all, macroscopic models consider aggregated travel decisions for the zonal population. Trip generation and attraction are calculated based on the characteristics of a zone. The number of trips produced could be predicted by the characteristics of households in the area (van Nes, 2018). For instance, consider a situation in which only a distinction is made between households with and without a car. It is found that those with a car make on average four trips a day and those without two. If it is known how often each household occurs in a certain zone, the total number of trips generated can be estimated. Other parameters that are often considered are income, household structure, density and more. Next, trip attraction could be estimated based on explanatory variables like office space, number of shops and density. The result of the first step is the grand total of trips attracted and produced in each zone. The next step is to link one trip produced with one attracted to create an origin-destination matrix, which indicates how many trips are made between any two zones. One of the most frequently used methods to achieve this is called the “double-constrained gravity model” (Wilson, 1967). This procedure is based on Newton’s Law of universal gravitation. Namely, the number of trips made between any two zones is determined by the “mass” of each zone and the “distance” between them. In this case, mass is the number of trips generated/attracted and the distance represents the travel impedance. The travel impedance is defined by a decay curve that describes the willingness to make a trip as a function of travel costs (van Nes, 2018). The higher the costs, the less likely the trip. The discussed approach does not ensure spatial consistency (the start of the next trip should be at the same location where the previous one ended), nor temporal consistency (the start time of the next trip should be later than the end time of the previous one) (Chu et al., 2012). Also, the personal and temporal constraints of an individual as elaborated upon in Sections 2.1.3 and 2.1.4 are mostly ignored. Next, the number of travellers between each OD pair is distributed over available transport modes in the modal split. The trip distribution and modal split could be combined by creating decay functions for each modality. This approach is often considered in the Netherlands. These decay functions can be applied to calculate accessibility, which will be elaborated upon later in this report.

3.1.2 Microscopic models

There is an increasing demand to look more specifically into the accessibility of individuals and differences therein as discussed in the first chapter. A possibility to do so would be to evaluate accessibility based on microscopic transport demand models. These kinds of models are constructed by deploying data at the household or individual level. The premise of microscopic models is to predict when and where an individual will perform specific activities, given temporal, monetary and spatial constraints. (Puhe & Vortisch, 2019). The first modelling step is to create a population in which each person is represented by a so-called ‘agent’. Each agent is given characteristics. For instance, their gender, income, home location, capabilities and so on. The characteristics of the agent should match their real-life counterparts as accurately as possible. It is (currently) not realistic to gather information about and model each real person. Instead, statistical procedures are applied to synthesize the most likely population given several constraints. In doing so, people with homogeneous tastes and socioeconomic attributes are often combined into groups called “market segments” (Tye et al., 1982). These shall be referred to as "segments" further in this report. The characteristics of agents that belong to the same segment are considered equal. Furthermore, an individual is not an entity in isolation. Instead, they interact within their households. The decisions of one agent could influence those of another. For instance, four agents in a household with one car cannot all take this car to different destinations at the same time. In addition, members could interact if accessibility is at stake (van Wee & Geurs, 2011). Next, the decisions each agent will make, like for what purpose am I going to travel (trip generation), to what location (distribution) and by which modality (modal split) can be predicted by deploying discrete multinomial choice models. The benefit they experience with each alternative is then defined with utility functions as explained in Appendix A. The differing tastes and socioeconomic attributes of an agent as well as the characteristics of their household are taken into account to estimate the specific behaviour of each agent (McFadden & Reid, 1975). The probability that an alternative is chosen by each agent could then be estimated based on the values resulting from their specific utility functions. The found probabilities should then be applied to define the discrete choices of each agent. For instance, agent p residing in zone z will take the car to a shop in zone y. This involves the use of certain algorithms to ensure that the behavioural choices of individual travellers match macroscopic outcomes as closely as possible. In doing so, noise reduction techniques are applied to ensure that differences due to the probabilistic nature of these models are minimized (Train, 2001). Next, disaggregate models that consider spatial consistency, as explained in the last section, are called “tour-based” approaches. A tour is a set of trips to visit some locations. For instance, going from home to work, from work to a shop and then from that shop to home. Tour-based approaches that also take into account temporal consistency are “activity-based” (Davidson et al., 2007).

3.1.3 Comparison

The discussed modelling approaches in the last two sections seem vastly different. They could therefore be perceived as mutually exclusive or competitive approaches. Instead, McFadden and Reid (1975) argue that they are complementary, as disaggregated models provide the theoretical foundations under which aggregated models will give valid forecasts. Furthermore, the aggregation of behaviour at lower levels should be consistent with overall observed patterns. In other words, aggregating behaviour from microscopic models should be equivalent to results obtained with macroscopic models. It should therefore theoretically be possible to convert one approach into the other. For instance, by creating decay functions for each specific population segment. This approach is in practice difficult because of data constraints to shape each curve. The other way around should also hold. That is, discrete choice models are drafted in such a way that they predict the behaviour of an ‘average’ person. The main differences that arise between models are at what level of aggregation they predict the behaviour of travellers in practice. In other words, to what degree individuals are combined into segments. The main goal should be to create an appropriate model that satisfies the tasks it should fulfil. To this end, an appropriate degree of aggregation must be chosen. To do so accordingly, the advantages and disadvantages of each application must be considered. For instance, a sizable amount of data is necessary to model individual behaviour for microscopic models. It could be costly and time-consuming to collect it if it is not readily available.

Furthermore, macroscopic methods to model mobility have been employed in the Netherlands for the last decades. However, there is a need to analyse mobility not only on an aggregate scale but also to examine specific groups as discussed in Section 1.1. In a new proposed approach, mobility should not be seen as the objective in itself, but as a way for everyone to reach sufficient destinations in a reasonable time (Hoen et al., 2019). Deploying disaggregated models therefore has the potential to meet the current need in Dutch transport policy. A move to develop such models could be observed during the last years.

3.2 Accessibility measures

What accessibility implies has been discussed. Still, it remains uncertain how to determine or quantify it in a real-life situation. This can be remedied by using accessibility measures. Because of differing views on what accessibility is and its many facets, measures come in many shapes and forms. In this way, studies often consider their own balance between the discussed transport, land use, individual and temporal components. The key objective should be to identify the most fitting measures for a particular situation. To do so, different perspectives on accessibility will first be explored. Also, differences between measures are highlighted.

3.2.1 Categorization of accessibility measures

First of all, Morris et al. (1979) make the distinction between relative and integral accessibility. Relative accessibility describes the degree of connectedness between any two points, while integral accessibility outlines the degree of connectedness between a given point and a certain set of points (Morris et al., 1979). Currently, most accessibility measures seem to fall into the latter category. Further, Morris et al. (1979) also distinguish between “outcome” and “process” indicators. They state that process indicators interpret accessibility as the property of individuals and their (living) environment. Results are independent of actually made tours. They therefore depict the potential or opportunity to travel. On the contrary, outcome indicators are based on observed travel behaviour. This is in essence the difference between measuring mobility, which involves the actual movements of people and the opportunities to do so (E. Miller, 2020) A problem is that observed behaviour is just the response to current circumstances. This makes it difficult to disentangle the effect of choices and constraints (Morris et al., 1979).

Next, Geurs & van Wee (2004) identify four perspectives for measuring accessibility. The first perspective is related to *infrastructure-based measures* which primarily consider the transport component. They analyse the performance of the transport network and are often used in transport planning (Geurs, 2018). Measures that fall into this bracket are for example travel times, average speeds and the level of congestion. The second perspective is related *to location-based measures.* These describe the accessibility to spatially distributed activities and are primarily used in urban planning and geographical studies (Geurs & van Wee, 2004). Location-based accessibility measures are introduced by Hansen (1959) and primarily include the land use and transport components. Often used location-based measures are the travel distance to the nearest location, the number of services within a particular area and gravity-based measures. One of the most commonly employed measures from the latter is the potential accessibility, which will be elaborated on in more detail in Section 3.4. location-based measures are most useful for comparing accessibility between different locations (Kwan, 1998). The main disadvantages however are their lack of attention to an individual’s characteristics and time constraints (Kwan, 1998; Neutens et al., 2010). They would therefore ascribe the same level of accessibility to individuals in the same zone.

The third perspective according to Geurs & van Wee (2004) is related to *utility-based measures*. The origins of these measures lie in economic studies and measure the total benefit a consumer would receive to reach opportunities in the land use system (Nassir et al., 2016). In addition, people perceive the attractiveness of opportunities differently. An important factor is that utility-based measures capture this random nature of users' preferences. It is not possible to know or model why people take certain decisions. Instead, their decision-making is predicted by taking into account the individual's own characteristics and the possible alternatives they face (Train, 2001). The logsum accessibility which is categorized as a utility-based measure is further elaborated upon in Section 3.3.

The last perspective relates to *person-based measures* which describe an individual’s travel behaviour in a space-time environment (Kim & Kwan, 2003; Kwan, 1998; Neutens et al., 2010). They are consequently more suitable for defining and investigating differences in accessibility between individuals, households or groups of people. To achieve this, more disaggregated analyses must be employed. This also has certain requirements. First, more data is needed to model the complex behaviour of individuals Neutens et al. (2010). Also, there may be problems with computational intensity and operationalization (Kim & Kwan, 2003; Kwan, 1998). This is in contrast to place-based measures which yield valuable insight with relatively little data and are easy to interpret (Neutens et al., 2012).

3.2.2 Similarity between measures.

One could infer that choosing one measure is enough for a complete analysis. It is however found in several studies that the results of an analysis heavily depend on the decision of which measure is chosen. For example, Neutens et al. (2010) conducted an equity analysis in the city of Ghent, Belgium, using ten different accessibility measures. Results showed that the correlation between the measures vastly differs. Even a negative correlation was observed between some. Likewise, Tillema et al. (2011) investigated the effectiveness of road pricing with multiple accessibility measures. They also found that there was a significant difference between the results depending on the measure chosen. The same was found by Kwan (1998), who investigated accessibility in Ohio using thirty measures. She also concluded that differences especially occur between people- and location-based measures. It may not be surprising that results diverge, as it was stated before that accessibility is not a well-defined or agreed-upon construct. Instead, accessibility indicators often work together and capture different facets of accessibility (Geurs, 2018). Geurs also states that this implies that it is better to choose a set of indicators rather than choosing a single best one.

The two accessibility measures that are central to this study are the logsum and potential accessibility measures. The logsum measure is categorized as a utility-based measure, while the potential accessibility is location-based. These two will be elaborated upon in the next two sections.

3.3 The logsum accessibility

Whenever a person makes a journey, many decisions have to be made amongst alternatives. Like, for what purpose am I travelling, to what location, by what means of transport, via what route and at what time. Such choices could be modelled through discrete choice models, which are explained in Appendix A. The expected maximum utility from such choice sets depicts the extent of opportunities a person has is related to the concept of accessibility (Ben-Akiva & Lerman, 1985). This can be calculated with the so-called logsum measure. The logsum is rooted in economic theory and is consistent with rational economic behaviour (Zondag et al., 2015). They are hence appropriate for economic evaluations, for which they are often used in practice.

The logsum could firstly be categorized based on Geurs & van Wee (2004) as a utility-based measure. In most cases, it satisfies most dimensions for an ideal accessibility measure, except the temporal one. In addition, studies like Neutens et al. (2010) would classify it as a people-based measure. One of the main advantages of such measures is that they are able to differentiate heterogeneity across individuals. The logsum could therefore be suitable to analyse differences in accessibility between groups of people. Besides, multinomial and/or nested logit functions are often incorporated in existing traffic demand models. An advantage of this is that logsums could be derived from them without much computation. On the other hand, logsums are more complicated to explain and communicate to the general public and city planners (Geurs, 2018). Especially compared to the often-implemented location-based measures. Lastly, more data is required to estimate the parameters in the utility functions within logsums. Such data may be unavailable or expensive to collect.

The logsum is used in several studies. For instance, to calculate consumer surplus, as an alternative to the more conventional rule-of-half (e.g., Beria et al., 2018; de Jong et al., 2007; Geurs et al., 2012). Customer surplus is often expressed in monetary terms to find the benefit of a certain project. Such projects include for example a new public transport line in Milan (Beria et al., 2018), a new road pricing policy in the Randstad (Tillema et al., 2011) or several policy scenarios in greater London (Dixit & Sivakumar, 2020). The equation that is commonly used in these studies in some shape is shown in Equation 1.

$$\Delta E = \frac{1}{a_n}\left[\ln\left(\sum e^{v_j^1}\right) - \ln\left(\sum e^{v_j^0}\right)\right] \tag{1}$$

Some general remarks can be made about this equation. First, the absolute value resulting from a logsum does not say much by itself, as discussed in Appendix A.3. Therefore, the relative difference is estimated between the original situation (depicted by v_j^0) and the expected new situation (v_j^1). In addition, the resulting values are converted into monetary terms by dividing them by a_n. This parameter is sometimes called “the marginal utility of income” (Ben-Akiva & Lerman, 1985). It changes depending on the characteristics of an individual (Geurs et al, 2010). For some occasions however, it may be assumed that it is constant. If not, Equation 1 becomes more complicated. Another option is to convert the outcome into time savings, as done by Dixit & Sivakumar (2020).

In practical situations, utility functions are often defined in various ways. For instance, Dixit & Sivakumar (2020) included characteristics related to an individual (age, income, gender), the trip and mode (time, costs, distance) and land use (number of jobs, occupation, and type). Tillema et al. (2011) created a nested logit about route choice, departure time choice and demand. Included characteristics are related to travel time, toll cost, preferred arrival time and mode. Beria et al. (2018) consider time, travel costs and "other components". In general, factors related to the cost and duration of using a particular mode seem to be the most important. Individual characteristics are often considered to identify differences between people.

Next, logsums are frequently used in transportation, LUTI (land use–transport interaction) and other (choice) models (de Jong et al., 2007; Zondag et al., 2015). Their purpose is to represent the expected maximum utility of alternatives related to modes of transport, destinations, departure time, or a combination thereof. For instance, the LUTI model for the Netherlands TIGRIS XL employs logsums within the residential location choice module (Zondag et al., 2015). In short, this part models the decision of households whether to move and if so, to which location. A factor in this model is the accessibility for various travel purposes according to the National Model System (of the Netherlands). The logsum therefore represents the expected utility of living in one area by (log)summing all possible combinations of modalities and destinations. The NMS is a discrete choice type of transport model based on economic utility theory (Zondag, 2007). Included parameters are personal characteristics, preferences as well as characteristics of the transport and land-use systems.

3.4 The potential accessibility

Location-based measures to determine accessibility are introduced in Section 3.2. These measures are especially suitable to express differences in accessibility between locations, hence why they are primarily used in urban planning (Geurs & van Wee, 2004; Kwan, 1998; Neutens et al., 2010). One of the most well-known measures in this category is the potential accessibility. This measure is based on Newton's law of gravitation. Namely, accessibility is mainly determined by the attractiveness of a location (could be seen as mass) and its impedance to other locations (distance) (Kwan, 1998). The impedance indicates the disutility to travel between a pair of locations, which could be expressed in time, cost or something else. The potential accessibility measure is associated with the well-known gravity spatial interaction model to calculate the number of trips between certain zones (E. Miller, 2020). Basing a human spatial interaction model on Newton's theory may not seem particularly logical at first glance. However, Wilson (1967) showed that certain gravity models are derived from information theory. This theory is about finding the most likely estimate given the known information, which is equivalent to entropy maximization (Reggiani et al., 2011). The general formula to calculate the potential accessibility (PA_i) is shown below.

$$PA_i = \sum_{j=1}^{n} (D_j * f(C_{ij})) \tag{2}$$

In this equation, D_j is the number of opportunities at location *j* and $f(C_{ij})$ the impedance function based on a certain cost C_{ij} to travel between *i* and *j* (Hansen, 1959). The impedance function could be shaped by several functions. For instance, an inverse power, negative exponential or modified Gaussian (Kwan, 1998). Generally, the power function yields the best fit (Geurs, 2018). The parameters in such functions could be calibrated based on observed travel behaviour in the considered study area.

This can be achieved by extracting functions from existing demand models or creating ones for the accessibility study itself.

Further, the temporal component can be included to some extent in the potential accessibility measure. For instance, by estimating different travel times during rush hours. However, the temporal constraints of activities themselves and whether people have time to participate in them are difficult to incorporate (Geurs & van Wee, 2004). Another issue is that the measure is less able to distinguish differences based on individual characteristics. These problems could be partially resolved by establishing separate impedance functions for different groups of people.

3.5 Comparison between the potential and logsum measure

It seems that accessibility measures based on gravity functions and discrete choice models differ significantly. On the one hand, discrete choice models are based on utility maximization and gravity models on the other hand on information theory. Anas (1983) proved that they are actually identical when equivalently specified. Taking this into consideration, it is proven below that the logsum and potential accessibility are almost identical in a hypothetical situation.

First, accessibility to go to work from zone i based on an unspecified modality is calculated. Let's consider the utility function as shown in Equation 3. V_{ij} Represents the utility for travelling to zone j from home location i and D_j the number of opportunities at location j. C_{ij} is the disutility to travel between j & i with its corresponding parameter y. y will be a negative value as travelling a larger distance will decrease utility.

$$V_{ij} = ln(D_j) + y * C_{ij} \tag{3}$$

The logsum accessibility to travel from zone i to all possible locations j in the study area (B_k) is calculated by employing Equation 33 which is also shown below.

$$E\left(Max_{i \in C_t} U_{ij}\right) = \ln\left(\sum\nolimits_{j \in B_k} e^{V_{ij}}\right) + C \tag{4}$$

The utility function in Equation 3 could be inserted into Equation 4 to calculate the expected maximum utility to travel to all considered zones from the home location i. So, the sum is over the number of zones meaning that $B_k = n$. The new equation is then:

$$= \ln\left(\sum\nolimits_{j=1}^{n} e^{\ln(D_j) + y * C_{ij}}\right) + C \tag{5}$$

The exponent could be split into a product of two by considering that $e^{x+y} = e^x * e^y$, resulting in:

$$= \ln\left(\sum\nolimits_{j=1}^{n} e^{\ln(D_j)} * e^{y * C_{ij}}\right) + C \tag{6}$$

Then, $e^{\ln(D_j)}$ is equal to D_j, so:

$$= \ln\left(\sum\nolimits_{j=1}^{n} D_j * e^{y * C_{ij}}\right) + C \tag{7}$$

The term $e^{y * C_{ij}}$ could be recognized as an exponent-based decay function and could be abstractly represented as shown below (Reggiani et al., 2011).

$$e^{y * C_{ij}} = f(C_{ij}) \tag{8}$$

This results in:

$$= \ln\left(\sum_{j=1}^{n} D_j * f(C_{ij})\right) + C \qquad (9)$$

One could recognize the equation for the potential accessibility measure from Equation 2 with two alterations. First, results are logarithmically scaled. Therefore, equal improvements will impact the accessibility differently depending on the original accessibility in the logsum measure. Second, the constant C remains. Still, the same ranking of accessibility is predicted by both measures as neither the logarithm nor the constant C causes differences between alternatives. The same process, as shown above, could be achieved by considering several other decay functions. Even, Anas (1983) shows that the parameters in both models are identical when based on the same data. Next, Miller (2020) states that the shown equivalency of both models is often overlooked since random utility models are most frequently applied at disaggregate levels of individuals whilst gravity models are usually formulated at aggregate zonal level. Also, the two models are usually applied in different fields. Geographers typically work with gravity models whilst economists and engineers apply random utility models more often (Miller, 2020).

As said before, differences between both measures occur because of the level of aggregation considered in accessibility studies. A more disaggregate approach indicates that more individual characteristics are included to interpret differences in accessibility between segments of the population. In the example before, it was shown that the two measures are identical at an aggregate level. This comparison becomes more difficult when a more disaggregated accessibility analysis is considered. The reason for this is that individual characteristics are included with the logsum measure by extending the utility function. An example is shown below. β_{male} defines how males have a higher utility in this case than females. β_{male} is equal to one when a person is male, zero otherwise.

$$V_{it} = \ln(D_j) + y * C_{ij} + 1.2 * \beta_{male} \qquad (10)$$

On the contrary, disaggregation with the potential accessibility measure is often performed by creating different distance decay curves. In this example, by drafting one for males and one for females. The more individual parameters are considered, the more curves should be defined. This is more cumbersome than extending the utility function as more data is needed to estimate all the curves. The logsum measure is therefore more commonly applied at a more disaggregated level compared to the potential accessibility.

3.6 Presenting results & operationalizing equity

It will first be discussed in this Section how results from both accessibility approaches could be presented. With this, no judgment of value is made on what the inequality of a distribution is. The next step is to give this judgment for which the three perspectives on equity as discussed in Chapter 2 enter the picture. First, it was found that utilitarianism is a questionable perspective on equity as it ignores distributional effects. Further, it is advised in Dutch policy to move away from utilitarian measures (Snellen et al., 2022). Sufficientarianism is also cumbersome in relation to accessibility as it is difficult to set a threshold. Especially as there are multiple views on what accessibility is with countless measures to quantify it. Setting a threshold is also a political question which should not be answered in this research. Therefore, it is decided to consider egalitarianism to quantify the inequality of accessibility in this research. To do so, various measures will be explained in this chapter. This is achieved by discussing their theoretical background, how they are applied in similar studies and how they would relate to the outcome of the logsum and potential accessibility measures.

3.6.1 Presenting results

One of the most straightforward ways to provide the outcomes from accessibility measures is by directly presenting the resulting values. This approach is often considered with the potential accessibility measure. For example, to show the accessibility to employment opportunities in the Netherlands (Hoen et al., 2019), the accessibility to the population in Europe during the Covid-19 pandemic (Rosik et al., 2022), the accessibility to medical practises in the United Kingdom (Haynes et al., 2003) and more. This often involves creating maps with polygons that have different colours. This makes it immediately clear at first glance which areas are more accessible compared to others and patterns could be detected. The same could in essence be done with results from the logsum accessibility measure. The absolute results are however conditional to one particular discrete choice model. It is not possible to compare values between various versions of the same model or to other models. Furthermore, the additional unknown constant C as explained in Appendix A.3 should be considered as misleading impressions could be created. For instance, a zone with '2' accessibility surrounded by ones with '10' accessibility looks more dramatic in comparison to a situation in which these values are equal to 102 and 110. Both situations are perfectly feasible from the same data set. Next, it would be possible to rank relevant zones or segments of the population according to accessibility. This approach would be more appropriate for the logsum measure as the ranking is not susceptible to the constant C. Furthermore, the ranking based on the logsum and potential accessibility measures will be identical when both are equivalently specified (Anas, 1983). A drawback of ranking is that quantitative differences are ignored. One could therefore find the same ranking when differences between zones are high compared to when they are almost the same.

In addition, absolute values from all kinds of different ranges could be adjusted to a common scale. A way to achieve this is by applying min-max normalization to scale data into a pre-determined range (Yu et al., 2011). Generally, a range between 0 and 1 is considered. Data will therefore be uniform, regardless of the situation. The equation to apply min-max normalization is shown below. In this equation some value X_i is transformed to $X_{i,norm}$ using the minimum (X_{min}) and maximum value (X_{max}) from the dataset.

$$X_{i,norm} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{11}$$

Furthermore, the issue with the constant C when considering the logsum accessibility measure as discussed before could be solved by normalization as shown in Equation 12. This is because the constant is eliminated on both sides of the fraction.

$$X_{i,norm}(logsum) = \frac{(logsum_i + \boldsymbol{C}) - (logsum_{min} + \boldsymbol{C})}{(logsum_{max} + \boldsymbol{C}) - (logsum_{min} + \boldsymbol{C})} \tag{12}$$

3.6.2 Determining inequities

The next step is to investigate the degree of inequality between zones or segments of the population. A way to achieve that is by creating a ratio by dividing the accessibility by another accessibility value, the average, maximum or minimum accessibility. This is completely feasible for the potential accessibility measure. For instance, from zone x one could reach 1.5 times more jobs than average. Doing the same with the logsum measure is problematic because of the frequently mentioned constant C and since utility is interval scaled. Also, the unit itself is questionable. What does it mean to have 10% less utility? Another way to find relative differences is by computing a difference instead of a ratio. This approach is often applied with the logsum measures as discussed in Section 3.3. A major reason for this is that the constant C is eliminated nicely in this way. Also, results could be monetized (e.g., Beria et al., 2018; de Jong et al., 2007; Geurs et al., 2010) or converted into a travel time (Dixit &

Sivakumar, 2020) if the logsum is defined in a certain way. When this is not possible, the unit of the result remains difficult to understand. What does it mean to have less than two utility than the average person?

3.6.3 Simple statistical measures

One of the most straightforward ways to determine the degree of dispersion between a certain number of values is by computing the variance or standard deviation. Next, several similar studies consider the coefficient of variation (CV) which is the standard deviation divided by the average (van Wee & Mouter, 2021). In doing so, the dispersion is standardized allowing comparisons. This value is thus a ratio, which is problematic for the logsum measure as discussed before. Furthermore, the CV does not have an upper bound, which could make it more difficult to interpret (De Maio, 2007). Next, another simple statistical measure that determines the degree of dispersion is the interquartile range (IQR). It is calculated by finding the difference between the 75th and 25th percentiles of the dataset (Wan et al., 2014). It is a suitable metric for both the potential as logsum accessibility measures. However, the IQR does not consider the accessibility of the most severe cases, which may be the ones you want to explore.

3.6.4 Gini coefficient

A more comprehensive egalitarian indicator to express the inequality of a distribution is the Gini coefficient (Gini, 1912). It is originally applied to assess income inequality. It is nowadays also applied to evaluate accessibility. For instance, Dixit & Sivakumar (2020) analysed the equality of accessibility to jobs in Greater London, Mayaud et al. (2019) the inequities in accessibility to healthcare facilities in Portland, Seattle and Vancouver, Guzman et al. (2017) the accessibility to work in Bogotá and Pritchard et al. (2019) inequalities in accessibility to job opportunities with different modes in São Paulo. To calculate the Gini coefficient, individual observations are first sorted according to the unit to be investigated. In Figure 6, values on the y axis represents the cumulative value up to any point on the x axis. The Lorenz curve is also drawn, which shows the found cumulative distribution of a group of people ordered from low to high value. For instance, to show that 50% of people with the lowest income combined only hold 10% of all income. The equal distribution line is a Lorenz curve that represents, as the name suggests, the situation in which everyone has exactly the same accessibility. The Gini coefficient is found by dividing the area between the equal distribution line and Lorenz curve, as schematized in blue, by the area of the complete triangle. The Gini coefficient ranges from 0 to 1, where 0 is a perfectly equal distribution and 1 an extremely unequal distribution.

Next, a weakness of the Gini coefficient is that various distributions can result in a very similar Gini coefficient (Fellman, 2018). One may therefore miss certain information whilst only considering this one value. For this reason, it is beneficial to present both the Lorenz curve and the Gini coefficient. An example of the problem discussed is visualized in Figure 7. Different distributions are characterized by the various Lorenz curves. However, each one will result in a Gini coefficient of 0.5.

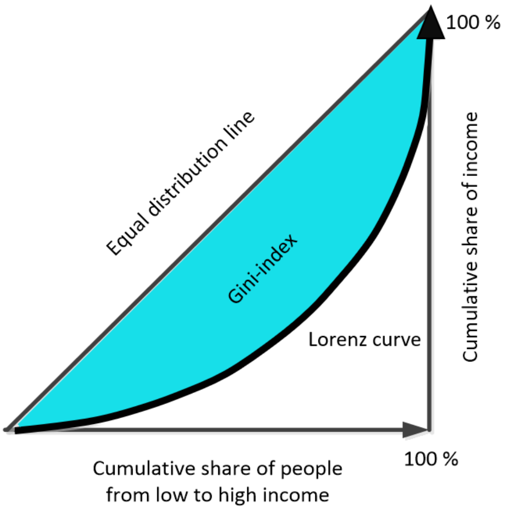

Figure 6: The Gini coefficient and Lorenz curve

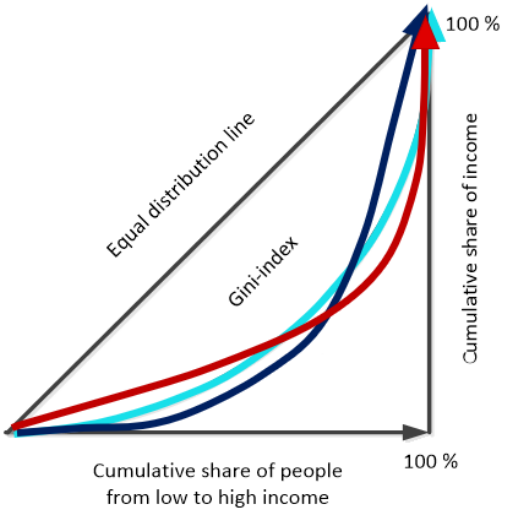

Figure 7: Different Lorenz curves with the same Gini coefficient

The Gini coefficient is the most sensitive to inequalities in the middle of the distribution (De Maio, 2007). It may therefore be less appropriate when the aim is to highlight differences at the highest and lowest ends of the spectrum. To still obtain some insight into these ends of the spectrum, it has been chosen to use a statistic that addresses them. How this statistic is calculated is shown in the Equation below. In this way, it can be determined to what extent the 10% of the population with the highest accessibility is better off compared to the 40% with the lowest accessibility. A situation in which everyone has the same accessibility results in a ratio of 0.25 ($= 10x/40x$). In addition, the higher the ratio, the less equal the distribution in accessibility becomes.

$$10/40\ ratio = \frac{combined\ accessibility\ of\ the\ 10\%\ with\ the\ highest\ accessibility}{combined\ accessibility\ of\ the\ 40\%\ with\ the\ lowest\ accessibility} \tag{13}$$

It has been chosen to construct the measure in this way since the 10% of the least well-off and 40% of the best-off combination are often analyzed in several accessibility studies by applying for instance the well-known Palma-index (e.g., Liu et al., 2022; Pritchard et al., 2019). Second, the measure must be able to investigate inequities in car accessibility. Those who cannot use the car which is about 33% of the population have an accessibility of zero. Dividing something by 0 does not work, which renders the measure useless. It is therefore convent to include at least a higher percentage than 33%.

4. Methodology

The aim of this research is to determine the extent of application and the additional benefits in assessing accessibility to work and related inequalities using a devised logsum measure grounded on the microscopic transport model Octavius compared to the IKOB approach. The following step is to apply both approaches in a practical real-world situation. In this chapter, it will first be explained what the study area will be. Hereafter, the necessary datasets to properly apply both models will be introduced. Finally, the two approaches for calculating accessibility themselves will be explained.

4.1 The study area

First of all, a microscopic strategic transport demand model called Octavius is developed by the company Goudappel. One practical application of Octavius is available for this study, providing the opportunity to determine accessibility based on it with the logsum measure. This application considers the municipality of Zwolle as the study area. Consequently, the IKOB approach will also be applied to this study area to ensure a proper comparison between both methods. Next, Zwolle is located in the East of the Netherlands and is the capital of the province of Overijssel. The municipality has 127,500 inhabitants with 56,600 households. Moreover, the municipality is divided into 550 zones. The study area is visualised in Figure 8. The historic centre of Zwolle is located in the middle which is an important shopping and leisure area. Moreover, this is a 'low car' zone, which means that there is relatively little motorized traffic. Furthermore, residential areas are located around the centre, to the north and southwest. Also, there are multiple large industrial zones in and around Zwolle where many jobs are available.

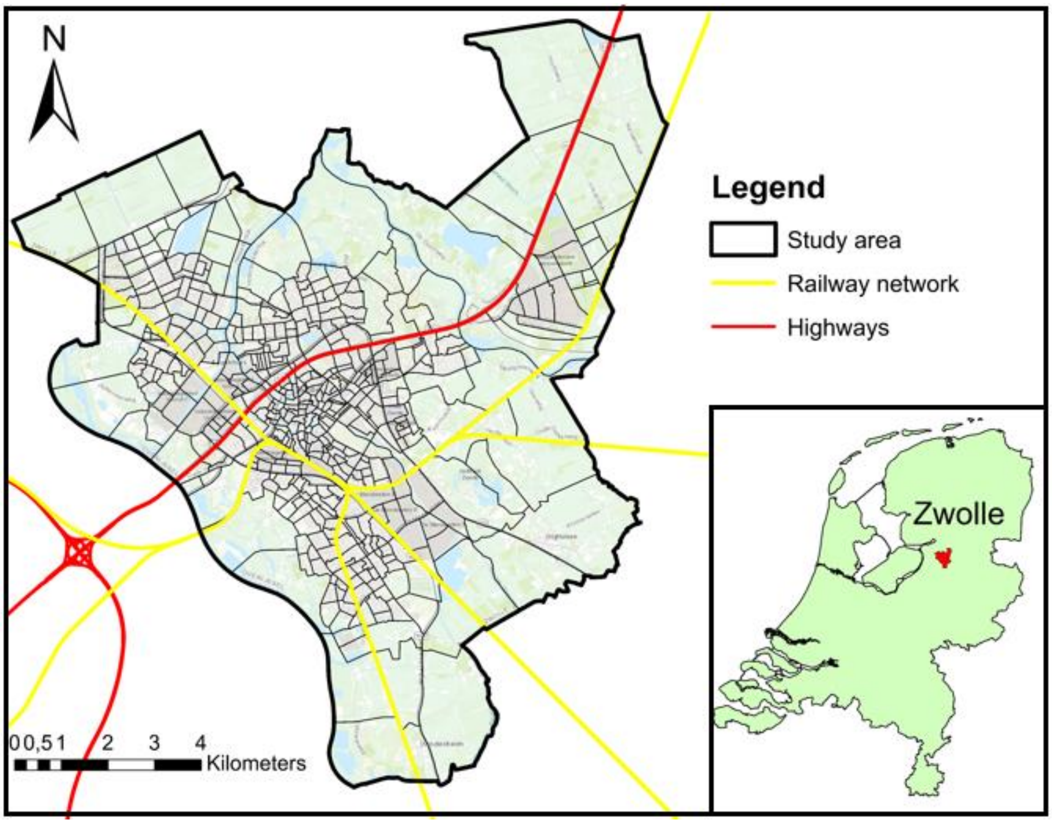

Figure 8: The study area

Zwolle is interconnected to the rest of the country with various links. First, the highway A28 passes through the city. On the east side, it leads to the cities of Groningen and Leeuwarden whilst the west side connects to the important Randstad area. There is also an intersection on the west as could be observed in the figure with the highway A50 which leads to Apeldoorn and Arnhem. Furthermore, Zwolle's main train station is one of the most influential ones in the Netherlands. It functions as an important and in fact the only connection between the Randstad and the northern part of the Netherlands. The network also offers the possibility of travelling from Zwolle in as many as seven different directions. Zwolle is therefore an essential interchange in the region and accommodates 52,300 visitors each day (NS, 2019).

Logically, Zwolle is not an island; people travel from it to all possible corners of the country. Because of this, a proper accessibility study must include not only the municipality itself, but also a "boundary area". For this boundary area, the accessibility itself is not determined, but the number of opportunities present there is considered as possibly accessible from the study area. For this study, the whole of the Netherlands is included, as visualised in Figure 9. In the considered approach, the areas will become increasingly larger and the road network will become less detailed as the distance to Zwolle increases. For example, the nearby city of Apeldoorn (165,000 inhabitants) is divided into 52 areas whilst the further located Groningen (203,000 inhabitants) is only captured as one area. It is hereby assumed that as travel time increases that an additional increment will have a lesser impact on the choices people make. Also, areas further away will have a relatively lower impact on the accessibility in Zwolle than those located nearby. The discussed approach is a way of not allowing computation times to increase excessively.

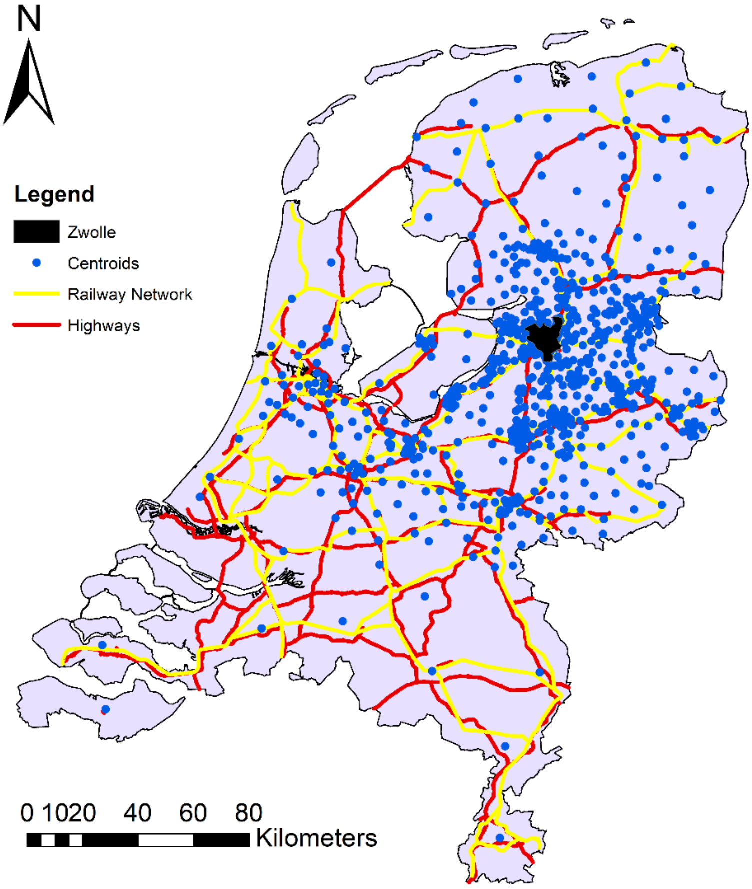

Figure 9: The study and boundary areas

4.2 Data

To calculate accessibility with both approaches, an extensive amount of data is necessary. In this section, the datasets that are used will be introduced. In this process, it will be explained where they originate from, what kind of data it consists of and some descriptive statistics will be presented using figures and tables. Next, the study area has been divided into several zones as explained in the previous chapter. About each zone, certain information must be known. In general, two types of datasets can be distinguished in this regard. On the one hand, this includes numerical information which can be indicated by a positive integer. For instance, the number of inhabitants. On the other hand, categorical information about how certain characteristics are distributed. For instance, 45% of the people are male and 55% female in zone x. All the necessary information about the study area has been presented in Table 1. It is shown what possible categories each parameter consists of, the source of the dataset and whether it is used in the Octavius and/or IKOB approach. Besides, the degree of urban density is a specific case which takes only one value for each zone.

Next, it could be observed in the table that most information is provided by the municipality of Zwolle. This information is available in the same dimension as the considered zones. An exception is that IKOB requires an income distribution variable that considers four groups. Each one represents 25% of the Dutch population (e.g., the 25% lowest income group). The required data is neither provided by the municipality nor available somewhere else. Because of this, another way was adopted to prepare this data. Two datasets are used to do so, which are the income distribution into 3 and 5 groups for "neighbourhood" polygons. For the distribution into three groups, a nationwide division of the population into 40% low, 40% medium and 20% high income is considered (CBS Statline, 2020). Next, each category represents 20% when the population is divided into five groups (CBS, 2019). To approximate a division into four groups, interpolation was performed using the two datasets. The last step is to link each zone in the transport model to a corresponding neighbourhood one. To this end, a zone is given the characteristics of the neighbourhood polygon in which it is located.

Table 1: Information about each zone

Parameter	Categories						Source*	Octavius	IKOB
Number of inhabitants	All possible positive integers						MoZ	✓	✓
Number of households	All possible positive integers						MoZ	✓	✓
Number of jobs	All possible positive integers						MoZ	✓	✓
Total number of cars	All possible positive integers						MoZ		✓
Age categories	0 to 17	18 to 29	30 to 44	45 to 64	64+		MoZ	✓	
Gender	Male	Female					MoZ	✓	
Ethnicity	Dutch	Western	Not western				MoZ	✓	
Driver's license	Does have one	Does not have one					MoZ	✓	✓
Household size	1 p.	2 p.	3 p.	4 p.	5 p.	6 p.	MoZ	✓	
Household type	One person	Without children	With children				MoZ	✓	
Number of cars in household	0 cars	1 car	2 cars	3 cars			MoZ	✓	
Income categories	Low	Medium low	Medium high	High			CBS		✓
Degree of urban density	Non-urban	Little urban	Moderately urban	Highly urban	Very urban		MoZ	✓	✓

** MoZ = Municipality of Zwolle, CBS = Centraal bureau voor de statistiek/ Statistics Netherlands*

Further, both accessibility approaches require input datasets called "skims". These skims represent the travel time, cost and distance between each origin and destination pair for every transport mode. These values are calculated by considering the present (multi-modal) network. The travel times are based on free flow times, so congestion is not considered. For the road network, each link is given a certain speed. Furthermore, the city centre is considered a car-free zone. To model this, it is assumed that the last distance is crossed on foot after parking the car. To do so, a speed limit of 5 km/h is assumed for roads in the city centre. Next, a change in the network would require these skims to be recalculated. The disutility to travel between zones is calculated according to their midpoints. Moreover, intrazonal information is estimated given the size of the zones.

4.2.1 The number of inhabitants and jobs

Next, the number of inhabitants per kilometre squared for each zone in the study area has been visualized in Figure 10. First, it can be observed that the zones with the highest density are located around the middle of the area. Many variations in population density are also noticeable among these locations. One reason for this is that these zones are quite small, making their density highly sensitive to their specific characteristics. Moreover, the zones at the boundary of the study area are more sparsely populated. Furthermore, the number of jobs in each zone is displayed in Figure 11. Each dot represents 150 jobs. The figure shows firstly that the job opportunities are scattered throughout the study area. In addition, several clusters can be identified that primarily represent industrial areas.

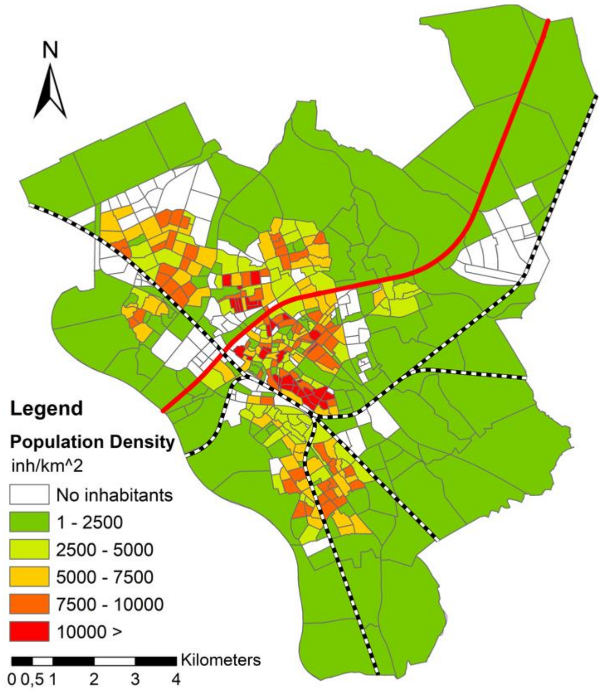

Figure 10: Population density in Zwolle

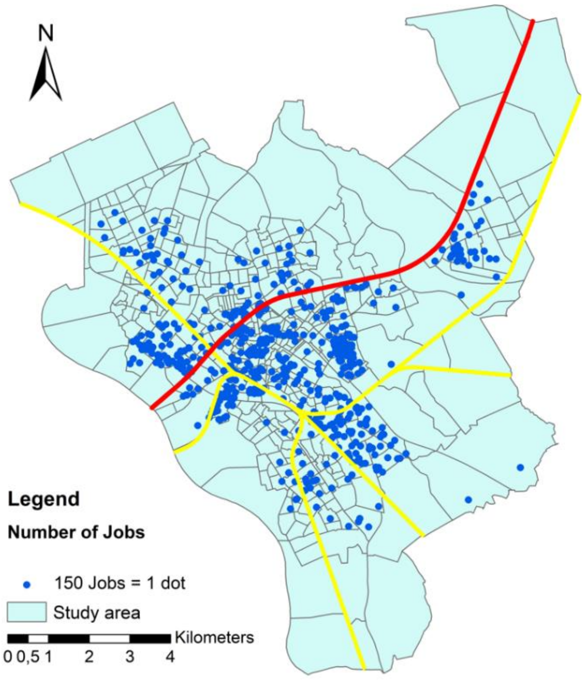

Figure 11: Number of jobs in Zwolle

4.2.2 Degree of urban density

A parameter that is considered in both accessibility approaches is the degree of urban density. This variable depends on the average number of addresses per square kilometre (CBS, 2023). The higher this value becomes, the higher the degree of urban density. Figure 12 shows the degree of urban density of each zone in the study area. It could be observed that the city centre which is located in the middle has been assigned the highest possible category; very urban. Areas surrounding the city centre are categorized as highly, moderately and little urban. These areas primarily represent residential and industrial zones. Lastly, non-urban areas are located on the edges of the study area. These represent a combination of scarcely built-up areas, farmlands and nature

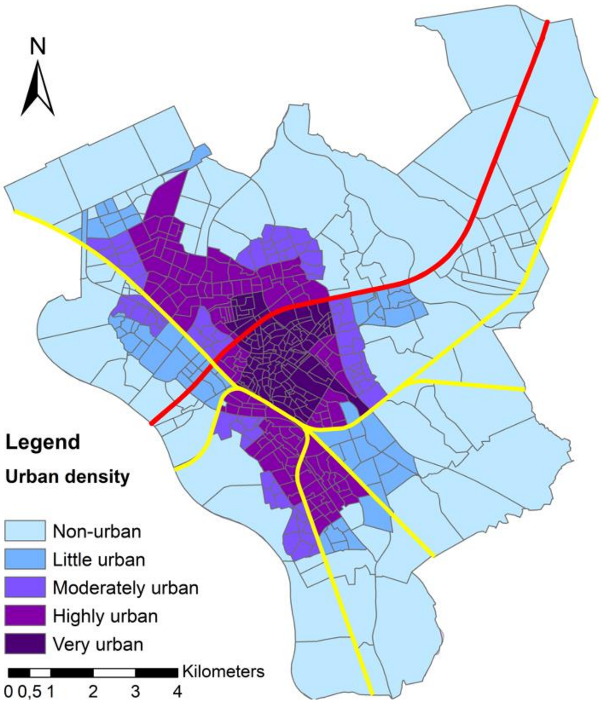

Figure 12: The degree of urban density

4.2.3 Car and driver's license possession

An important factor that affects people's accessibility is whether they possess a car or a driver's license. These two variables are therefore considered in the accessibility measures specified later in this report. To model this, certain information is gathered about each zone, as discussed before. Next, the average number of cars per household is visualized in Figure 13. It could be observed that households in the city centre have the least number of cars on average, for which there are several reasons. Most prominently, this area is a ‘car-low zone’, which means that several roads are not accessible by car. Instead, most streets in the city centre are only accessible by public transport, cycling and walking. Furthermore, these locations have a higher degree of urban density as visualised in Figure 12. It is often found that people in urban areas have fewer cars on average compared to those living in rural areas (CBS, 2018). Next, car ownership increases in the neighbourhoods around the centre. In this regard, people living in the northeast of the study areas have on average the most cars. One reason for this is that this is a relatively high-income area, which will be further elaborated upon in the upcoming Section. Furthermore, Figure 14 shows the percentage of people in each zone who possess a driver's license. The observed pattern is relatively similar to the one in Figure 13, which is not entirely surprising. One could expect that driver's license ownership rates are lower in those zones in which people own fewer cars on average.

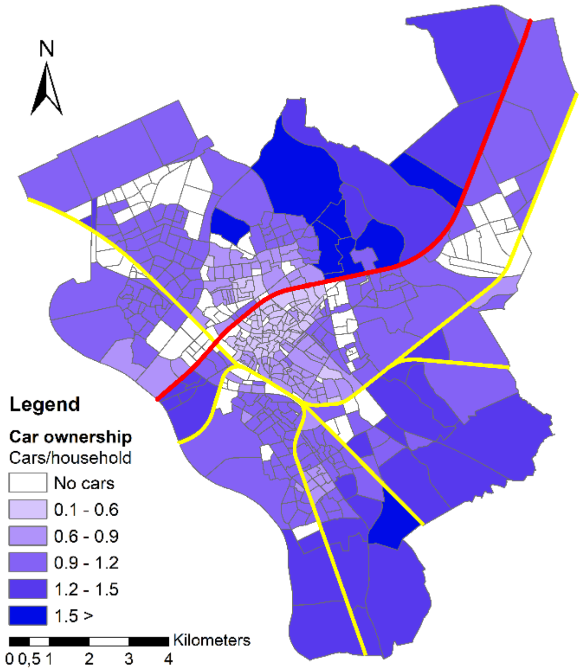

Figure 13: Car ownership in Zwolle

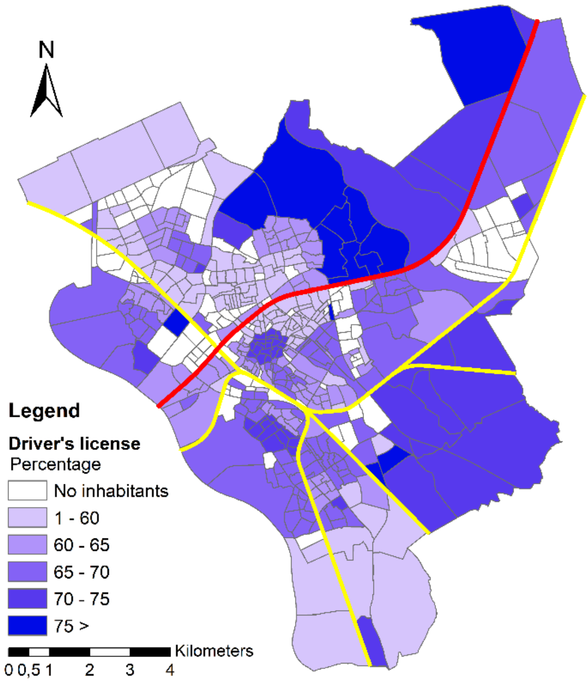

Figure 14: Driver's license ownership in Zwolle

4.2.4 Income categories

A parameter that has been estimated is the income distribution in each zone, as elaborated upon in Chapter 4.2. It is a categorical variable with the possible categories: low, medium-low, medium-high and high. Figure 15 illustrates how often the categories high and low occur in each zone. First, these figures show that people with lower incomes are more prevalent in the central and northern parts of the study area. Next, people with higher incomes are more common in the zones at the edges of the study area. One reason for this could be that larger plots and properties are available here due to the lower degree of urban density, which are more expensive. Besides, most considered parameters in this study are specific to each zone. The income distribution, on the other hand, is estimated with data about larger zones than in the considered model as explained in Section 4.2. As a result, it can be noted in the figures that certain zones located near each other have identical income distributions.

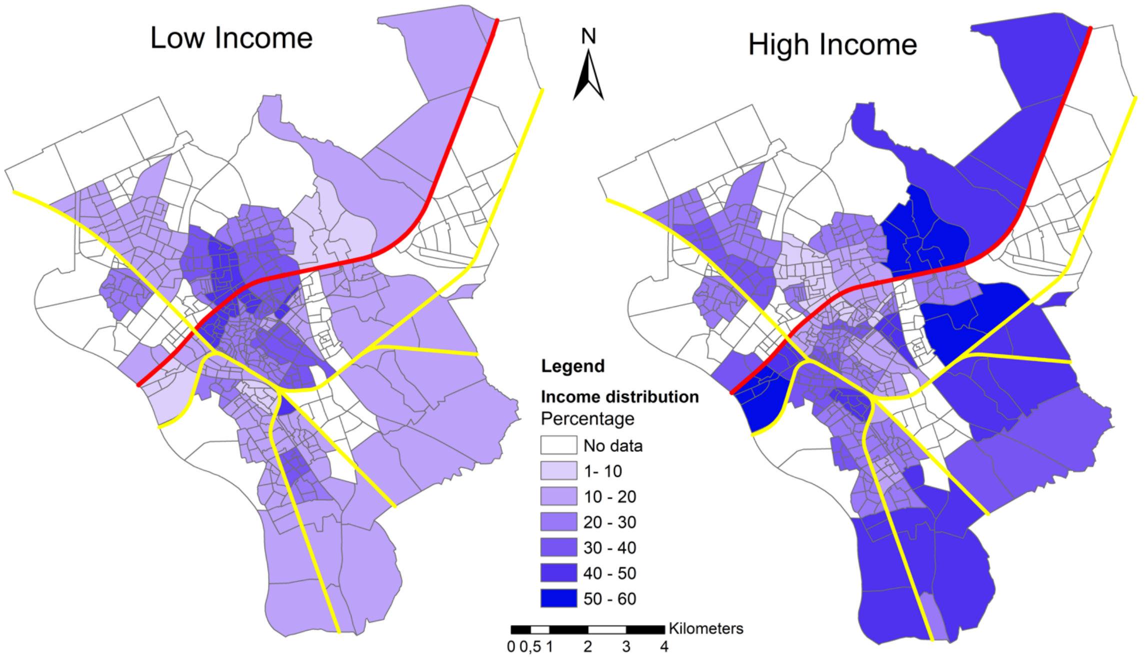

Figure 15: The occurrence of the "low" and "high" income categories

4.3 Accessibility analyses in practice

In this section, it will be explained what the considered models are and how accessibility can be determined with them. To do so, the IKOB approach will first be elaborated upon. Following this, the model Octavius is explained. After this, the accessibility measures that are based on this model with the logsum approach will be introduced.

4.3.1 The IKOB approach

In the Netherlands, mobility analyses are often founded on aggregated transport demand models. Such models have several limitations, as discussed in Section 3.1.1. For instance, only the "average" population is taken into account whilst individual characteristics are ignored. However, these characteristics do have a defining impact on an individual's possibilities in the built environment. The decisions taken to create these transport models have ramifications for subsequent accessibility measures. In Dutch transport policy, there is a greater need to examine differences in accessibility between people with various characteristics. With the existing aggregated models, which are still mostly used in practice, this need cannot adequately be addressed. To combat this, the IKOB (Voerknecht, 2021) has been devised. It employs a post-process approach to overcome the limitations of said aggregate models. Primarily, by introducing a way to retrospectively disaggregate the general population into sixty segments and finding the specific accessibility of each of them. At its core, it applies the Hansen-based potential accessibility measure. In this section, it will be described step by step what actions should be performed to execute IKOB. This chapter is based on Voerknecht (2021), Hoen et al. (2019) and internal documents. Besides, there are multiple versions of IKOB. In this section, the one explained is applied in this research. For this, the assumptions in the approach were made by the authors discussed, not in this research.

4.3.1.1 Segmentation

The first step in IKOB is to distribute the general population in each zone across various segments. The number of inhabitants in a zone can be obtained from a transport demand model as well as from the CBS. Segmentation is performed based on the five criteria listed in the table below. These have also been elaborated upon in Section 4.2. A stepwise approach is considered, in which the segments are further refined every iteration into smaller ones. This procedure could be compared to the one used to create a decision tree.

Table 2: Parameters for segmentation in IKOB

Having a driving licence	Having a free car
Having a car	Income categories
Having free public transport	Preference for a modality

At first, the general population is divided according to income categories in each zone. Then, for each income category it is estimated what percentage of people do not have a driving licence, do have a driving licence but do not have a car and those that have both. These three groups are mutually exclusive and should add up to 100%. The sizes of the groups are initially calculated based on two parameters. The first one is the degree of urbanization in a zone to account for the fact that people in cities have fewer cars on average compared to the countryside. Second, the income distribution to model that people with a higher income do more often have a car. Then, the found percentages are compared to car ownership data of that specific zone from CBS. The initial estimates based on the income distribution and degree of urbanization can be lowered in a zone if they are calculated too high compared to CBS data. When doing so, the frequency of the other two groups (no car, no driving licence) is increased to keep all of them adding up to 100%.

Subsequently, it is determined from the people that have a car, how many of them can use it for 'free' with data from VZR[2]. For instance, because they got a car from the company. This percentage is dependent on the income category because people with a higher income are more likely to receive a 'free' car. After this, the same is done to make a distinction between people who can make use of free public transport and those who cannot. It is assumed[3] that 3% of the population could benefit from free public transportation based on data from the Dutch Railways (NS). At last, the identified groups are segmented based on preference for some modality. Possible values are bicycle, car, public transport and neutral. How often each category occurs is estimated with data from OVIN[4]. In this step, certain combinations are excluded. For instance, people who have a 'free' car and do not have access to 'free' PT can only prefer the car. Similarly, people who do not have a 'free' car but do have access to 'free' PT can only prefer PT. People who have access to both for 'free' have no preference. Sixty groups are created after the discussed steps. These and the discussed process to establish them are visualised in the figure below.

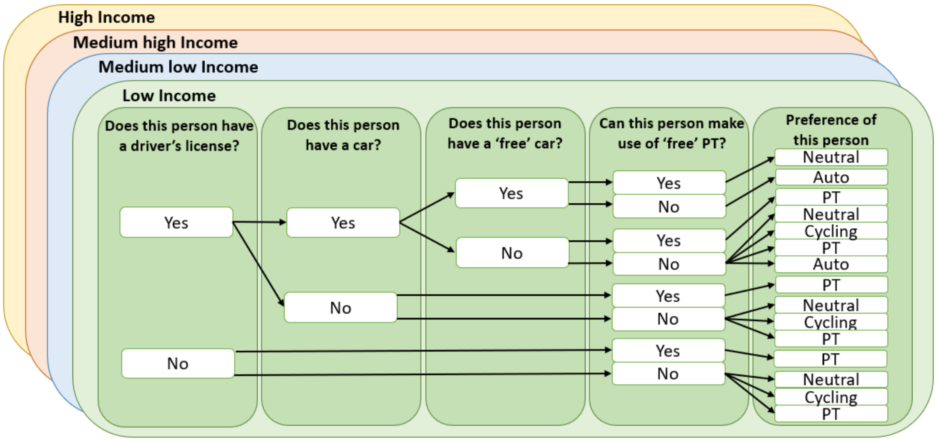

Figure 16: The considered segmentation in IKOB

4.3.1.2 Calculating generalized travel time

The next step is to calculate generalized travel times to commute to any area in the study area for each segment. The generalized travel time consists of two parts: the travel time and costs. The costs are converted to travel times by using the "time value of money" (TVOM). This number indicates how much a euro is worth in minutes for each income group. The higher the income, the lower the TVOM. The values range between 4 to 12. In essence, this parameter is the 'value of time' which is often considered in many studies but inverted. The values for the TVOM are estimated by experts and not directly calculated by applying certain travel information. The resulting equation is shown below.

$$Generalized\ travel\ time = travel\ time + TVOM * costs \tag{14}$$

Generalized travel times are calculated for each combination of segment and modality. The core of the travel times is found by taking the travel time between any two zones from a transport demand model. Then, certain parameters are added to calculate the time to travel from door to door. What parameters the experienced travel time for taking the car as well as the costs of doing so consists of is shown below. The properties that are obtained from a transport demand model are highlighted in bold. The time to reach the car and parking search times is based on average values from "local institutions" if

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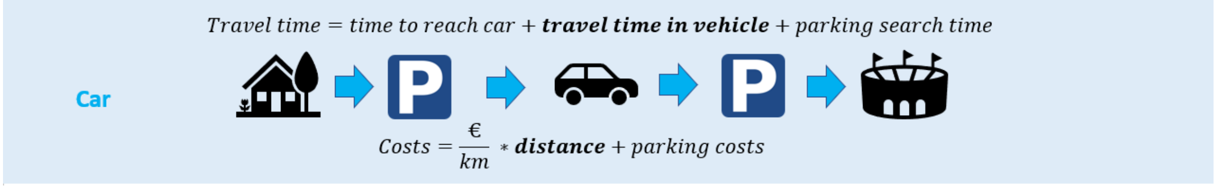
[2] Interest group for business mobility; belangenvereniging voor zakelijke mobiliteit

[3] This assumption sand others in this chapter are made by the creators of IKOB themselves. Not by the writer of this study.

[4] "Onderzoek Verplaatsingen in Nederland", Travel survey in the Netherlands

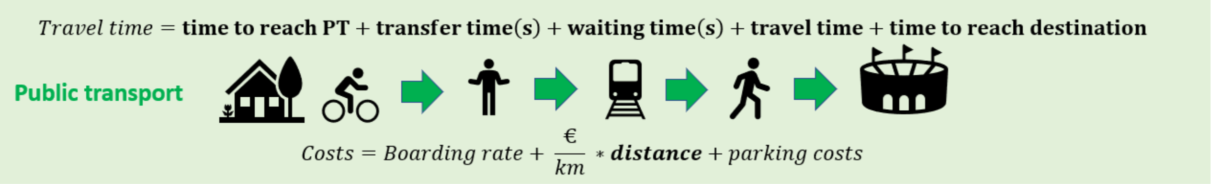
available. If not, a table with values for the whole country is considered. These are however not important for the travel motive “work” as it is assumed that someone can freely park there.



$$Travel\ time = time\ to\ reach\ car + \mathbf{travel\ time\ in\ vehicle} + parking\ search\ time$$

$$Costs = \frac{€}{km} * \mathbf{distance} + parking\ costs$$

Next, how the travel times and costs of public transport are calculated is visualized below. The properties for determining the travel time are extracted from a transport demand model. In this model, it is assumed that the time to reach the public transportation stops at the start of the trip and the last stretch to reach the destination is travelled by bicycle. Besides, an incorporated parameter for calculating the cost is the ‘boarding rate’, to model that ticket prices do not start at 0 euros. The fees for storing a bike in a paid facility could be considered with the parking costs. Again, this parameter is not important for the travel motive work.



$$Travel\ time = \mathbf{time\ to\ reach\ PT + transfer\ time(s) + waiting\ time(s) + travel\ time + time\ to\ reach\ destination}$$

$$Costs = Boarding\ rate + \frac{€}{km} * \mathbf{distance} + parking\ costs$$

Moreover, the travel times for the bicycle are directly extracted from the transport demand model. The costs are assumed to be neglectable. Subsequently, the variable costs per kilometre for using PT and the car are zero for people who can make use of a ‘free’ car or ‘free’ public transport. In addition, it is assumed that the group of people who have a driver's license, but no car will rent shared cars. Likewise, people who have neither a car nor a driver’s license will make use of taxis. The costs of these alternatives are much higher, reducing the attractiveness of the car modality significantly. Lastly, the comfort of travelling is incorporated in certain implementations of IKOB. It is however difficult to determine how comfort could be related to travel time. Expert judgment is used for this. This makes it difficult to assess whether the estimated parameters are accurate in any shape whatsoever. These comfort parameters are not considered in the provided model for this research and are therefore out of scope.

4.3.1.3 Calculate accessibility.

The next step in the IKOB method is to calculate the specific accessibility of each defined segment based on its characteristics. To do so, the potential accessibility measure as explained in Section 3.4 is applied. It consists of several parts, as shown in the equation below. In this equation, $PA_{s,i,p,m}$ is the accessibility of segment s in zone i travelling for purpose p with modality m and $D_{p,j}$ the number of opportunities for purpose p that people can assess in zone j. $f_{v,p.m}(C_{i,j,s,m})$ is the decay curve for people with preference v for purpose p with modality m as a function of the generalized travel time between zones i and j for combination s and m. A total of 180 potential accessibilities are calculated for each zone. (60 population segments, 3 modalities, to work) It is a bit cumbersome to present all of them. Therefore, the segments could be aggregated in certain ways as will be explained at a later stage in this section.

$$PA_{s,i,p,m} = \sum\nolimits_{j=1}^{n} (D_{p,j} * f_{v,p.m}(C_{i,j,s,m})) \tag{15}$$

The decay curves describe the willingness to make a trip as a function of travel impedance, which is in the IKOB approach the generalized travel time. The higher the generalized travel time, the less attractive the trip becomes. In most approaches, a decay curve is estimated for each modality. IKOB considers a more comprehensive approach, in which a decay curve is estimated for each combination of modality and preference. In this way, the decay curves of someone who prefers public transport are different compared to someone else who prefers taking the car, as visualized in Figure 17. The parameters as well as the mathematical function to shape the curves are based on expert judgment to fit observed travel behaviour. They are however not consistent with the decay curves from a transport demand model. This makes it difficult to determine whether the created curves are appropriate.

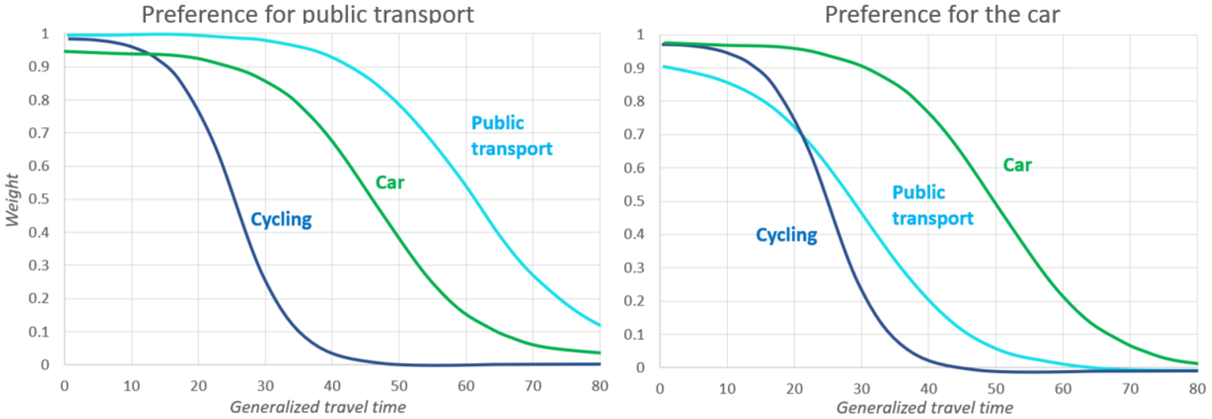


Figure 17: Decay curves for segments with different preferences

With the chosen formulation, accessibility is at last calculated per segment, per modality for each zone. Depending on the question, there is a need to aggregate them (e.g., over all modalities and or all segments). The IKOB method has also developed methods to do so. Three methods will be highlighted. The first one aims to calculate the accessibility of segment s in zone i for purpose p considering all modalities. This will be referred to as "total accessibility" from now on. To accomplish this, the preferred mode for travelling between every OD pair is first identified for each segment. This is achieved by assessing which modality has according to the decay curves the highest weight for travelling to each specific zone. For example, someone who prefers the car travels in a hypothetical situation where the generalized travel times of all three modalities is exactly 30 minutes. Figure 17 shows that $W_{cycling} = 0.22$, $W_{PT} = 0.48$ and $W_{car} = 0.90$. This person takes the car since this weight is the highest. There are no probabilities involved. The resulting equation is shown below.

$$PA_{s,i,p} = \sum\nolimits_{j=1}^{n} \left(D_{p,k,j} * \max\left\{f_{v,p.m}\left(C_{i,j,s,m}\right): m = car, bicycle, pt\right\}\right) \tag{16}$$

Another approach is to further aggregate the results from Equation 16 to calculate the average accessibility in each zone i for purpose p. These values can be visualised to create well-known accessibility maps with polygons that have different colours. For this purpose, the accessibility of all segments in each zone is averaged using the weighted average, as shown in Equation 17. In this Equation, $F_{s,i,p}$ is the number of people that belong to segment s in zone i travelling with purpose p with corresponding accessibility $PA_{s,i,p}$. $\sum_{k=1}^{n} F_{s,i,p}$ should be equivalent to the number of inhabitants in zone i. The same approach is considered to calculate the average accessibility in each zone for every modality.

$$PA_{i,p} = \frac{\sum_{s=1}^{m} (F_{s,i,p} * PA_{s,i,p})}{\sum_{s=1}^{m} F_{s,i,p}} \tag{17}$$

In addition, the IKOB approach can be applied to analyse the effects of certain policies. To do so, assumptions should be made about what parameters are changing. For instance, by reducing the travel times for cycling when proposing new infrastructure. The results could be compared to the ones before the policy changes to calculate and visualize their effects.

A similar approach as discussed in the sections before could be utilized to calculate how many people a company or institution could reach. The main difference is that the number of inhabitants is regarded as D, rather than the number of opportunities. There is also a method defined to calculate accessibility with competition, this is however out of scope for this research.

4.3.2 The microscopic strategic transport demand model Octavius

In the Netherlands, mobility analyses are often founded on aggregated transport demand models. A major developer of transport models is the company Goudappel. Their models are one of the most frequently used ones for transport planning in the Netherlands. At the same time, a move towards micro-demand models is made by introducing a new module, named Octavius (Brederode et al., 2020). With Octavius, the aim is to investigate travel patterns by modelling the behavioural choices of individual travellers. The most detailed behaviour could be modelled in theory, which may not be realistically achievable in a practical situation. Therefore, a balance is struck for creating Octavius between accuracy and the availability of data and computation times. In addition, the model provides the opportunity to extend it relatively easily with new choices and applications. Next, many behavioural choices are dependent on previously made ones and those made by others. For instance, a person cannot use a car when the only car in their household is already in use. Or, that someone cannot take the car from their work to the store when they earlier commuted to work by bike. To properly model such dependencies, the circumstances in which decisions are made should be known at the level of the individual traveller. Therefore, Octavius considers tour-based microscopic modelling. However, temporal consistency is not considered which implies that the approach is not activity-based. Octavius consists of multiple modules which will be elaborated upon in the next sections. It should be noted that the development of Octavius is progressing rapidly. Therefore, it is likely that the information to be discussed is outdated. However, the version that is explained in the upcoming sections will be used for this research.

4.3.2.1 Population synthesizer

First, agents will be created to model the real population as accurately as possible with the “population synthesizer.” Each agent will be given characteristics based on the parameters and their corresponding categories as shown in Table 1 and Table 3. To do so, the frequency of the various categories will first be gathered for every zone based on available data. The first four parameters are about individual characteristics and the last three are about household characteristics. Then, two algorithms are applied that each creates a population that meets the specified frequency of each category as closely as possible. For this, one algorithm considers the individual characteristics, the other the household characteristics. This also involves some basic logic to create realistic agents. For instance, an agent with an age category of 0 to 17 cannot have a driving license. Subsequently, the resulting information is combined in the final step to create the population in each zone. The ultimate result is that each agent has personal and household characteristics according to the considered categories. For instance, a male who is 0 to 17 years old, is Dutch and belongs to a four persons household with children that have one car.

Table 3: Parameters in the population synthesizer

Individual characteristics	Household characteristics
Age categories	Household size
Gender	Household type
Ethnicity	Number of cars in household
driver's license possession	

4.3.2.2 Tour generator

Next, it will be established with the “tour generator” how the travel schedule of each agent will look like. So, for what motive(s) is this person going to travel? First, it will be estimated how many tours an agent will make. Possible options are 0, 1 and 2. A person with 0 tours will logically not travel. Then, it is modelled for each agent that is at least going to make one tour how each tour will look like. A tour can consist of 2 (1 destination) and 3 trips (2 destinations). The possible travel motives are education, work, business, social-recreational, shopping and other. Next, only one motive is chosen for a tour which consists of 1 destination. Next, a combination of two motives is selected for a person who makes three trips. One is chosen as the primary motive and the other one as the secondary one. Depending on the main motive, there is a set of secondary motives available as possible choice options. The logic for this is shown in Figure 18. The possible secondary motives can only be located to the right of the primary one. So, work (primary) and shopping (secondary) is possible while social-recreational (primary) and education (secondary) is not. Also, it will be modelled whether the primary or secondary destination is travelled to first. The characteristics of each agent influence the likelihood of each decision at every stage. For instance, a younger person is more likely to make a trip for education.

Figure 18: Primary motives and possible secondary ones

4.3.2.3 Destination choice

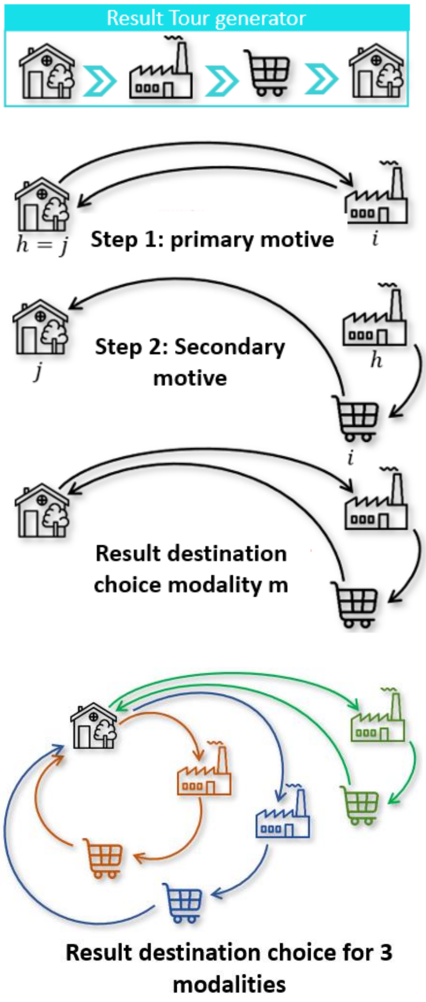


Figure 19: Destination choice in Octavius

The next step is the destination choice, in which each trip with a certain motive as determined in the last step will be assigned a location. For instance, a person from zone p will travel for work to zone m. To achieve this, a location is first selected for the primary motive given the home location of the agent. Then, a location is chosen for the secondary motive if the tour consists of three trips given the home and primary location. The discussed process is visualized in Figure 19. For each trip, there are many alternatives to travel to in the considered study area. Which specific location will be chosen is modelled with multinomial choice models, which are explained in Appendix A.

The utility to travel to each location is modelled with Equation 18. In this Equation, $V_{p,m,c,i\,|h,j}$ is the systematic utility of agent p travelling to location i given the previous point h and the next point to be reached j with modality/modalities m given the chosen tour c. The attractiveness of each location consists of four sets of factors. The first set addresses what the travel time is from location h travelling to i and on to j. The second set of parameters are individual characteristics that indicate how agents with specific attributes experience travel times. For instance, to model that males are willing to travel for larger distances in comparison to females. The last set determines the attractiveness of the location to be reached by itself. In more detail, $t_{m,hi}$ and $t_{m,ij}$ are travel times with modality m between two points. The travel time of public transport is similar to the one defined for IKOB, as discussed in Section 4.3.1.2. Namely, it consists of the time to reach a PT stop, transfer time(s) waiting time(s) and the in-vehicle time. In Octavius, each one of these components could be perceived differently. For instance, a one-minute waiting time is perceived as longer compared to a one-minute in-vehicle time. All data about travel times is obtained from a transport demand model. Next, s represents several personal and household characteristics as shown in Table 3. r consists of dummies representing cost parameters. Subsequently, $m_{i,k}$ represents the supply of activities on location i for each travel motive. For instance, the number of jobs is considered for the work and business motives and the number of inhabitants for the social-recreational one. The degree of urban density is also considered in $m_{i,k}$. The idea of this is to model that denser locations are more attractive than rural ones.

$$V_{p,m,c,i\,|h,j} = \sum(\beta_{p,c,m} * s) * \beta_{c,m} * \left(t_{m,hi} + t_{m,ij}\right) + \sum(\beta_{r,c,m} * r) + \sum(\beta_{m,c} * m_{i,k}) \qquad (18)$$

All the discussed components are connected to a parameter β, which are estimated based on observed travel behaviour with data from OViN. Furthermore, a set of parameters is estimated for each combination of modality, primary motive and secondary motive if the tour consists of two destinations. The different combinations are denoted in Equation 18 by the letter c. Only parameters that are found relevant and statistically significant are included. As a result, the created utility functions for two distinct travel motives may consist of different parameters.

Subsequently, the utilities to travel to each location found with Equation 18 are deployed to calculate the percentual chance that each one is chosen by an agent. The multinomial logit function as shown below is used for this purpose.

$$P_{p,m,c,i\,|h,j} = \frac{e^{V_{p,m,c,i\,|h,j}}}{\sum_{j=1}^{n} e^{V_{p,m,c,i'\,|h,j}}} \tag{19}$$

Then, one discrete choice is assigned in the following step to each traveller based on the found percentages with a “discretization step”. This involves the use of certain algorithms to ensure that the behavioural choices of individual travellers match macroscopic outcomes as closely as possible. The discretization error is the deviation between the continuous distribution from the choice model and the frequency distribution for the choice alternatives after discretization.

In short, it can be observed in Figure 19 that the destination choice consists of two steps for a trip chain with two destinations. The first step is equivalent to the process for a single-destination tour. This involves determining the utility of traveling to every zone in the study area from the home location of an agent as discussed before. Then, a discrete choice is made about which zone to travel to from the home location. For the second step, a similar process is executed as the first one. The difference is that the earlier selected location is considered to be the start location in the second step. After this, the utilities are calculated to travel from this location to every zone given the last trip to return to the home location of the agent. The discussed processes have been performed for each agent for every (available) modality, resulting in a certain trip train for each one of them as visualized at the bottom of Figure 19.

4.3.2.4 Mode choice

The last stage is the mode choice. In this module, the modality or combination of modalities by which every agent will reach its destination(s) is chosen. Multinomial choice models are also utilized for this purpose. The systematic utility is calculated with Equation 20. In this Equation, $V_{p,h,m}$ is the utility for agent p from location h to travel with modality or combination of modalities m. The attractiveness of each modality is generally based on three factors. The first one is the $logsum_{p,h,m}$, which represents the attractiveness of all the possible destinations to travel to from location h with modality or combination of modalities m for agent p. The second set of factors are personal characteristics that indicate how agents with specific attributes experience each modality. Several parameters as listed in Table 3 are included with dummy variables p with corresponding parameters $\beta_{m,p}$. The last factor is the alternative specific constant $(asc_{m|k})$ which represents the general preference for certain modalities that has not been captured by the other variables.

$$V_{p,h,m} = asc_{m|k} + logsum_{p,h,m} + \sum (\beta_{p,m} * p) \tag{20}$$

Again, a set of parameters is estimated for each combination of modality, primary motives and the secondary motive is considered when the tour consists of three trips. However, some possibilities have been excluded. For example, taking the car is not possible for an agent who does not have a driver’s license and/or belongs to a household that does not have a car. Subsequently, the utilities are converted to percentages that each motive is selected with multinomial logic functions. After this, discretization is applied to assign microscopic choices to each agent.

The final result of Octavius is a travel diary for each agent. This data can be transformed into origin-destination matrices.

4.3.3 Accessibility with Octavius

Next, methods will be created to calculate accessibility based on information from Octavius. As explained in Section 4.3.2.3, the behaviour of agents is modelled in Octavius using multinomial discrete choice models. The expected maximum utility achieved from a set of alternatives can be expressed as a measure of accessibility (Ben-Akiva & Lerman, 1985). This value is calculated with the logsum measure as explained in Appendix A.3. Multinomial discrete choice models are applied at two stages in Octavius. First of all, by modelling the destination choice. Calculating the expected maximum utility of this set of alternatives would represent the accessibility for an agent p to travel from location h to all other zones in the considered study area for trip chain k with modality m. Next, the accessibility is a measure which reflects the potential to travel which is independent of the trips people actually take. This definition is valid when tours are considered which consist of one destination. However, the same does not hold for trips consisting of two destinations. This is because the decision for the second destination depends on the discrete choice for the first one, as discussed in Section 4.2. The utility is therefore probabilistic. The selection of an other first location would result in a different utility, changing the accessibility. As a result, the actual choices agents make are reflected in the accessibility measure which is not desirable. It has therefore been decided to alter the tour generator so that every agent will make a tour that consists of only two trips. The chosen trip chain k turns into travel motive work c because of this. Furthermore, five age categories are included in Octavius including the category younger than 18 years old. This includes children going to primary and high school. This is also visible in the Octavius itself, as most agents in this age group have been assigned the travel motive "school". Calculating the accessibility of this age group to work is not relevant or meaningful. Because of this, it has been decided to remove agents from this age category from the dataset.

Next, the equation to calculate the accessibility from the destination choice module in Octavius with the logsum measure is shown below. In this equation, $A_{p,h,m,c}$ is the accessibility of agent p from zone h travelling with modality m for motive work (w). $V_{p,m,c,i\,|h,j}$ is the systematic utility as calculated with Equation 18 whilst $U_{p,m,c,i\,|h,j}$ represents the actual utility. n is the number of zones in the considered study area C_{sa}.

$$A_{p,h,m,w} = E\left(Max_{j\in C_{sa}} U_{p,m,w,i\,|h,j}\right) = \ln\left(\sum_{i=1}^{n} e^{V_{p,m,w,i\,|h,j}}\right) \tag{21}$$

The other stage where multinomial choice models are applied is for the modality choice. Calculating the expected maximum of this set of alternatives would represent the accessibility of agent p to travel from zone h to work (w) considering all possible modalities. This will be referred to as "total accessibility" in this report. The equation to calculate the discussed total accessibility is shown below. In this equation, $V_{p,m,h,c}$ is the systematic utility as calculated based on the nested logit as shown in Equation 20 whilst $U_{p,m,h,c}$ represents the actual utility. g is the number of possible (combination of) motives in the considered study area (C_{sa}). In this research, these are cycling, the car and public transport.

$$A_{p,h,w} = E(Max_{j\in C_{sa}} U_{p,m,h,w}) = \ln\left(\sum_{m=1}^{g} e^{V_{p,m,h,w}}\right) \tag{22}$$

The accessibility by each modality and the total accessibility are calculated for every agent in the study area. Presenting the accessibility of each agent in the study area is a bit cumbersome. Therefore, certain information should be aggregated to produce relevant results that can be appropriately presented. This can generally be accomplished in two main ways. On the one hand, by aggregating agents with similar characteristics by using the weighted average. For example, by showing the average accessibility of males compared to females in the study area. On the other hand, by aggregating agents that live in the same zone. In this way, the mean accessibility in zone h for travelling with modality m can then be found by averaging the calculated accessibility of all agents in that zone. With the resulting information, the well-known accessibility maps in which each zone is assigned a colour can be created. One must keep in mind however that logsum is a relative value. It is only meaningful when the accessibility of some segment is compared to that of others or when the situation in some scenario is compared to the baseline as discussed in Appendix A.3.

4.3.4 Establishing a proper comparison

Two methods to calculate accessibility have been elaborated upon in the last three sections. On the one hand, this includes the IKOB method. On the other hand, the logsum approach estimated with information from the microscopic traffic demand model Octavius. However, it is not appropriate to compare them yet as some matters need to be resolved first. The main idea of this is to make the comparison of the measures as appropriate as possible. That is, we are comparing apples with apples, instead of apples with grapefruits. In this section, it will be discussed what issues should be resolved or at least considered and potential solutions to overcome them are introduced.

4.3.4.1 Different zones

The first challenge is that the IKOB approach is estimated based on 'neighbourhood' ('wijk & buurt' in Dutch) polygons from the CBS. However, the traffic model on which Octavius is defined considers a different partitioning of the study area. These are in essence the same 'neighbourhood' polygons, but further segmented. The transport demand model therefore effectively incorporates more, smaller areas. Because of this, segments in the model will only belong to one neighbourhood polygon. This has been illustrated in Figure 20. It could be observed that the boundaries of the neighbourhood polygons will always coincide with those in the transport model. Only, each polygon has thus been further segmented.

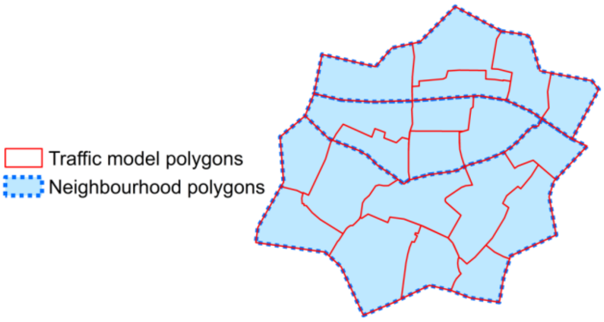
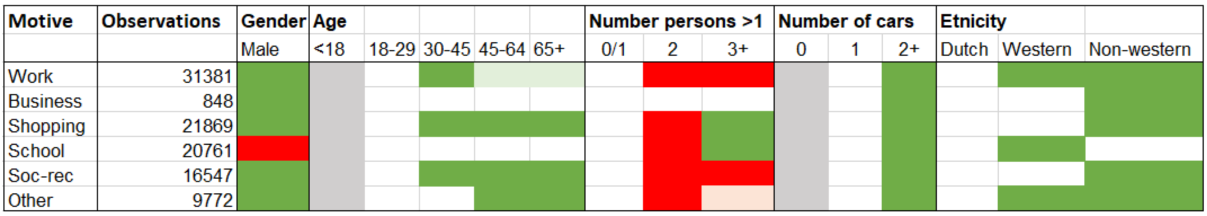


Figure 20: Traffic model & neighbourhood polygons

To make a proper comparison between both approaches, one kind of area distribution must be chosen. In other words, IKOB will be applied in accordance with the areas in the transport demand model, or Octavius will be applied with neighbourhood polygons. The first alternative is preferred for several reasons. Firstly, information about travel times and distances is calculated with the transport model. Choosing a different area division would mean that this information must be obtained in a new way. This would require modifying the transport model itself or aggregating current information, which is not desirable. Second, most of the information needed for IKOB is available at a more detailed level. It is therefore possible to apply IKOB to the available transport model. Third, choosing larger polygons would result in information loss, which is unnecessary when IKOB could be applied at a smaller scale.

4.3.4.2 How they are created

The next distinction is that both methods are created based on widely divergent principles. On the one hand, parameters that create variations in the decisions people make when travelling are included in Octavius when two conditions are met. First, their effect has been demonstrated by literature. For instance, it has been found that males tend to use the car more often compared to females. Second, such parameters are proven statistically significant from observed travel behaviour in the Netherlands. This is verified when the behavioural parameters for the different multinomial choice models in Octavius are estimated. An example of such an estimation is shown in Figure 21. In this table, it can be observed which factors have a significant negative (red) and positive (green) effect on choosing the car. For instance, it can be seen that someone in the age group 30-45 is more likely to take the car to work.



Motive	**Observations**	**Gender**	**Age**					**Number persons >1**			**Number of cars**			**Etnicity**		
		Male	<18	18-29	30-45	45-64	65+	0/1	2	3+	0	1	2+	Dutch	Western	Non-western
Work	31381	🟩	▨		🟩	🟩	🟩		🟥	🟥	▨		🟩		🟩	🟩
Business	848	🟩	▨								▨		🟩			🟩
Shopping	21869	🟩	▨		🟩	🟩	🟩		🟥	🟩	▨		🟩			🟩
School	20761	🟥	▨						🟥	🟩	▨		🟩		🟩	
Soc-rec	16547	🟩	▨		🟩	🟩	🟩		🟥	🟥	▨		🟩			🟩
Other	9772	🟩	▨			🟩	🟩		🟥	🟥	▨		🟩		🟩	🟩

Figure 21: An estimation in Octavius for a multinomial choice model

The IKOB approach has been constructed with a different angle compared to Octavius. First, the factors influencing the travel opportunities of people are examined. A group of researchers subsequently decided which factors to include in the approach and what population segments to consider (Hoen et al., 2019). This consideration involves first assessing what data is available. Second, by establishing the number of segments that are still manageable for model development and simulations. Third, by determining what parameters and segments are of interest in Dutch accessibility policy. The last point aims to ensure that the method matches the needs of policy makers. Besides, the IKOB method is quite flexible. It is possible to modify a number of features when requested. This allows tailor-made services to be provided for each study by establishing an IKOB method that is the most appropriate. However, this also has its drawbacks. For instance, it could be time-consuming to discuss which parameters to include and to model them for each specific study. Furthermore, stakeholders can shape the results to their liking by picking parameters that are important to them. This affects the neutrality and accuracy of the approach.

Sections 4.3.1 and 4.3.2 show that the different approaches lead to large differences in segmentation and parameters that are considered, which will also be discussed in the following section. Furthermore, one could argue that the IKOB approach is more flexible and subjective compared to Octavius. Such differences are not something to ‘fix’. It is caused because they are created based on different principles. It is however important to keep in mind when comparing the methods.

4.3.4.3 Segmentation

The complete population is divided into various segments according to certain parameters in both methods to determine accessibility, which have been presented in Table 4. It could be observed that the considered parameters and resulting segments between both methods are very different. Moreover, the number of segments also varies significantly. Ideally, the segments in both methods are equalized to make comparing them more accurate. In this way, it can be concluded for example that the accessibility of some segment x is affected by 12% with a certain measure in IKOB whilst it is only 1% with the logsum approach. Unfortunately, this is not possible because of multiple reasons. First, the various parameters are correlated in some way. This makes it difficult for instance to establish how the four income categories from IKOB are distributed within the five age categories in Octavius. It seems likely that older people will have higher incomes on average, but the question is how exactly. To answer this, some data must be collected and assumptions made. Differences will then arise from the chosen assumptions and data rather than the theory behind each approach which is not desirable. Another issue is how the various segments are incorporated into each approach. In IKOB, accessibility is determined for every segment in each zone. In doing so, the number of people that are considered in a segment may be a fraction. For instance, 1.45 people in some zone belong to segment x. By contrast, microsimulation is performed in Octavius resulting in only a round number of agents. Therefore, not every segment appears in each zone. Because of the discussed reasons, it is not realistic to equalize the considered segments in both approaches.

Table 4: Considered parameters for segmentation in both models.

Octavius	IKOB
Age	Driver's license possession
Gender	Having a car
Ethnicity	Having free public transport
Driver's license possession	Having a free car
Household size	Income categories
Household type	Preference
Number of cars in household	
Total segments: 4320	**Total segments: 60**

4.3.5 Presenting results

The various values resulting from both accessibility approaches must be presented in an appropriately designed manner. In doing so, the goal is to conveniently present and compare results. Different ways to do so are elaborated upon in Section 3.6. First, it could be chosen to simply present the absolute values. Comparing results in this way is however complicated since the units from both accessibility approaches are vastly different. For instance, results from the logsum measure are between 6 and 12 "utility." However, results from the IKOB measure range up to hundreds of thousands. It is difficult to match them in some way. One way to solve this is to establish a ranking. For example, by showing which zones are among the 10% with the lowest accessibility. Another alternative would be to apply min-max normalization as discussed in Section 3.6.1. In this way, the results are scaled between 0 and 1. When applying this method, the unit will be the same for results from both models. Moreover, quantitative differences between zones are accounted for. Because of these reasons, min-max normalization will be applied. One disadvantage of this method however is that it is sensitive to outliers. One very low or high value would have a significant impact on the complete scale. To mitigate this in some capacity, it has been decided to base the minimum on the lowest five values and the maximum on the highest five. Besides, normalization is only applied for presenting the average accessibility of each zone. The same will not be done to compare accessibility between segments, since the segments themselves differ greatly between the two approaches, as discussed in Section 4.3.4.3. Equating the units is then of very little use. Because of this, it is decided to present the absolute values when showing the accessibility of various segments. Furthermore, the Gini coefficient and 10/40 index were introduced in Section 3.6 and will be applied in this study. Moreover, various distributions can result in the same Gini coefficient. Because of this, not only the Gini coefficient will be shown but the Lorenz curves will also be plotted.

5. The Assessment framework and scenarios

Two different kinds of accessibility measures are the focus of this study. On the one hand, this includes the logsum measure as introduced in Section 3.3. On the other hand, the potential accessibility measure as explained in Section 3.4. It was proven earlier in this report that both measures are identical when equivalently specified. However, this is more straightforward to achieve on an aggregate scale than when a disaggregated approach is considered. Especially when the IKOB approach is used to apply the potential accessibility and the logsum measure is founded on Octavius. Because of this, there will be differences between both measures. One of the aims of this study is to identify these differences and to interpret their implications for accessibility studies. To achieve this, an assessment framework will be created based on which the comparison will be performed. The framework will consist of various criteria formulated with the literature collected in this report. These criteria specify how a proper accessibility measure should behave in certain conditions. The criteria will be established in accordance with the components of accessibility according to Geurs & van Wee (2004). Namely, the transport, land-use, temporal and individual components. An ideal accessibility measure should consider all of them (Geurs & van Wee, 2004). By doing so, important interdependencies are ensured. Hereafter, the various criteria will be deployed to create scenarios which will be performed with the accessibility models.

5.1 The components of accessibility

5.1.1 The land use component

First of all, the demand and supply for opportunities are spatially distributed. An accessibility measure should consider where and how much demand and supply are generated in the land use system (Geurs & van Wee, 2004). Fundamentally, increasing the number of opportunities should have a positive effect on accessibility. Next, it is most of the time not realistic to model the impact of each specific building on the supply and demand for opportunities. Instead, the number of trips generated from and attracted to each demarcated region in a study area is frequently considered. In the Netherlands, this is often performed by applying data from the Central Bureau of Statistics (CBS) to obtain the boundaries and various data about each specific zone. The demand could be a function of the number of inhabitants in each zone, whilst the supply could be based on the number of jobs, shops, education places and more.

Furthermore, most opportunities have capacity limitations. For instance, one job opportunity can only be filled by one (qualified) worker. The situation in which individuals compete for a limited number of opportunities is called competition, as explained in Section 2.1.2. Shen (1998) states that not considering competition could lead to unrealistic results. An appropriate accessibility measure should therefore consider the confrontation between demand and supply for opportunities. In other words, increasing the demand for opportunities for an activity with capacity restrictions should decrease the accessibility to that activity. Lastly, the presence of remote working has accelerated rapidly during the Covid-19 pandemic (Rosik et al., 2022). This involves both completely working remotely or a hybrid approach where physical presence is only required on certain days. Virtual access is therefore provided to opportunities that are normally located in space. Providing more remote working opportunities makes physical distances less important (Cavallaro & Dianin 2022). Therefore, increasing the availability of remote working opportunities should increase accessibility. However, this does not include the effect that also more people are able to reach the jobs which increases competition and may have a negative effect on accessibility. Competition is already included in another criterion and is therefore not considered for this one.

5.1.2 The transport component

Next, the disutility to cover the degree of spatial separation between the supply and demand for opportunities as discussed in the previous section is reflected by the transport component (Geurs & van Wee, 2004). Fundamentally, an increase in the number of opportunities in an area ‘close’ to people should have a greater effect on their accessibility compared to a situation where the same number of opportunities is applied in a zone further away. Further, the stated ‘degree of spatial separation’ could be defined in various ways. One of the most straightforward methods is to only consider the distance. For instance, by taking the Euclidean, Manhattan or distance through the network. Apparicio et al. (2008) argue however that travel times are more appropriate. Firstly, because the distance does not provide an appropriate representation of the network with its different kinds of roads, congestion and more. Based on the distance, it could be concluded that it is preferable to follow a route right through the centre of a city rather than using the ring road around it. With this in mind, reducing the (maximum allowed) speed of a modality should have a negative effect on accessibility. Secondly, the distance does not give the right representation of varying transport modes. For instance, it could be concluded that the bicycle is just as beneficial as the car when travelling the same distance. Because of these reasons, an appropriate accessibility measure should include the travel time in some shape as a way to reflect the degree of spatial separation between supply and demand. Furthermore, increasing the level of service of a transport modality should increase the accessibility of that specific modality.

Moreover, the monetary cost of travel also influences the resistance to travel (Hoen et al., 2019). The costs are especially decisive for choosing between transport motives. For instance, taking the car may just be the fastest alternative, but the costs of doing so could make it less attractive. Hence, increasing the cost of travelling whilst keeping everything constant should reduce accessibility. As highlighted, differences in accessibility between various modalities should be considered. In the Netherlands, the car (46%), the bicycle (28%), walking (16%) and public transport (6%) are the most important ones (CBS Statline, 2022). Walking may not be entirely relevant for this study as only the accessibility to job locations is considered, which are often distances too long for walking. The other three motives are certainly relevant and should be considered in a proper accessibility analysis.

5.1.3 The individual component

As discussed in Section 2.1.3, accessibility depends on personal characteristics such as an individual's needs, abilities and opportunities. First, people with certain characteristics and abilities perceive the attractiveness of transport modalities differently or even cause that they cannot use certain ones. Someone without a driving license cannot take a car as a driver, for example. So, improving the service of a transport modality should not increase the accessibility of those with insufficient abilities or capacities to use that mode. Furthermore, each person perceives the cost of travelling which was elaborated upon in the previous section differently. That is, someone with a higher income is willing to pay more to reduce their travel time compared to someone who has less to spend. For instance, Dixit & Sivakumar (2020) found that the sensitivity to travel costs by train is much higher for someone with a low income compared to middle and high incomes. Likewise, Fournier & Christofa (2021) found that the value of time in relation to travelling increases as the income of a person rises. A person with a higher income is therefore willing to pay a higher price to reduce their travel time.

Second, different individuals have varying needs. For instance, an 18-year-old participates in different activities compared to a retired person. One could therefore state that increasing the number of opportunities should not increase the accessibility of those who do not seek those particular activities. Third, not every opportunity is available to everyone because of limitations such as skills, income or travel budget. For example, some people may not be suitable for certain jobs. Increasing the number of opportunities should thus not increase the accessibility of those with insufficient abilities or capacities to participate in them. Because of the discussed elements, significant disparities in accessibility may be overlooked when the individual component is ignored (Kwan, 1998). Therefore, an appropriate accessibility measure should incorporate the criteria as discussed.

Likewise, there is a greater need to examine differences in accessibility between population segments in Dutch accessibility policy, as discussed in Section 1.1. The individual component is therefore an important element. For this, it is not only important that the population is divided into segments, but that they are also relevant to current and future policy objectives. In other words, that individual needs, abilities and characteristics that cause significant differences in travel options in the Netherlands are taken into account. Next, Olde Kalter et al. (2015) investigated how changes on individual and household level affect people's mobility choices in the Netherlands with travel survey data. First, it was found that personal preference has a major influence on mode choice. Second, household characteristics, such as whether people have a car, the number of people in the household and whether people have children, have a significant effect. Likewise, personal information like age, gender and income are important explanatory variables. Furthermore, Snellen et al. (2020) argue that possessing a car or a driving license has a direct impact on the available opportunities to people.

5.1.4 The temporal component.

The last component to consider is the temporal one (Geurs & van Wee, 2004). It takes into account that accessibility is not the same for everyone over time. First, more realistic travel times could be found by establishing a better representation of the transport network. For instance, by accounting for rush hours. Accessibility is lower when the duration of the same journey is longer due to congestion. In the Netherlands, the severity of congestion is on the rise again since the Corona pandemic (Rijkswaterstaat, 2022). How this affects accessibility is frequently studied. Likewise, it was found that on average people could reach 12.5 % fewer jobs by car during rush hours (CBS et al., 2020). Another important temporal element is the availability of opportunities at different times throughout the day. Some activities have specific schedules that make them unavailable at certain moments. So, increasing the number of opportunities should only increase the accessibility during its opening hours. Furthermore, opportunities could also be unreachable due to the time constraints of individuals, as discussed in Section 2.1.4. In short, an accessibility measure should both consider the availability of opportunities at different times as well as the time availability of people to participate in them. Thus, opportunities that cannot be reached due to temporal constraints should not increase accessibility.

Even when a suitable accessibility measure is created that meets all the earlier discussed criteria, it should still be understandable, or at least trusted by policymakers, as they are the ones using it for decision-making (Morris et al., 1979). An important part is that the unit of the outcomes should be understandable. For instance, the unit of a measure which assesses how many opportunities can be reached within a fifteen-minute range is the “number of jobs”. It is clear what such a unit indicates as no mathematical or statistical background is necessary to understand it. Furthermore, the calculated results could be visualized as often practised in Dutch policy. On the one hand, this includes preparing the well-known accessibility maps in which each zone is assigned a certain value and colour. On the other hand, the possibility to show and compare the accessibility of certain segments of the population.

5.2 The framework

The criteria that are discussed in the previous two sections have been put in Table 5. Besides, Geurs & van Wee (2004) acknowledge that it is not feasible in a real-life scenario to consider all the discussed criteria as it would require a level of complexity that is not realistically achievable. Still, they state that one should discuss when certain components are not adequately modelled and understand the subsequent ramifications. Moreover, a measure that meets more criteria compared to another one does not automatically make it more accurate or suitable. Furthermore, criteria cannot be compared one to one. Instead, the assessment framework may indicate in what aspects a measure may fall short.

Table 5: The assessment framework

	The assessment framework
1	**The land-use component**
1.1	Increasing (reducing) the number of opportunities should have a positive (negative) effect on the accessibility.
1.2	Increasing (reducing) the demand for opportunities for an activity with capacity restrictions should decrease (increase) the accessibility to that activity.
1.3	Increasing (reducing) the availability of remote working opportunities should increase (reduce) accessibility
2	**The transport component**
2.1	An increase (decrease) in the number of opportunities in an area ‘close’ to people should have a greater effect on their accessibility compared to a situation where the same number of opportunities are added (removed) in a zone further away.
2.2	Reducing (increasing) the speed of a modality should have a negative (positive) effect on accessibility.
2.3	Increasing (reducing) the service level of a transport modality should increase (decrease) the accessibility of that specific modality.
2.4	Increasing (reducing) the cost of a transport modality should decrease (increase) the accessibility of that specific modality.
3	**The individual component**
3.1	Improving (decreasing) the service of a transport modality should not increase (reduce) the accessibility of those with insufficient abilities or capacities (e.g., driver's licence, education level) to use that mode.
3.2	Increasing (decreasing) the number of opportunities should not increase (reduce) the accessibility of those with insufficient abilities or capacities to participate in them.
3.3	Increasing (decreasing) the cost of transportation should reduce (increase) the accessibility for those with less to spend to a greater degree compared to those with more to spend.
4	**The temporal component**
4.1	Increasing (decreasing) the number of opportunities should not increase (reduce) the accessibility of those who do not have time to participate (meaningful) in them because of their specific time schedules.
4.2	Increasing (decreasing) the number of opportunities should only increase (reduce) the accessibility during its opening hours.
5	**Additional criteria**
5.1	Is the measure consistent with the transport demand model on which it is based?
5.2	Is the unit of the measure an understandable term?

5.3 Scenarios

The following step is to apply the various criteria to assess the extent of application and additional benefits in assessing accessibility to work and related inequalities using the devised logsum measure grounded on Octavius compared to the IKOB approach. To do so, several scenarios will be created with three strategies. First, at least one scenario must relate to each of the considered three components of accessibility (transport, land-use, individual). The temporal component cannot be investigated as both models do not consider any variations in time. For instance, different working hours, time conflicts with other activities of people and so on. Second, another aim is to investigate how the logsum and IKOB approaches are able to assess inequalities in accessibility. Therefore, scenarios are introduced that contribute to this. For instance, by creating a scenario in which one particular population segment is provided additional services. Thirdly, it would already be possible based on the theory behind the approaches to predict the behaviour of the two accessibility approaches. It would not be worthwhile to propose scenarios in which the same results are anticipated beforehand. Instead, it is interesting to find scenarios in which differences between them are expected. Lastly, the remaining criteria in the framework are verified based on the results of all scenarios together.

5.3.1 Travel costs and inequities in accessibility

The first criterion that has been chosen is: "*Increasing (reducing) the cost of a transport modality should decrease (increase) the accessibility of that specific modality".* This criterion ensures that the cost of travelling is included properly in the accessibility measure. In addition, the next criterion could also be included as it elaborated upon it: *Increasing (decreasing) the cost of transportation should reduce (increase) the accessibility for those with less to spend to a greater degree compared to those with more to spend.*

These criteria have been selected for several reasons. First, travel costs are an important characteristic that creates differences in the number of opportunities people have and thus has a significant impact on inequalities within a population. This inequality is also of importance in Dutch policy, as discussed in Chapter 1. Subsequently, this scenario firstly has an impact on the transport component, as costs play a factor in the disutility to travel between the demand and supply for opportunities. Secondly, how costs are perceived depends on personal characteristics which makes the scenario also impact the individual component.

In addition, the costs are considered in a completely different way in the two approaches. In short, the cost parameter is connected to the variable "TVOM" to calculate the generalized travel time in IKOB, as shown in the equation below. The TVOM is higher for people with lower incomes to model that they experience the effect of travel costs more severely.

$$Generalized\ travel\ time = travel\ time + TVOM * travel\ costs \tag{23}$$

Within Octavius, the attractiveness to travel to some zone is calculated with the utility functions as discussed in Section 4.3.2.3. Schematically, the formula looks as shown below. It could be observed that personal and household characteristics are connected to the travel time. In this way, it could be modelled that people with certain characteristics are willing to travel for a longer distance. However, these personal and household characteristics are not connected to the travel costs.

$$\begin{aligned} Utility = {} & personal\ \&\ household\ factors * travel\ time + travel\ costs \\ & + location\ specific\ characteristics \end{aligned} \tag{24}$$

To test the impact of travel costs on the (equality of) accessibility, it has been decided to increase the costs of using the car by 30%. This scenario will be implemented by modifying certain input data. The proposed scenario is also relevant in the Dutch context, as it is often proposed to make driving a car more expensive as a measure to combat climate change (de Rooy, 2023).

5.3.2 Closing roads and accessibility

In general, it could be stated that: *Reducing (increasing) the service level of a transport modality should decrease (increase) the accessibility of that specific modality.* This criterion is selected because it is relevant to Dutch accessibility policy. The reason for this is that roads and train lines are frequently closed due to construction work. In doing so, both travel times and costs will increase which is modelled differently in both approaches, as already touched upon in Section 5.3.1. By mimicking such a situation, it is possible to investigate the subsequent effects on accessibility and inequalities therein. Logically, accessibility will reduce as travel times increase. With this scenario, it can be determined whether the effects from both approaches are similar. Thus, this scenario affects primarily the transport component of accessibility according to Geurs & van Wee (2004).

In the study area, the river IJssel poses a barrier between the municipality and the west of the country including the Randstad region. There are only a few bridges to cross the IJssel. It has been decided to close two important bridges to test in a more extreme situation what will happen according to both models. The selected two bridges are visualized in Figure 22. The first one is for the highway A28 to cross the river. The other is located below it and is significantly smaller. Closing these two bridges would force a significant increase in travel times as the closest way to get across the IJssel is located ten kilometres to the north, or thirteen to the south. This scenario will be implemented by modifying the transport network. Then, travel times, distances and costs by car are recalculated with the model. The resulting skims will be used as input for both accessibility approaches.

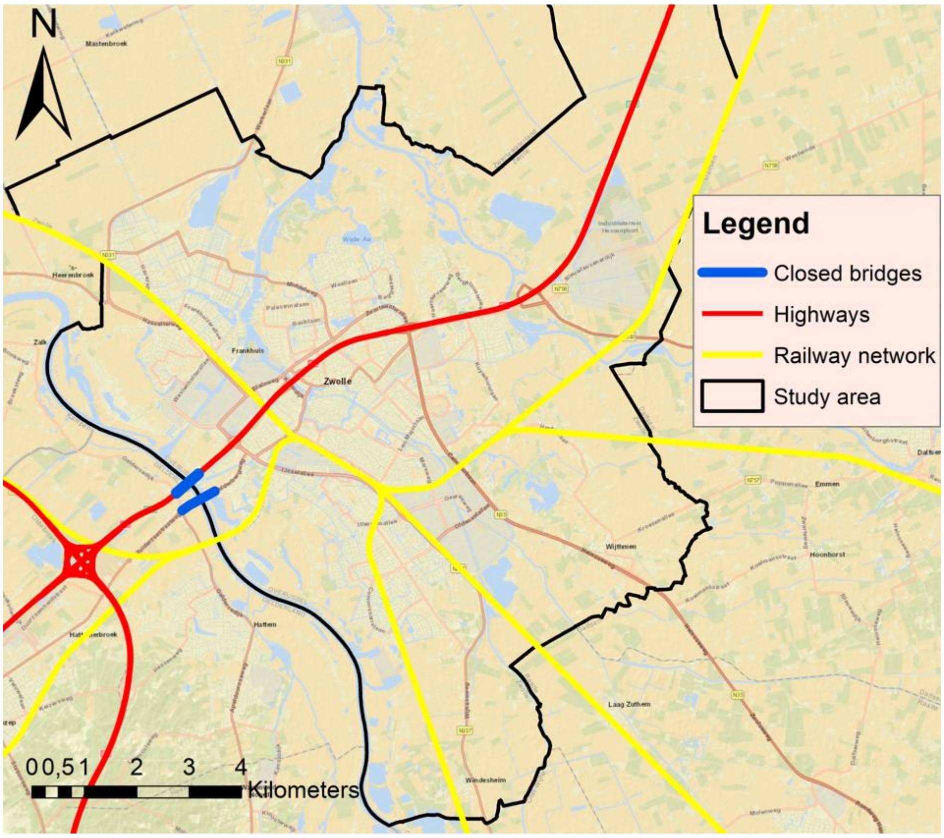


Figure 22: Closing roads in the second scenario.

5.3.3 Accessibility and its connection with driver's license and car ownership

The next criterion that has been chosen is: *Improving (decreasing) the service of a transport modality should not increase (reduce) the accessibility of those with insufficient abilities or capacities (e.g., driver's licence, education level) to use that mode.* This criterion is chosen based on two reasons. Comparable to the first scenario, whether people have a car and/or a driver's license is an important characteristic that causes differences in the number of opportunities people can reach. This scenario primarily relates to the individual component of accessibility according to Geurs & van Wee (2004).

The second reason is the way driver's license and car ownership are modelled contrasts between the two accessibility approaches. Initially, both approaches use information about whether people have a car or a driver's license to segment the population. Logically, those segments without either of them have poor accessibility by car. In Octavius, the accessibility by car is zero in this case. In fact, it is not even calculated. In IKOB, the assumption is made that people without a car but with a driver's license will rent a shared car whilst those with no driver's license will take a taxi. The costs of this option are much higher, resulting in low accessibility. Not zero, however, which thus contrasts with Octavius. Additionally, driver's license and car ownership are initially estimated based on income distribution and the degree of urban density of a zone in IKOB. This can be adjusted using CBS data for that zone about car ownership per household. However, this adjustment can only reduce it, if car ownership is estimated too high. Moreover, further segmentation takes place in IKOB using the 'preference' parameter. People who have a preference for a certain modality are willing to tolerate more costs/travel time compared to those people who do not have a preference for it. Thus, accessibility will be higher with that modality. People who do not have a car or a driver's license cannot have a preference for the car, whilst those with a license can. Changing the number of people who can use the car will thus have an impact on how many people have a preference for it. The number of people with a preference for public transport and bicycles will consequently also change, as all the segments must add up to 100%. Therefore, the accessibility by public transport and bicycle will change if driver's license and car ownership are altered.

So, it seems that the anticipated effects in both models are different, which makes it an interesting situation to consider. To do so, the average number of cars per household will be reduced by 30% in every zone in the study area.

5.3.4 Increasing job opportunities in a zone and accessibility

The following criterion that has been chosen is: *Increasing the number of opportunities should have a positive effect on accessibility.* This criterion primarily relates to the land-use component which has not been explored by the beforementioned scenarios. Second, the logsum as the name suggests considers a logarithm. The potential accessibility does not. The numerical effects on the accessibility could therefore be different when the number of job opportunities is altered. The chosen criterion will be assessed by adding a significant number of job opportunities to one zone in the municipality of Zwolle. It has been decided to do so by adding 10,000 jobs in a less well-off neighbourhood. The idea of the scenario is to increase the number of opportunities close to people who have relatively poor accessibility to reduce inequalities. The chosen neighbourhood is highlighted in red in Figure 23. With the scenario chosen, the numerical effect on accessibility in the municipality of Zwolle can first be examined. Second, to investigate if and to what degree the distribution of accessibility will become more equitable.

5.3.5 Making public transportation faster and accessibility

The fifth scenario aims to investigate the equity effects when a segment with relatively poor accessibility is provided additional public transport services. It has firstly been chosen to implement a measure which helps people who neither have a car nor a driver's license. This concerns 13.2 % of the population in Zwolle. This segment of the population is chosen since it has on average the lowest accessibility in Zwolle. Moreover, the segment is considered in both the Octavius and IKOB allowing a direct comparison of the subsequent effects. Subsequently, it seemed suitable to make public transport more accessible for the chosen segment by allowing them to use it for free. The inconvenient part is that the cost parameter of public transport is not found statistically significant in Octavius for travelling to work. Therefore, it is not included in the following discrete choice models. Reducing the cost of public transport will therefore not affect accessibility according to the logsum approach. Allowing people without a driver's license to use public transport for free is therefore not a suitable scenario as equity effects cannot be compared. Instead, it has been decided to make public transport faster since travel times are considered in both models. In doing so, the criterion that is tested is: "*Increasing the speed of a modality should have a positive effect on accessibility".* The scenario is implemented by reducing the travel time to each zone by 40% with public transport. It does not matter exactly which measures achieve this. Instead, the primary goal of this scenario is to investigate the equity effects when the segment with the lowest accessibility is provided additional services.

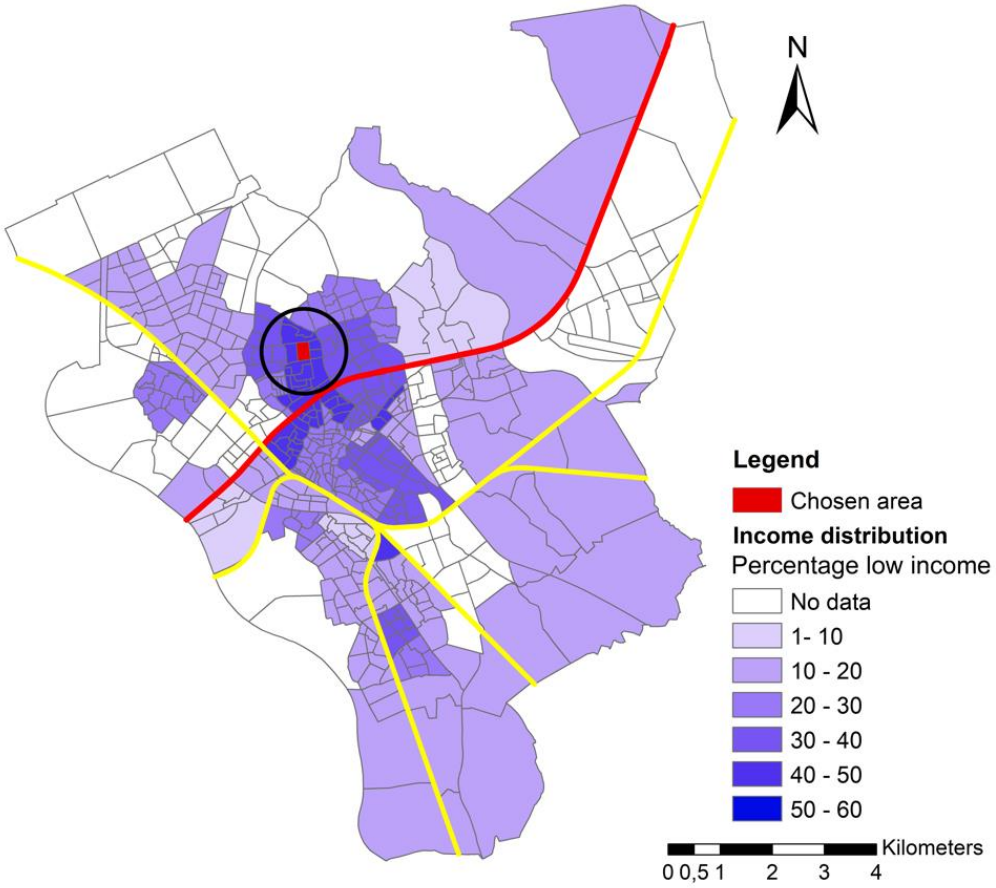


Figure 23: Chosen area for the fourth scenario

6. Results

The two approaches to determine accessibility explained in the previous chapters are performed. On the one hand, this includes the IKOB approach that makes use of the potential accessibility measure. On the other hand, the logsum measure derived from the Octavius model. The subsequent results are presented in this chapter. First, the accessibility in the municipality of Zwolle will be discussed under current conditions. To this end, the standard input data is applied. This situation will be referred to as the “baseline scenario”. Next, several scenarios were introduced in Section 5.3. For each one, certain parameters have been altered. The subsequent results will also be presented in this chapter. In doing so, the most important findings will be discussed in several steps. The complete results can be found in the appendix. Appendix B is about the baseline situation, Appendix C is about the first scenario, Appendix D is about the second one and Appendix E is about the third one.

6.1 The baseline situation

6.1.1 Zonal accessibility in the baseline situation

First of all, the average accessibility in each zone has been calculated for each transport modality in the baseline situation. Results have been normalized, as discussed in Section 4.3.5. As a result, the accessibilities are scaled from one (highest average accessibility in the study area) to zero (lowest). Next, Figure 24 shows the average accessibility of cycling to work. It could be observed that both approaches predict a similar pattern. That is, accessibility is the highest in the centre of the study area and reduces towards the edges. The primary reason is that not many employment opportunities outside the municipality are within cycling distance. The accessibility will therefore be largely determined by the opportunities in the municipality itself. These are fairly evenly distributed throughout centrally located areas as shown in Figure 11. On average, the travel time to these will be lowest in the middle of the study area. As a result, accessibility will be higher in the centre.

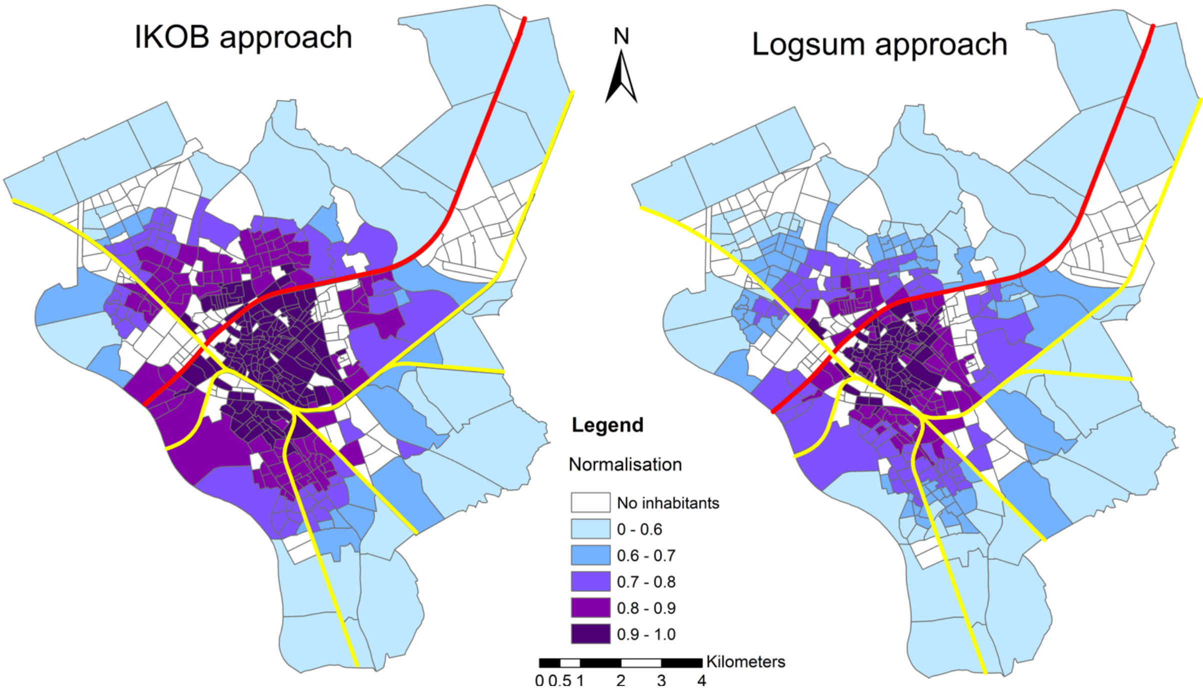


Figure 24: Zonal accessibility by bicycle

Next, Figure 25 shows the accessibility to work with public transport. The observed patterns resemble those for cycling. That is, the accessibility is the highest in the city centre for both approaches whilst it reduces towards the edges of the study area. One cause is that the main station of Zwolle is located in the centre of the study area, as marked by the green dot in the dark purple area. Travel times will be shorter to other cities close to the station. The other train station in the municipality is located in the northwest. This is however a small station where only a line to Kampen is available. The figures show that this station does not have a major impact on the accessibility of nearby zones. In addition, it is assumed that the time to reach the public transportation stop at the start of the trip is travelled by bicycle. Because of this, it is understandable that the pattern resembles those for accessibility by bicycle. Moreover, it can also be noticed in the figures that with the logsum approach, accessibility decreases less rapidly to the outskirts of the study area compared to IKOB. A reason for this is that with normalization, the minimum is determined based on the five zones with the lowest accessibility. In Octavius, these minima are relatively smaller than in IKOB making the accessibility in the other zones appear higher in comparison.

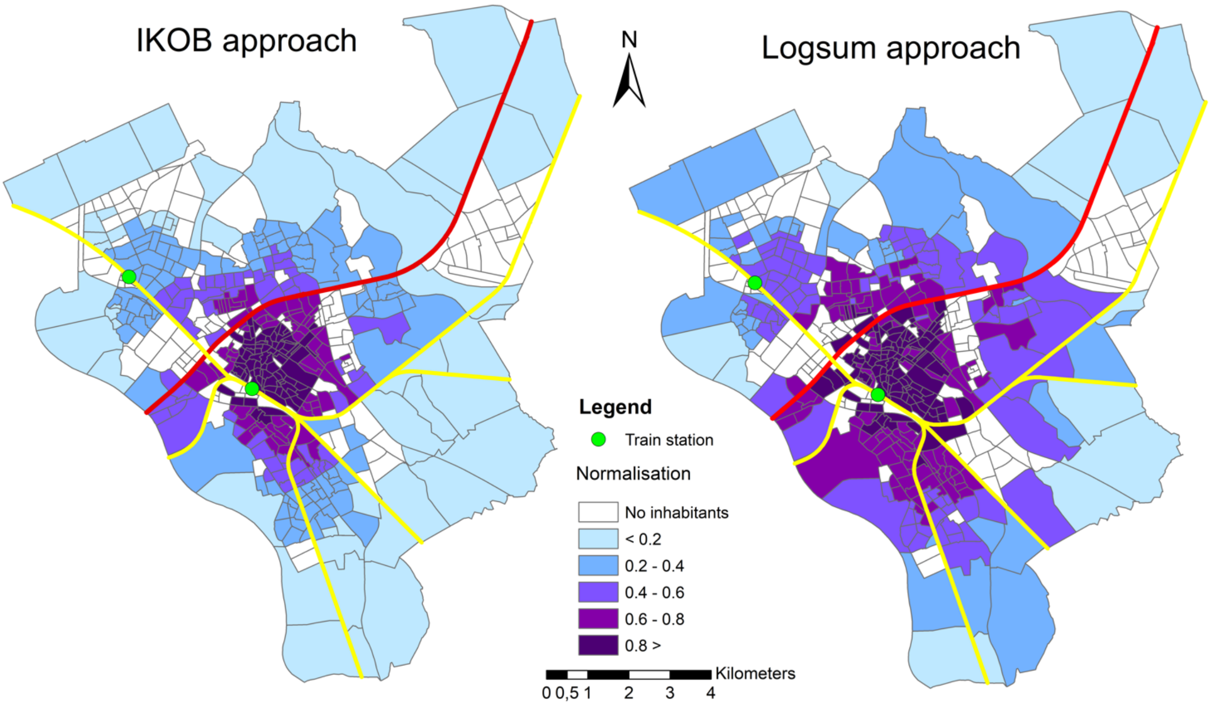


Figure 25: Zonal accessibility by public transport

Lastly, the average accessibility to work by car in the study area is shown in Figure 26. A reversed pattern could be observed compared to the accessibility by bicycle and public transportation. That is, accessibility is higher around the edges of the municipality and the lowest in the centre. This can be explained by several factors. First, the accessibility by car is found by the weighted average of all segments in a zone. Some segments cannot make use of the car. The accessibility of those segments will be (close to) 0. Increasing the frequency of such segments will pull the average down. Next, the city centre is a “car-low” zone in which people have fewer cars. The average accessibility in these locations will thus be lower. On the contrary, people in the outskirts of the city have generally more cars and thus a higher accessibility on average. Furthermore, the patterns in these outskirts do vary between both approaches. From IKOB, two areas can be observed where accessibility is particularly high. One is located in the northeast and the other in the west of the municipality. These areas correspond with those where higher-income segments are most common as discussed in Section 5.4. People with higher incomes are less sensitive to travel costs, increasing accessibility. The pattern from the logsum measure seems more erratic. One reason for this is that Octavius considers microsimulation in which each inhabitant is represented by an agent with specific characteristics.

Therefore, the size of each segment is specified only with positive integers, while decimal numbers are possible in IKOB. In this way, the accessibility in sparsely populated areas is more sensitive to the characteristics of the few people who live there.

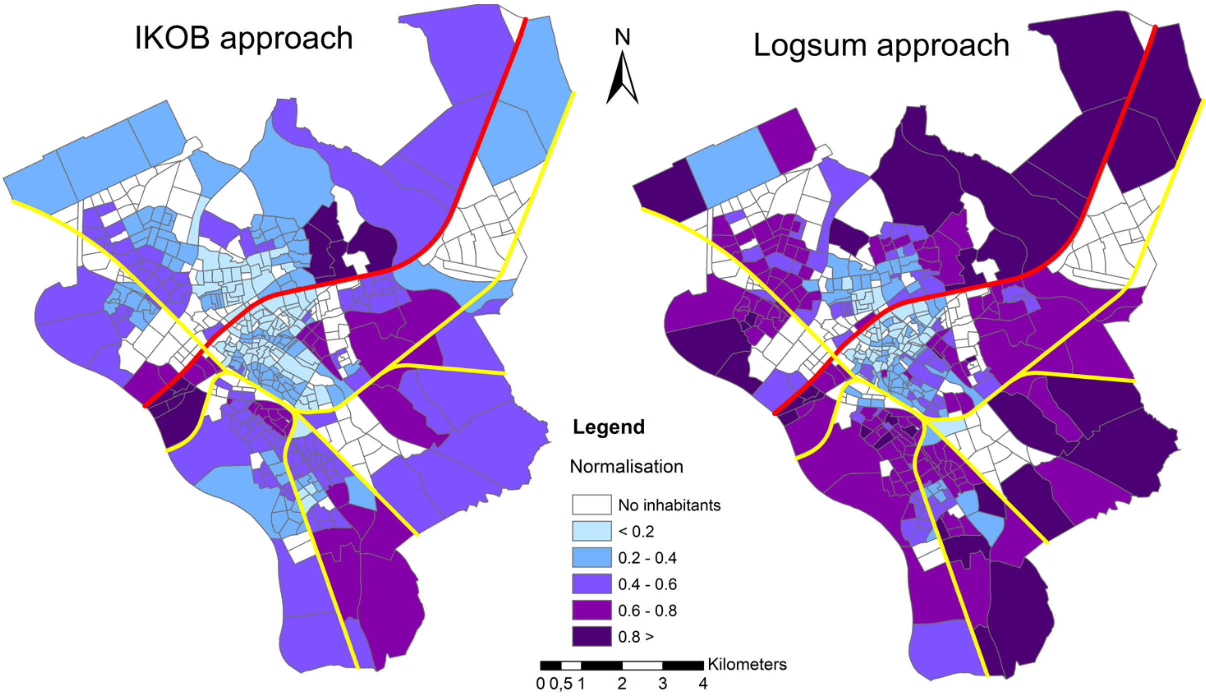


Figure 26: Zonal accessibility by car

6.1.2 Ranking of zonal accessibility in the baseline situation

To further investigate the similarities and differences between the zonal accessibilities as shown in the previous figures, zones in the study area have been ranked according to the average accessibility. Then, scatterplots as provided in Appendix B.1 show the correlation between the rankings according to the IKOB and logsum approach. First, these figures show that there is a clear relationship in the rankings for accessibility by bicycle and public transport. These findings correspond to the similarities displayed in the maps in Figure 24 and Figure 25. Further, outliers are primarily caused by less populated zones where accessibility is subject to the few people living there. Furthermore, there is a weaker relationship between the rankings for accessibility by car. These variations are largely caused by zones at the edges of the study area. Lastly, no correlation at all is visible for the total accessibility considering all modalities. The primary reason is that the process to calculate the total accessibility various much between both approaches. In IKOB, the modality that provides the highest accessibility to travel to each individual zone is determined, as discussed in Section 4.3.1.3. Then, the resulting accessibilities to every zone are summed to determine the total accessibility. In contrast, the logsum approach involves the retrospective application of the logsum technique based on the modality choice model. Calculating the expected maximum value of the set of alternatives would represent the accessibility of an agent to travel to work considering all possible modalities.

6.1.3 Relation between income categories and accessibility in the study area

Next, possible income categories in the considered dataset are “low”, “medium low”, “medium high” and “high”. Figure 27 and Figure 28 show the relation between how often the "high" and "low" income categories occur in each zone and the average accessibility by car resulting from both approaches. Each dot depicts a zone in the study area and its size represents the number of inhabitants in that zone. It could be observed that there is a clear relationship between the two parameters. That is, the more people that fall into the "high" income category in a zone, the higher the accessibility. It also applies the other way around; the more people who fall into the "low" income category, the lower the accessibility. The described relationships are due to two primary factors. First, the location of some high-income areas are located in more accessible locations. For instance, close to highway exits. Secondly, the costs of travelling in IKOB are related to income categories. People with lower incomes are more susceptible to travel costs which lowers their accessibility. In addition, a similar pattern is predicted by the logsum measure whilst the income parameter is not explicitly considered in this approach as a variable. However, there seems to be more dispersion compared to IKOB. From this, it can be inferred that the income parameter is approximated by others to a certain extent. For instance, the age parameter. Moreover, the logsum approach seems to predict the accessibility structurally higher. The reason could be due to the normalisation process. For instance, a few lower minimums could raise the values of the rest of the observations. Next, similar figures have been prepared to visualize the relation between accessibility by public transport and income categories. These have been presented in Appendix B.2. It is concluded there is a weaker relationship between the two parameters. In fact, there seems to be a slight opposite effect. Namely, that accessibility by public transportation is higher in less wealthy areas. A reason for this is that several of such areas are located close to the central train station.

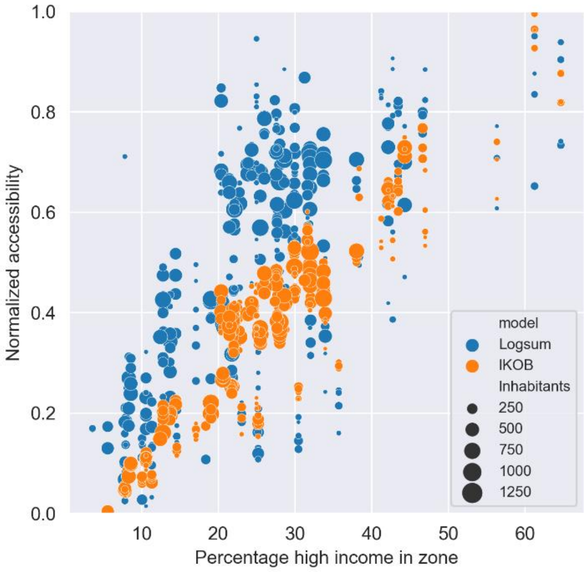


Figure 27: Relation between high income and accessibility to work by car

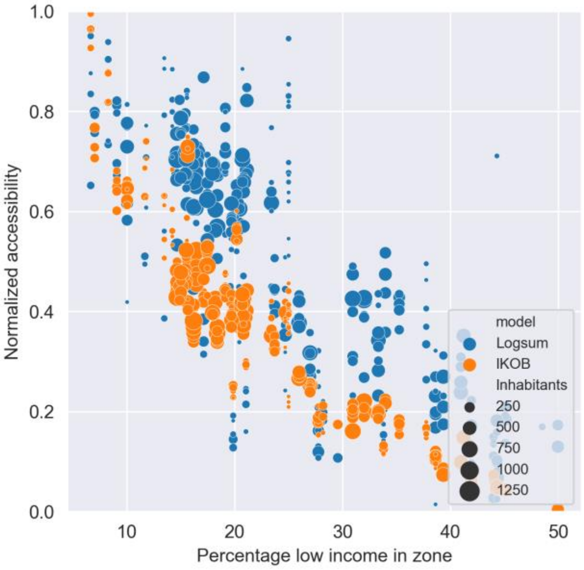


Figure 28: Relation between low income and accessibility to work by car

6.1.4 Accessibility in the baseline situation according to IKOB.

In IKOB, the population is initially segmented into four groups; those who have a 'free' car, have a car but have to pay for it, do not have a car but have a driver's license and do neither have a driver's license nor a car. The accessibility of each of these segments and the distributions therein are visualised in Figure 29. Certain attributes can be found about each segment, such as the average, median and distribution of accessibility. In this figure, the size of the boxes is based on the median, first quartile and third quartile. The whiskers represent 1.5 times the interquartile range $(q_3 - q_1)$ whilst the white dots show the average values.

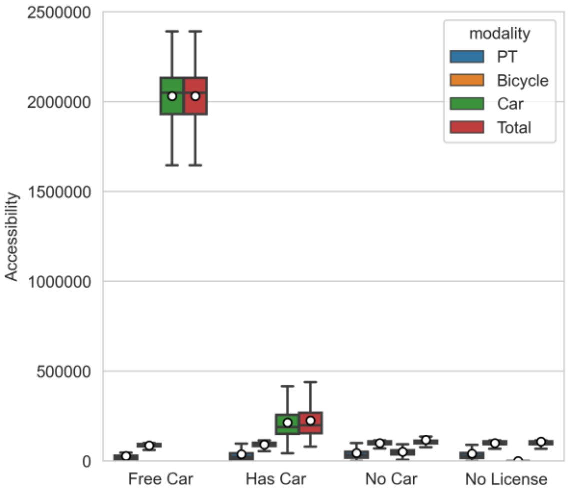


Figure 29: Accessibility for each segment in the baseline situation according to IKOB

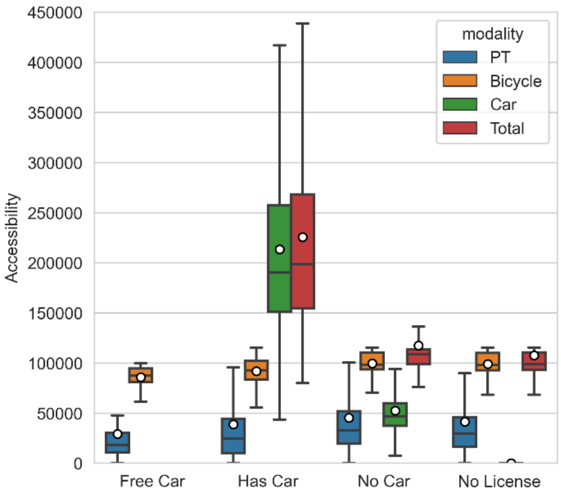


Figure 30: Figure 29 but with an altered y-axis

First, it can be observed in Figure 29 that someone who possesses a 'free' car has substantially higher accessibility compared to any other segment. The reason for this is that several major cities like Utrecht, Arnhem, Amersfoort and Enschede can be reached from Zwolle in 30 to 60 minutes. In IKOB, the weight for the potential accessibility measure is determined based on a decay curve as a function of the generalized travel time, which has been discussed in Section 4.3.1.3. The generalized travel time consists of the travel time and costs. When the costs are ignored, a generalized travel time of 30 to 60 minutes corresponds with a weight of 0.8 to 0.2. However, these approach 0 when the costs are included. Because of these reasons, people with a 'free' car can reach the major cities as stated before whereas those who have to pay cannot do so, creating substantial differences. This has been further explained in Appendix B.3. Next, the range of the y-axis has been altered from Figure 29 to Figure 30 to provide a clearer understanding of the accessibility of the other modalities and segments. First, Figure 30 shows that public transport is the least attractive modality in the study area on average. This is the consequence of the high travel times and costs of PT. Moreover, people who possess a car have significantly higher total accessibility compared to those who do not. Next, it seems counterintuitive that the accessibility of people who do not have a car is not zero. This is because it is assumed in IKOB that people who do not have a car but have a driver's license will rent a shared car. The costs of this alternative are higher compared to owing a car, but will still result in some accessibility.

Subsequently, the accessibility according to income categories in IKOB has been visualised in Figure 31. The first apparent observation is that the boxplot for the car and total accessibility for the high-income group are rather high. This is because 27.5% of people in this category have a 'free' car which almost have nine times the accessibility of someone who cannot use the car for 'free', as discussed in Appendix B. The 3rd quartile is therefore represented by a person with a 'free' car. In addition, it could be observed that the car and total accessibility increases with income. For this, there are two primary reasons. First, the accessibility of people with a (free) car is thus much higher compared to those who do not have one. People with a higher income are more likely to have a (free) car which results in a higher average accessibility. The second reason is that accessibility is modelled in such a way that someone with a lower income perceives a euro extra cost more heavily compared to someone with a higher income, as elaborated upon before.

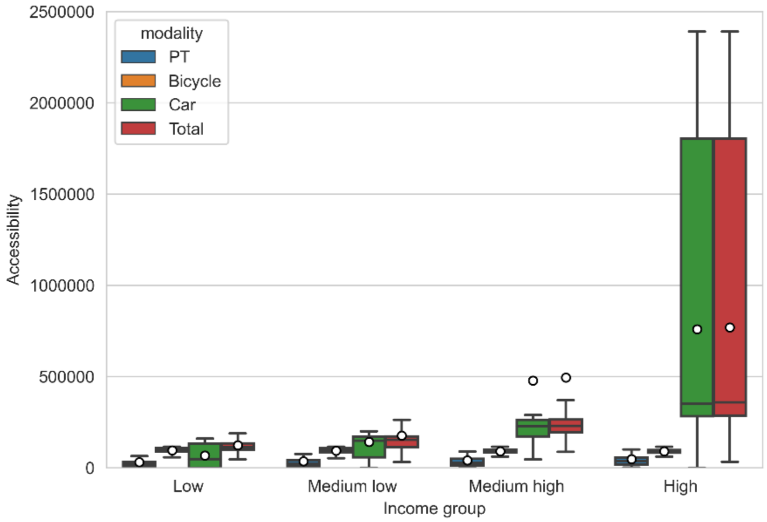


Figure 31: Accessibility by income categories in the baseline situation according to IKOB

6.1.5 The segments in the baseline situation according to the logsum approach.

A similar approach to group various segments with similar characteristics is also performed for the logsum measure. First of all, the logsum is a relative measure. The accessibility of each modality has been calculated with a specific discrete choice model and corresponding coefficients. Because of this, it is not possible to make comparisons between modalities. For instance, to conclude that the bicycle has a higher accessibility compared to public transport. It is only possible to make comparisons within modalities. For example, by stating that the accessibility by bicycle for person x is higher than for person y. The results will therefore be presented in different figures. The accessibility across age for cycling and public transport in the baseline situation is visualised in Figure 32 and Figure 33. It can be observed that the accessibility for the group "65 plus" is lower compared to the others. This is caused by the fact that people in this segment make shorter trips, regardless of modality. This reduces their accessibility. The accessibility by bicycle between the ages of 18 to 64 remains fairly constant. Figure 33 shows that the accessibility by public transport is the highest for agents between the age of 30 to 44. The accessibility decreases steadily thereafter as people become older.

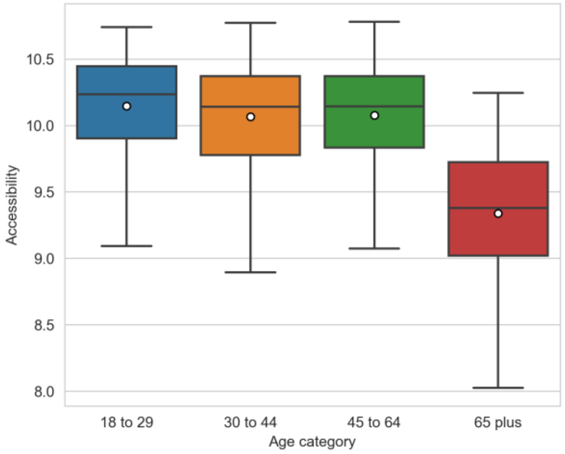


Figure 32: Accessibility by Bicycle across age categories

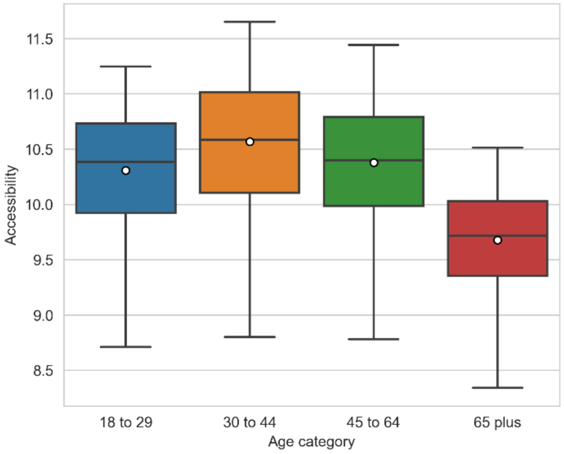


Figure 33: Accessibility by PT across age categories

Further, the accessibility by car for each age category is presented in Figure 34. It could be observed that agents from the age category 65 and older have relatively poor accessibility by car, because of the same reason as stated before. The accessibility of the subsequent three categories between the ages of 18 to 64 remains consistent. Lastly, the total accessibility considering all transport modalities is shown in Figure 35. A kind of pyramid shape could be observed in this figure. This implies that middle-aged people experience a higher level of accessibility compared to the young and elderly.

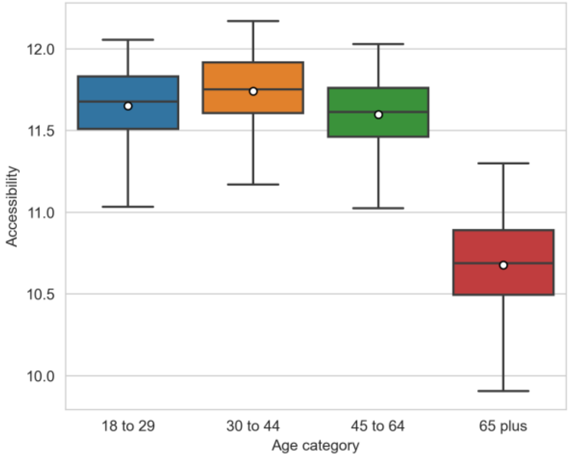


Figure 34: Accessibility by car across age categories

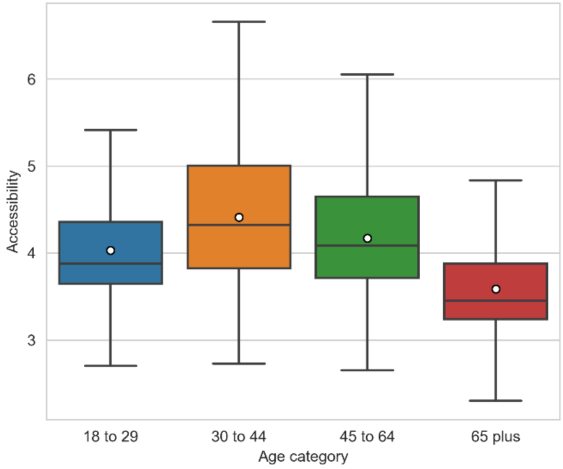


Figure 35: Total accessibility across age categories

6.1.6 The accessibility of an “average” person

Moreover, Figure 36 illustrates how the accessibility of an “average” person who does have a car from the centre of the study area is built up according to both accessibility approaches. The "average" person is defined as an individual with an accessibility close to the median in that zone. So, the figure shows the impact of job opportunities in each province on the accessibility of someone living in Zwolle. For the Octavius approach, the probabilities are based on those calculated with the multinomial logit model for the destination choice, as explained in Section 4.3.2.3. The probabilities according to IKOB are found by dividing the accessibility to each location by the total accessibility by car. The three northern provinces are Friesland, Groningen and Drenthe, the western ones are Utrecht, North- and South Holland and the southern ones are Zeeland, Noord-Brabant and Limburg. The figure first demonstrates that the accessibility determined by job opportunities in the study area itself is similar between both approaches. In contrast, job opportunities located in the remaining part of Overijssel have a smaller impact on accessibility in Zwolle compared to IKOB, which will be elaborated upon shortly hereafter. Next, the proportion of accessibility that depends on jobs in Gelderland, Flevoland

and the northern provinces is similar according to the two approaches. Results also show that jobs in the three western and southern provinces do have a small or non-existent influence on the accessibility of an average person in Zwolle according to both.

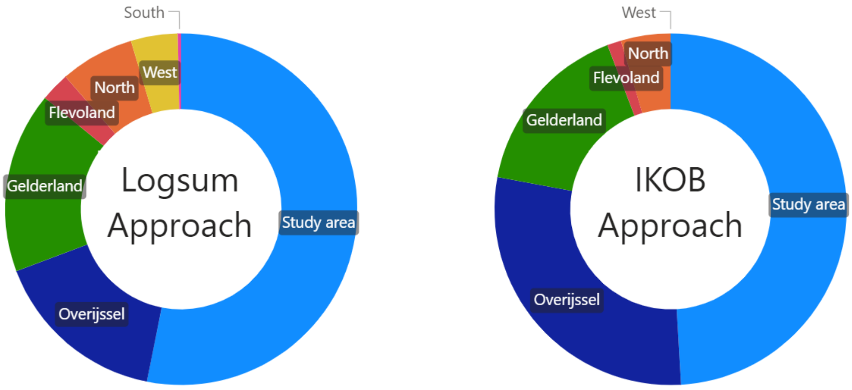


Figure 36: Breakdown of the accessibility of an "average" person

It was concluded before that the opportunities in the remaining part of Overijssel have a smaller impact on the accessibility of an average person in Zwolle according to the logsum approach compared to IKOB. Table 6 shows the contribution of job opportunities in several municipalities in Overijssel to the accessibility by car in a percentage. It could first be observed that the impact of municipalities that are located relatively close to Zwolle is estimated higher with IKOB compared to the logsum approach. Thereafter, they predict a similar impact from municipalities that can be reached by a travel time of around 36 minutes. Finally, municipalities that are located relatively further away are more important in the logsum approach. These findings show something about how the disutility of travel is accounted for in both approaches. Namely, the first minutes of (generalized) travel time are assumed to have little effect in IKOB. In addition, there is a cut-off after which the accessibility will be zero. The logsum approach assumes a higher disutility initially and a larger "tail", meaning that municipalities further away still have some effect on the accessibility.

Table 6: Contribution in percentage to the total accessibility of a person in Zwolle from several municipalities in Overijssel

Municipality	Travel time	Logsum	IKOB
Dalfsen	19 min	2.002	4.546
Kampen	21 min	3.072	7.737
Raalte	21 min	1.715	4.078
Deventer	35 min	1.239	0.915
Hardenberg	37 min	0.876	0.828
Almelo	47 min	0.431	0.052
Enschede	60 min	0.283	0.000

6.2 The first scenario: increasing the cost of using the car.

To test the effect of travel costs on (inequalities in) accessibility, it has been decided to increase travel costs for using the car by 30% in the first scenario. The proposed scenario is also relevant in the Dutch context, as it is often proposed to make driving a car more expensive as a measure to combat climate change (de Rooy, 2023). The two accessibility approaches have been re-applied using the new input data. The subsequent results will be elaborated upon in this section.

6.2.1 Zonal accessibility in the first scenario

First of all, the average accessibility in each zone has been calculated in the first scenario. It has been predicted by both approaches that accessibility has decreased the most at the borders of the study area, as shown in Appendix C.1. On the contrary, accessibility has decreased relatively speaking the least in and around the city centre. The discussed pattern is similar to the average car ownership, presented in Figure 13. This is caused by the fact that the accessibility by car is calculated based on all people in a zone. Thus, also those who do not have a car, which logically have an accessibility of (almost) 0. This group will not be affected by the measure as they do not have a car to begin with. The larger this share of people in a zone, the fewer people are affected which reduces the overall found change in that zone.

6.2.2 Segments in IKOB in the first scenario

The average accessibility of the segments “free car”, “have car”, “no car” and “no license” have been recalculated with the new input data as shown in Appendix C.2. It has been found that increasing the cost of using the car does not impact those who can use it for ‘free’, which is logical. Instead, people who have a car are mostly affected by the measure. It has been found that their accessibility has decreased by 14% on average compared to the baseline situation. Next Figure 37 shows how the accessibility of the four income categories is impacted by the measure according to the IKOB approach. It could first be observed that the accessibilities by public transport and cycling have not changed. This is foreseeable as no alterations have been made to them. Next, the accessibility of the car does decrease when the costs of it are increased. Moreover, it seems that the measure has impacted people with less income to a greater extent compared to those with a high income. The first reason is that people with a higher income are more likely to have a ‘free’ car. As discussed earlier, this particular group is not affected by the discussed measure. Therefore, the larger the share of people who have a ‘free’ car, the larger the share of people who are not affected which reduces the overall effect for that income group. On the contrary, people without a driver’s license are also not affected by the measure. People with a lower income are more likely to not have a car, thereby causing the opposite effect as discussed for the ‘free’ car segment. Still, the figure shows that the measure has impacted people with less income to a greater extend compared to those with a high income. This shows that the anticipated benefit of people who have a ‘free’ car is partly reduced but is still the superior effect.

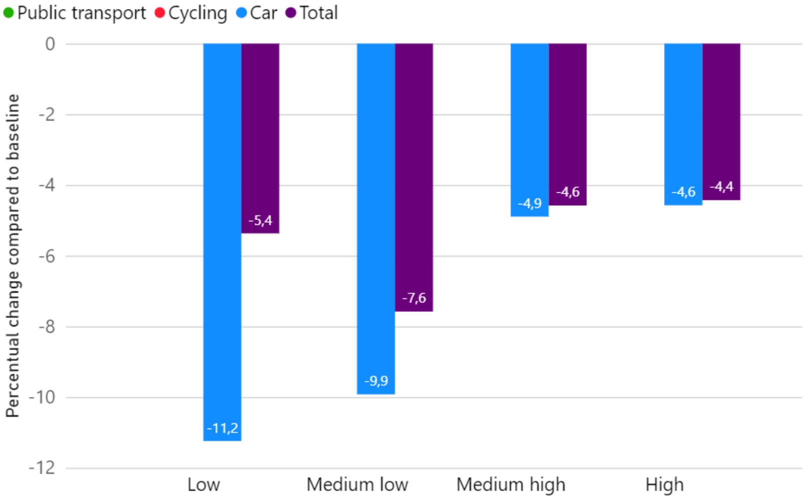


Figure 37: Change in accessibility across income categories in the first scenario according to IKOB

Next, Figure 37 shows that the total accessibility is less affected compared to the accessibility by car. This indicates that for certain trips, the car is being substituted by other modalities. By doing so, the impact of the measure is partially alleviated. A notable aspect is that the total accessibility of people with a medium-low income is impacted the most by the measure. This observation is mainly because people with a low income are proportionally more capable of mitigating the impact on the accessibility by car by using other modalities. This is because for people with lower incomes, their accessibility is determined by opportunities that are relatively close by. As a result, cycling can often be a suitable alternative. People with higher incomes however make longer trips which are less easily exchanged.

Furthermore, it is interesting to further explore the people who have a car but cannot use it for free. In this way, it is possible to examine in more detail how the measure affects such people by extracting the effect of having a 'free' car as well as having no car as discussed earlier. Figure 38 shows the subsequent impact of the measure on people who have a car but cannot use it for free. First, it can be noted that the opposite effect can be seen as found before. Namely, the highest income segment is relatively the most impacted. On the other hand, the accessibility of the low and medium-low segments declined comparatively less rapidly. With this information, it could be stated that the distribution of accessibility of people who do have a car has become more equal by increasing travel costs. At first, this seems counterintuitive considering the theory behind the IKOB approach. This is because the TVOM factor ensures that people with lower incomes experience the effect of travel costs more severely. Therefore, it would be expected that when costs are increased, those with relatively less income would be affected the most.

The unanticipated results seem to be caused by the specific characteristics of the study area. An extensive explanation has been given in Appendix C.3. In short, the municipality of Zwolle is mostly surrounded by sparsely populated areas. Other major cities are located relatively further away. The accessibility of people with a higher income is partly defined by the opportunities in cities outside the municipality of Zwolle such as Apeldoorn and Deventer. A small difference in travel costs will therefore have a great impact on the number of overall opportunities this group could reach. People with a "low" or "medium low" income are unable to reach these opportunities in the first place, so the discussed effect does impact them less. Instead, their accessibility primarily depends on opportunities in Zwolle itself. This causes differences between people with low and high incomes to become smaller.

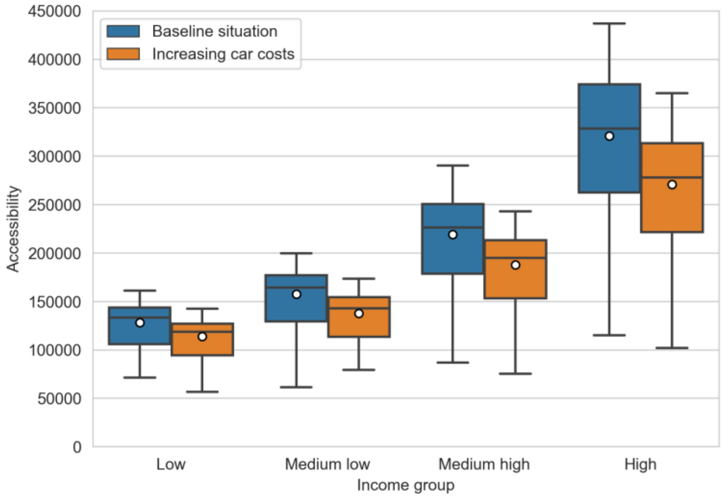


Figure 38: Accessibility by car across income groups of people who do have a car.

6.2.3 Segments in the logsum approach in the first scenario

Furthermore, Figure 39 shows how the accessibility by car across age is affected in the first scenario according to the logsum approach. First, it could be noted that all segments are equally impacted by the measure to increase the costs of taking the car. The same can be seen in Figure 40, which shows the accessibility across gender. These findings are caused by the fact that the cost component is not connected to any individual and household characteristics in the utility functions, as discussed in Section 4.3.2.3. The costs are thus perceived as the same by everyone. Changing the cost will therefore have the exact same effect on the accessibility of each individual. This has also been proven mathematically in Appendix C.4. It is also demonstrated that the accessibility by car for each agent that has a car is reduced by 0.097 utility compared to the baseline situation.

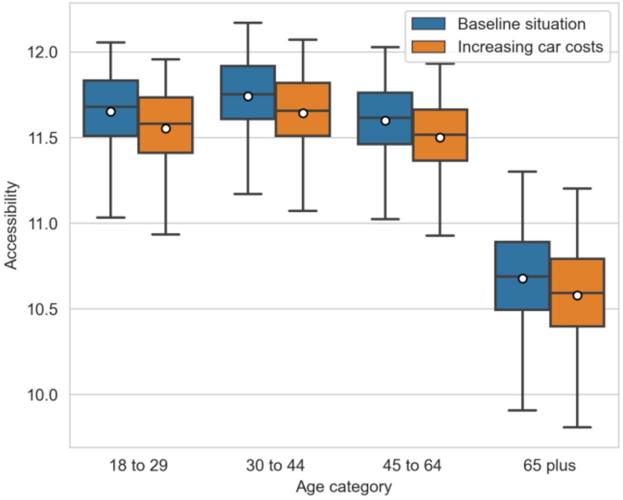


Figure 39: Accessibility by car across age categories according to the Logsum approach in the first scenario

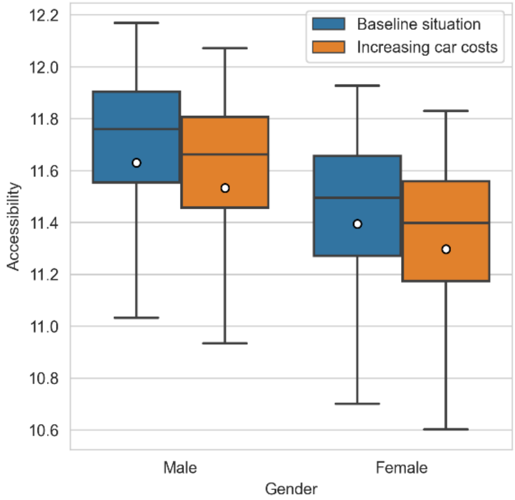


Figure 40: Accessibility by car across gender

Figure 41 shows how the total accessibility across age categories considering all transport modalities is affected according to the logsum approach. The figure shows that the accessibilities have only changed fractionally. This entails that its negative impact on using the car is largely mitigated by the other transport modalities, which is caused by a combination of two factors. First and foremost, the theory for calculating the total accessibility is different in both approaches, as explained in Section 6.1.2. The second factor is that the accessibility by car in itself was not affected that greatly to begin with according to the logsum approach. The subsequent effect on the total accessibility will then also be less.

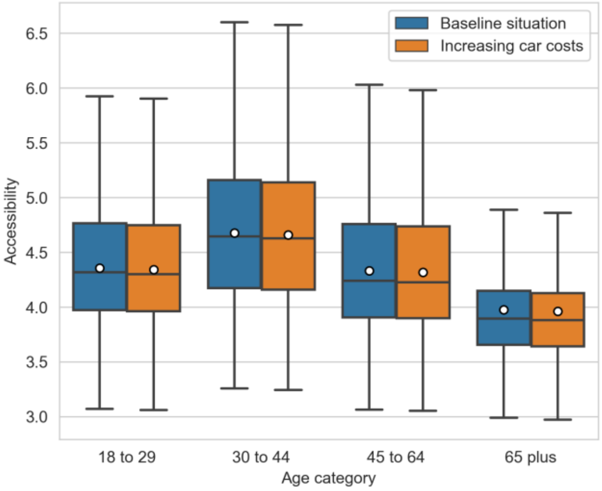


Figure 41: Total accessibility across age categories according to the logsum approach in the first scenario

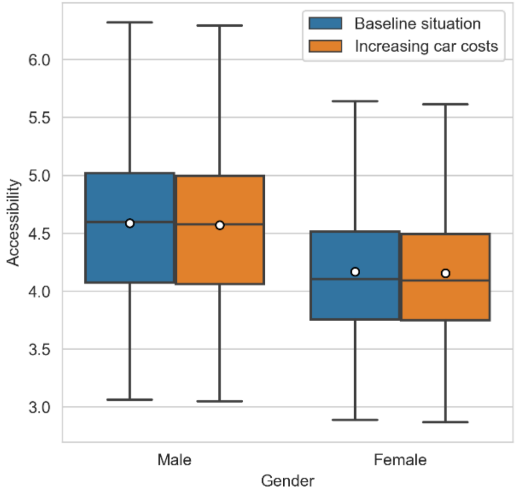


Figure 42: Total accessibility across gender according to the logsum approach in the first scenario

6.2.4 Findings about the first scenario

In the first scenario, the cost of using the car has been increased by 30%. Several conclusions could be made considering the results of this scenario. First of all, both accessibility approaches predict that the accessibility by car as well as total accessibility will decrease when the measure is implemented. Thereby, the criterion "*Increasing the cost of a transport modality should decrease the accessibility of that specific modality*" is ensured. Next, it was found that the measure has a bigger effect on the accessibility in the IKOB approach compared to the logsum one. It can therefore be said that travel costs have a more considerable influence on accessibility in the IKOB approach than in the Octavius model. This could also be established from the input skims since the travel costs account for 30% (high income) to 68% (low) of the total disutility to travel in IKOB. In Octavius, this is only 25% on average. In addition, the cost of travel is transformed in Octavius with a logarithm. As a result, as costs increase, the impact becomes proportionately less.

Furthermore, the second criterion that has been assessed with this scenario is: *Increasing the cost of transportation should reduce the accessibility for those with less to spend to a greater degree compared to those with more to spend.* In theory, this criterion is ensured by the IKOB approach, as the income category is related to the parameter TVOM. The same is found in a practical situation when the accessibility to one location is considered, as highlighted in Appendix C.3. However, the opposite is found when the complete study area is taken into account. Rather, this is due to the characteristics of the municipality of Zwolle. These characteristics involve a medium-sized city surrounded by rural areas. Other similar and larger cities are located further away. This could be different in other implementations, for example in the Randstad area. Furthermore, the stated criterion is not ensured directly as well as indirectly by the Octavius approach. Directly, since the income parameter is not considered at all. Indirectly, as the discussed measure impacts every person the same. As a result, it does not matter that income is approximated by other parameters.

6.3 The second scenario: closing two bridges.

In the second scenario, two important bridges to cross the river IJssel have been closed. Consequently, the river becomes a barrier on the west side of the municipality. This results in a significant increase in travel times to locations from the study area to the west and south-west of the country. For example, travel time to cities such as Harderwijk, Amersfoort, Utrecht, Arnhem and Apeldoorn have increased between 12 to 20 minutes from the study area. The travel times to the north and east of the country have remained the same. The resulting effects on accessibility have been calculated with both approaches. The subsequent results will be elaborated upon in this section.

6.3.1 Zonal accessibility in the second scenario

Figure 43 shows in which zones the accessibility changed relatively the most and the least according to both approaches. It could first be observed that both predict that accessibility will decrease the most in the western part of the study area. Moreover, both approaches predict that zones in the middle of the study area are affected to a moderate extent. Similarly, both show that the areas in the north and the west are the least affected by the measure. With these observations, it can first be concluded that zones near the closed roads are affected the most. Primarily, because the accessibility at these locations depends to a greater extent on opportunities on the other side of the blocked bridges. Hereafter, the effect decreases as the distance from the blocked bridges increases. In addition, IKOB predicts that the area in the northeast part of the study area above the highway will also be affected fairly severely. This area corresponds to the locations where many high-income people reside, as shown in Figure 15. Therefore, more people live here who can benefit from a "free car." This group will be impacted the most by this measure, which will be discussed later in this chapter. The larger this group, the bigger the effect. The opposite is predicted for this area by the logsum approach. That is, the effect of the measure is relatively little compared to the rest of the municipality of Zwolle.

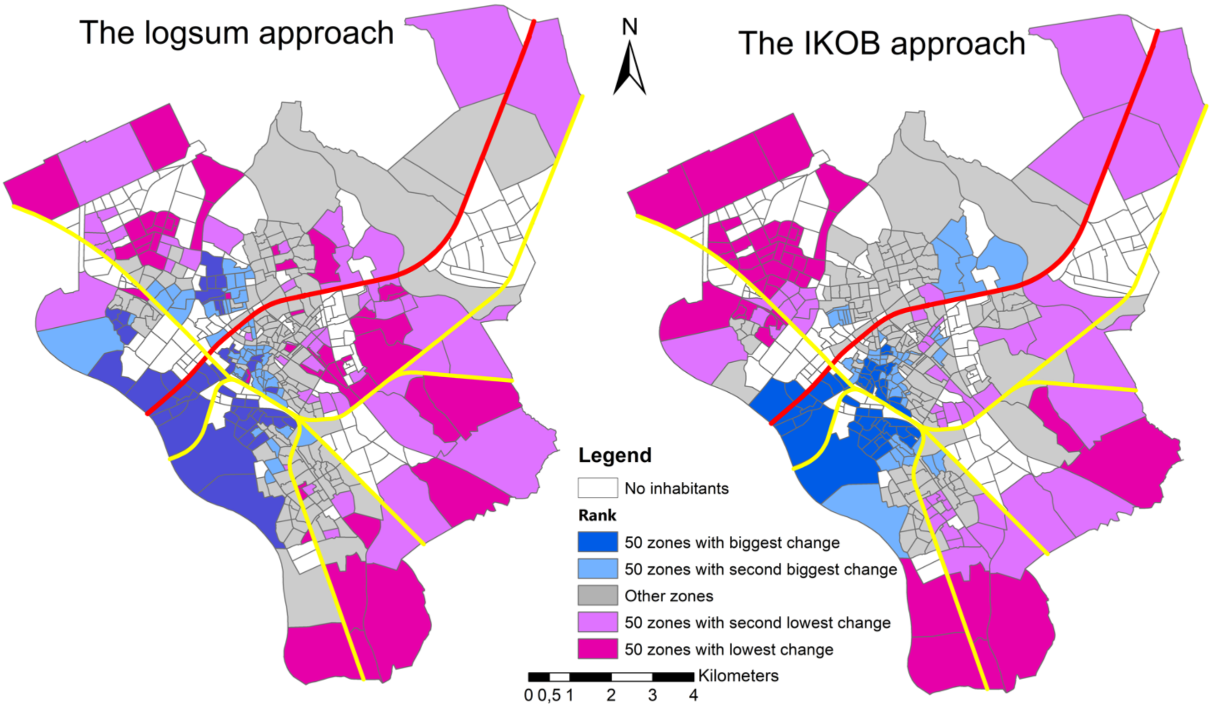


Figure 43: impacted zones according to accessibility by car in the second scenario

6.3.2 Segments in IKOB according to the second scenario

Next, Figure 44 shows how the accessibility by car of the four initial segments is impacted according to the IKOB approach in the second scenario. Figure 45 shows the same information, only the range of the y axis has been altered. It could first be observed that the accessibility for people with a ‘free’ car has decreased substantially (by 28%) on average. The group that has a car but cannot use it for ‘free’ is affected comparatively less (by 14%). It was discussed before that the accessibility of those who can use a ‘free’ car is largely defined by opportunities in major cities outside the study area. The travel time to some of these cities will increase considerably when the highway on the west side of the study area is closed.

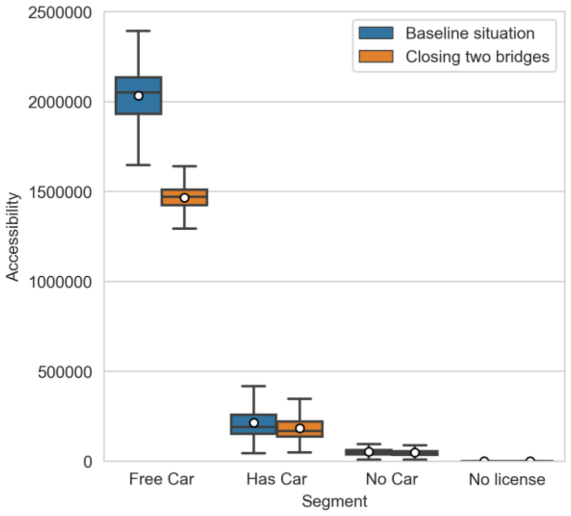


Figure 44: The accessibility across segments according to IKOB in the third scenario

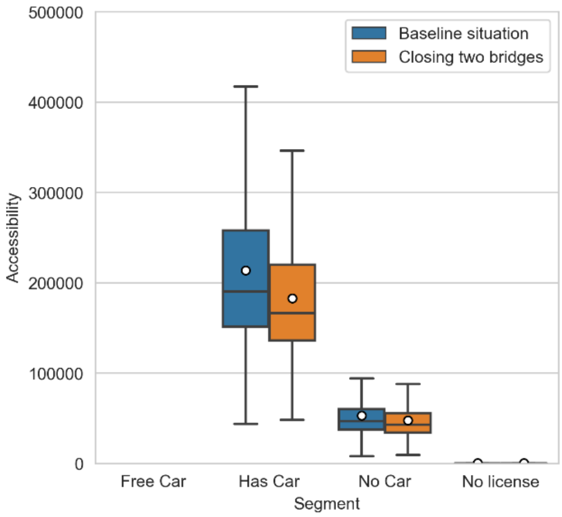


Figure 45: Figure 44 but with an adjusted y-axis

To further explore this assumption, Figure 46 shows how the accessibility of someone with a free car has changed due to the closing of the bridges. The outer circle in the graph on the left shows the impact of job opportunities in each province on the accessibility of someone living in Zwolle in the baseline situation. De inner circle represents the distribution according to the second scenario. Between the two situations, the accessibility of this person is reduced by over 600,000 which is represented by the grey section. A breakdown of this grey section to what locations the accessibility is reduced is shown in the diagram on the right. The three northern provinces are Friesland, Groningen and Drenthe, the western ones are Utrecht, North- and South Holland and the southern ones are Zeeland, Noord-Brabant and Limburg. The figure shows firstly that the measure has not affected the accessibility to job opportunities in the study area itself, Overijssel, Flevoland and the north of the country. Instead, the biggest change is caused by the fact that the provinces in the west and Gelderland have become less accessible. Especially the accessibility to the provinces of Utrecht and Gelderland has been reduced significantly. This shows that the highway in the west side of the study area is an important route to these locations.

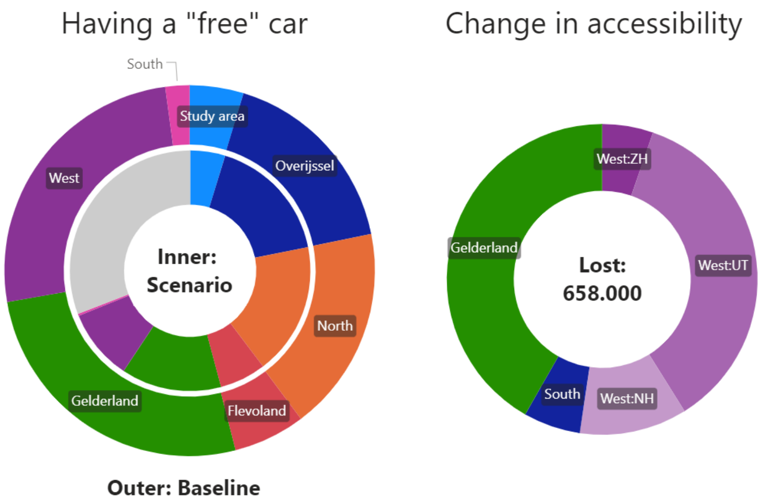


Figure 46: The effect of the road closures on a person with a ‘free’ car

Next, Figure 47 shows how the accessibility of the four income categories is impacted by the measure according to the IKOB approach. In the figure, it could be observed that the implemented measure disproportionately affects high income segments compared to low-income segments. First, people with a ‘free’ car have been affected the most as found before. The share of people with a ‘free’ car is larger as incomes increase, which enhances the effect. In addition, the accessibility of people with lower incomes is largely determined by opportunities in the municipality itself and the areas around it. Closing the two bridges over the IJssel does have a relatively small effect on the travel time to these opportunities. It is also visible in the figure that the proportion of decline in accessibility by car compared to the total accessibility increases by income. The reason for this has also been discussed before. That is, accessibility for those with higher incomes depends primarily on opportunities reached by longer travel times which are less easily replaced by cycling.

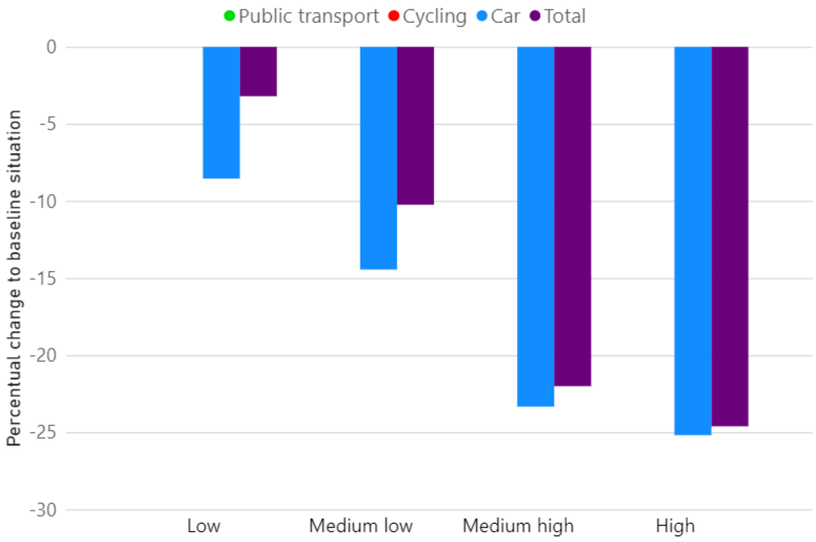


Figure 47: Change in accessibility across income categories in the second scenario according to IKOB

6.3.3 Segments in the logsum model in the second scenario

Further, Figure 48 shows the accessibility by car across age categories according to the logsum approach in the second scenario. The results of both the base situation and the second scenario are shown. It can first be noted that the measure affects people between the ages of 18 and 64 similarly. On the contrary, people older than 65 are impacted comparatively less. This is because people older than 65 are less willing to make longer trips. Because of this, the opportunities in areas that are located further away are less important to them. Closing two roads which mostly affects travel times to cities at longer distances will therefore have a smaller effect on their accessibility. Next, Figure 49 shows that men are just slightly more impacted compared to women. This is because males are slightly inclined to make longer trips, causing the same effects as stated before.

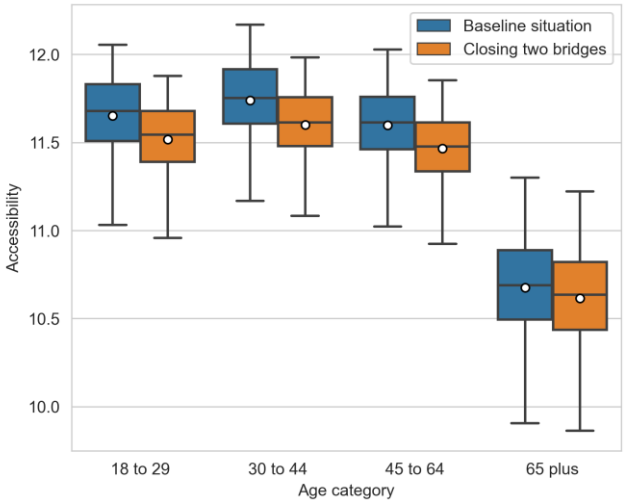


Figure 48: Total accessibility across age categories according to the logsum approach in the second scenario

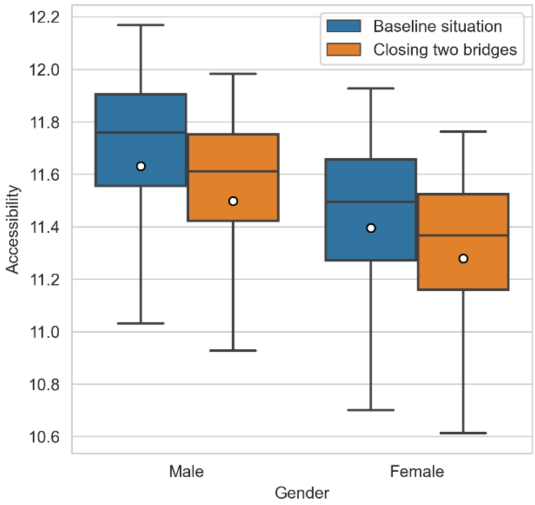


Figure 49: Total accessibility across gender according to the logsum approach in the second scenario

6.3.4 The accessibility of an average person

Next, Figure 50 visualises the accessibility of an “average” person in the second scenario and how it has been affected by closing the two bridges according to the two approaches. The outer circles show the impact of job opportunities in each province on the accessibility of someone living in Zwolle in the second scenario. The inner charts show a breakdown to what locations the accessibility has been reduced compared to the baseline situation. The figures first show that accessibility is for the largest part determined by jobs in Zwolle itself and the rest of the province of Overijssel after the two roads are closed according to both approaches. Less than 20% of the accessibility is still determined by jobs outside the province. Furthermore, reduced accessibility to jobs in Gelderland accounts for the biggest decline in accessibility. In fact, by IKOB this is estimated to be around 98%. The logsum approach also predicts that this proportion will be high, although slightly lower at about three-quarters. The other quarter is primarily caused by reduced accessibility to the west of the country. The effect on the other provinces is minimal.

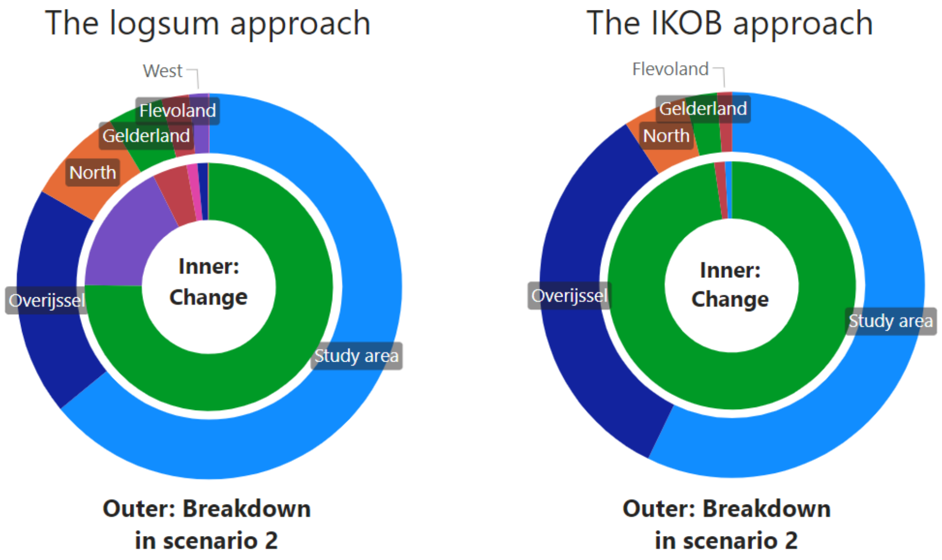


Figure 50: Breakdown of an average person's accessibility in the second scenario

6.3.5 Conclusions about the second scenario

In the second scenario, two important bridges over the IJssel have been closed. This has created some kind of imaginary barrier in the west of the municipality of Zwolle. As a result, travel times to locations in the west and south of the country have increased by around 10 to 15 minutes on average. First of all, the following criterion was tested with this scenario: *Reducing the service level of a transport modality should decrease the accessibility of that specific modality.* The presented results in the previous sections show that this criterion is upheld by both approaches. Namely, both predict that the accessibility will reduce compared to the baseline situation. However, the extent to which this happens is predicted differently. According to IKOB, those segments that can make use of a 'free' car are disadvantaged the most. Because people with "free" cars are more common as income rises, the measure has a larger impact on higher income segments on average. Next, people are impacted according to the Logsum measure quite similarly. Only those who make shorter trips are affected less. This includes those older than 65 years for example. Furthermore, the accessibility approaches show that accessibility is primarily decreased because the province of Gelderland has become more difficult to reach. First, since the IJssel river forms the border between Overijssel and Gelderland. So, the closures take place right on this border. All the opportunities that are located to the west of the IJssel that have become less accessibility are in Gelderland. The logsum approach also estimates that the accessibility for an average person to the province of Utrecht has decreased considerably. The accessibility was already low in the first place to this province according to IKOB, so the effect is lower.

6.4 The third scenario: reducing car ownership.

In the third scenario, car ownership in the study area has been reduced by 30%. Consequently, fewer people can make use of the car modality, which is the most important modality for accessibility. The subsequent results will be elaborated upon in this section.

6.4.1 Zonal accessibility

Next, the average accessibility in each zone is subsequently recalculated. It has been found that the logsum approach predicts that accessibility will decrease in every zone. The reason is that fewer people will have a car because of the changed input data. This increases the number of people who have accessibility of zero, bringing down the weighted average. Likewise, the IKOB approach also predicts that accessibility decreases almost in every zone. However, there are a few zones where this is not happening. The cause of this is further elaborated upon in Appendix E.1. In short, it is caused by a specific modelling decision for the segmentation approach in the IKOB model. This firstly involves estimating how many people in a zone own a car based on the degree of urban density and income distribution. This number can subsequently be adjusted using data from the CBS. In the third scenario, a scenario is constructed where this data from the CBS is 30% lower. The initial estimation is the same in the baseline as well as in the third scenario as the degree of urban density and income distribution do not change. Hereafter, the initial car ownership information is not changed in both situations when it is estimated too low. As a result, the average accessibility in a zone remains the same compared to the baseline situation.

6.4.2 Accessibility by each modality in the third scenario

Moreover, the accessibility of each modality has been recalculated and presented in Appendix E.2. In short, it has been found that the logsum approach predicts that the accessibility by bicycle and public transport will remain the same compared to the baseline situation. On the contrary, accessibility by car has decreased on average. This is not surprising as fewer people will have a car in the third scenario. This increases the frequency of people who have an accessibility of zero, which brings down the weighted average. Next, the IKOB predicts that accessibility by car will also decrease. Further, Figure 51 shows the change in accessibility compared to the baseline situation by income categories predicted by IKOB. Remarkable is that the figure shows that the accessibility by bicycle and public transport has increased. This has to do with people's preferences for some modality. People who have a preference for a certain modality are willing to tolerate more costs/travel time compared to those who do not have a preference for it. Thus, accessibility will be higher with that modality. People without a car cannot have a preference for it, whilst people who have one can. Reducing the number of people with a car will reduce how many people have a preference for the car. Instead, more people will have a preference for public transport and cycling. Because of this, the accessibility of these two modes will thus increase. In addition, the discussed effect increases with income. The reason is that people with a higher income are more likely to have a car. Reducing car ownership by a steady 30% will therefore impact a relatively larger group, increasing the total effect. In general, the discussed measure does not impact the individual accessibility of each specific segment. Instead, it influences how large each segment is. The sizes of segments with poor accessibility by car have increased whilst those with good accessibility have decreased.

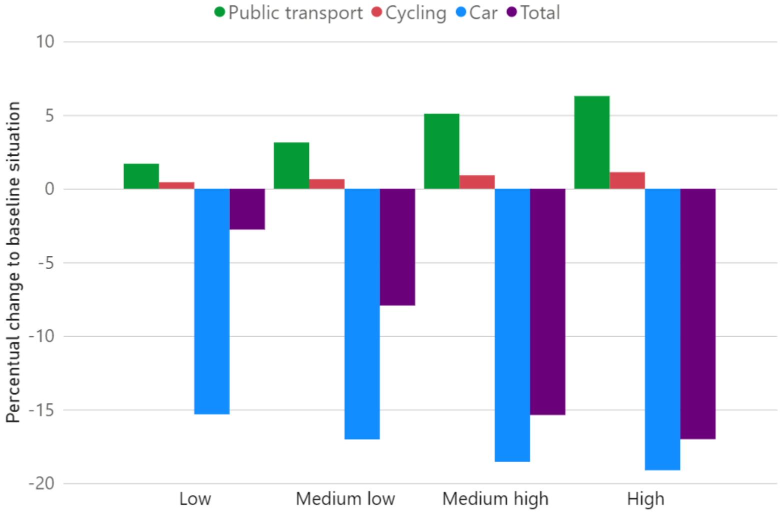


Figure 51: accessibility according to IKOB in the third scenario

6.4.3 Findings in the third scenario

In the third scenario, car ownership in the study area has been reduced by 30%. This has been modelled by reducing the estimates collected from the CBS. The altered data from the CBS is considered as input in both accessibility approaches. The subsequent results of the third scenario reveal interesting behaviour from both models. First of all, both approaches predict that the accessibility by car will reduce on average compared to the baseline situation. This is because the number of people who do not have a car whose accessibility is (almost) zero will rise. Increasing the frequency of such segments brings down the total weighed average. Furthermore, the accessibility by bicycle and public transport has not changed according to the logsum approach. On the contrary, the IKOB approach shows that the accessibility of these modalities will increase when car ownership is reduced. It has been found that this is the result of how the preference parameter is modelled. Furthermore, the logsum approach predicts that accessibility decreases in every zone in the third scenario. In general, the IKOB approach shows the same. However, there are a few zones where this is not happening. This is caused by the method for calculating car ownership.

6.5 The fourth scenario: increasing job opportunities

In the fourth scenario, it has been decided to increase the number of available job opportunities in a zone by 10,000. The zone that is chosen is located in a neighbourhood in the north of the municipality in which incomes are less on average as visualised in Figure 24 in Section 5.3.4. The subsequent results will be elaborated upon in this section.

6.5.1 Zonal accessibility change

First of all, Figure 52 shows how the average accessibility considering all transport modalities in each zone has changed compared to the baseline situation according to both approaches. It could first be observed that the logsum approach predicts that accessibility increases the most in de zone in which the jobs have been added and the surrounding ones. Thereafter, the effect decreases as the distance to the chosen zone increases. The most important reason is that the increased travel times and costs cause the added jobs to become less attractive. Next, the figure shows that accessibility decreases similarly towards each direction without sudden jumps. Therefore, the distance and cost parameters seem the most important factors for the created pattern. Furthermore, Figure 12 shows that the IKOB approach predicts a different pattern compared to the logsum approach. The first distinction is that there are several clusters in which accessibility has been increased the most. These clusters are not necessarily in close proximity to the zone where the jobs were added. There are multiple reasons for this. First, the decay curves in IKOB follow a kind of s-shape as shown in Figure 17 (Section 4.3.1.3). Therefore, the first minutes of generalized travel time do not increase travel resistance. As a result, a gradual decline is not initially expected as similar to the logsum approach. This is especially prevalent for people with a high income who can make use of a (free) car. Therefore, the more people that have a car and higher incomes live in a zone, the better they can reach the added jobs on average. This could be concluded from the figure as the two rich neighbourhoods located in the west around the highway and in the northeast are categorized as “very high”.

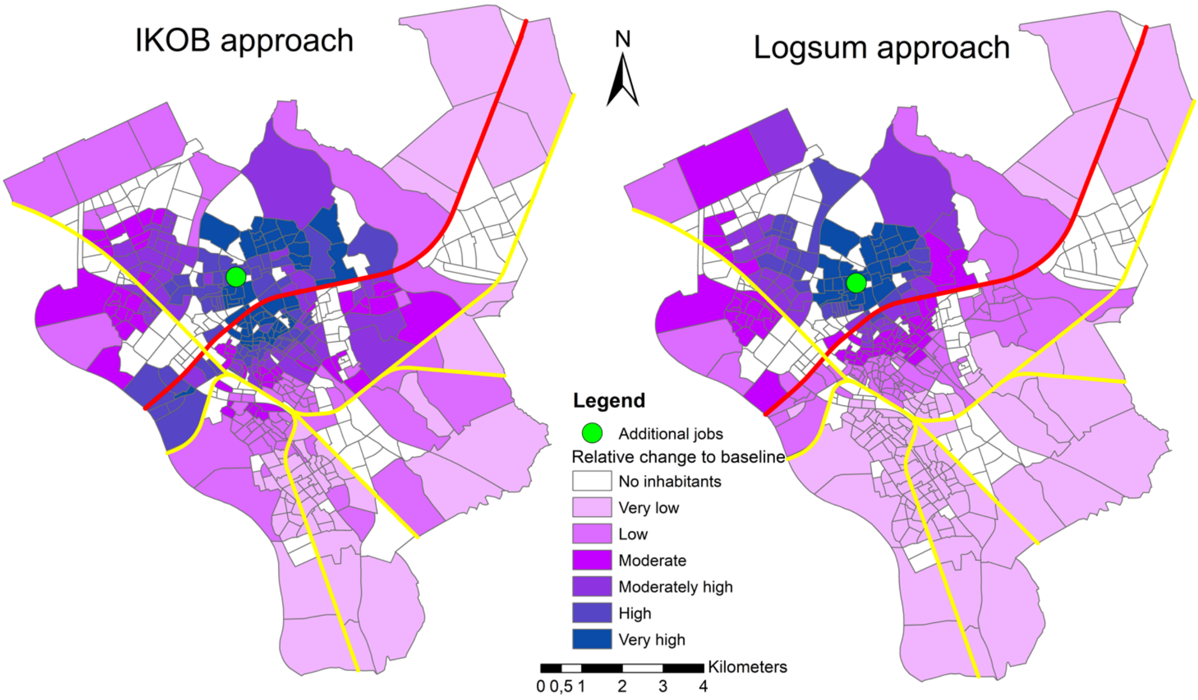


Figure 52: Average zonal changes in the fifth scenario compared to the baseline situation.

6.5.2 Average change across segments

Furthermore, Table 7 shows how the average accessibility in Zwolle of the four initial segments is increased in the fourth scenario according to IKOB. These segments are people who have a car and can use it for ‘free’, have a car but cannot use it for free, have a driver’s license but no car and those who have neither a car nor a license. The lefthand side of the table presents the accessibilities in the baseline situation while the right-hand side indicates how much the accessibility has increased compared to the baseline. The table first shows that accessibility by bicycle has increased the most for the segments “no car” and “no license”. The first reason is that job opportunities have been added in a region in Zwolle in which incomes are relatively low. More people from the segments “no car” and “no license” therefore live close to the new jobs compared to the other two segments. The average effect is subsequently higher. The second reason is that more people from the stated segments have a preference for cycling compared to people who have a car. Such people are willing to make longer trips with these modalities making the impact more powerful. The table secondly shows that the accessibility by car is increased the most for people with a (free) car. The primary cause is that having a car is much cheaper compared to a rented car (assumed for the segment ‘no car’) and a taxi (no license) reducing travel resistance. Lastly, the accessibility considering all modalities has increased the most for people with a ‘free’ car whilst it has decreased the least for people with no driver’s license. This shows, again, that the car is the most important modality in Zwolle according to IKOB. Still, the accessibility of the segments ‘no license’ and ‘no car’ has relatively speaking increased the most (7.88% for no car and 8.51% for no license) compared to the segments ‘free’ car (0.48%) and has car (4.30%).

Table 7: Change in accessibility according to IKOB in the fourth scenario

Baseline situation					Increasing number of jobs in a zone			
	Cycling	Car	Public transport	Total	Cycling	Car	Public transport	Total
Free car	87,449	2,046,936	33,754	2,046,948	+8,717	+9,857	+2,958	+9,857
Has car	92,922	212,041	41,873	225,216	+8,915	+9,049	+3,920	+9,682
No car	97,394	55,694	41,307	117,167	+9,111	+3,967	+3,933	+9,231
No license	97,395	112	39,371	107,395	+9,112	+14	+3,727	+9,138

Furthermore, Table 8 shows how the average accessibility in Zwolle of the three initial segments is increased in the fourth scenario according to the logsum approach. These segments are people who have a car, have no car but have a driver’s license and those who have neither. It could first be observed that accessibility by bicycle and public transport has increased the most for the segments “no car” and “no license”. The reason is the same as elaborated upon before. Namely, more people from these two segments live close to the zone in which the jobs have been added. The table also shows that the accessibility by car is only increased for those who have a car. This is expected as people with no car and/or no license cannot use the car. This contradicts the IKOB approach because of the taxi and shared car assumption. Lastly, the table shows that the accessibility considering all modalities is increased the most for people with no driver’s license followed up by those who do have a license but no car. The opposite was predicted by the IKOB approach. This shows that Octavius considers public transport and cycling more important for the total accessibility compared to IKOB. Furthermore, the effect of the car on the total accessibility is deemed smaller in Octavius.

Table 8: Change in accessibility according to the logsum approach in the fourth scenario

Baseline situation					Increasing number of jobs in a zone			
	Cycling	Car	Public transport	Total	Cycling	Car	Public transport	Total
Has car	10.055	11.578	10.317	4.410	+0.107	+0.061	+0.048	+0.024
No car	10.077	0.000	10.398	3.553	+0.115	+0.000	+0.049	+0.035
No license	10.039	0.000	10.296	3.523	+0.127	+0.000	+0.053	+0.039

6.6 The fifth scenario: Improving public transport for those without a driver's license.

In the fifth scenario, it is modelled that additional public transport services are provided to those who neither have a car nor a driver's license. It is assumed that travel times by PT have been decreased for the targeted segment by 40% as a result. The subsequent results will be elaborated upon in this section.

6.6.1 Accessibility according to the logsum approach

First, Figure 53 shows the accessibility by public transport of the three initial segments in the fifth scenario compared to the baseline situation according to the logsum approach. These segments are people who have a car, have no car but have a driver's license and those who have neither. The figure shows that the accessibility only affects people with no driver's license, as planned beforehand. The introduced measure causes accessibility by public transport to be improved in such a way for the targeted population that they have on average the highest accessibility. Furthermore, Figure 54 shows the distribution of accessibility by public transport considering all people in the study area in more detail. The blue bars represent the distribution in the baseline situation and the orange one the distribution in the fifth scenario. It could first be observed that the number of people who have a relatively poor accessibility between eight and eleven in the baseline situation has been reduced with the proposed measure. These are thus the people without a driver's license. Instead, several people from the targeted population group now have accessibility above twelve. Such high accessibilities were not present in the study area in the baseline situation. Interestingly, differences between people are greater than in the baseline situation as a result. Because of this, inequalities related to accessibility by public transport will actually increase.

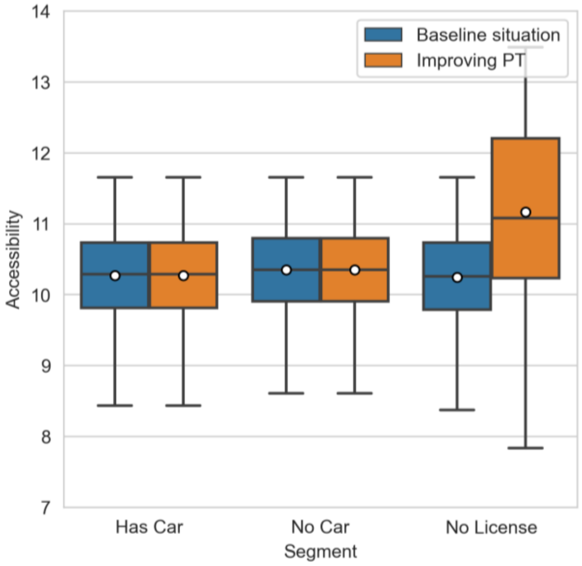


Figure 53: Accessibility by public transport to work according to the logsum approach in the fifth scenario

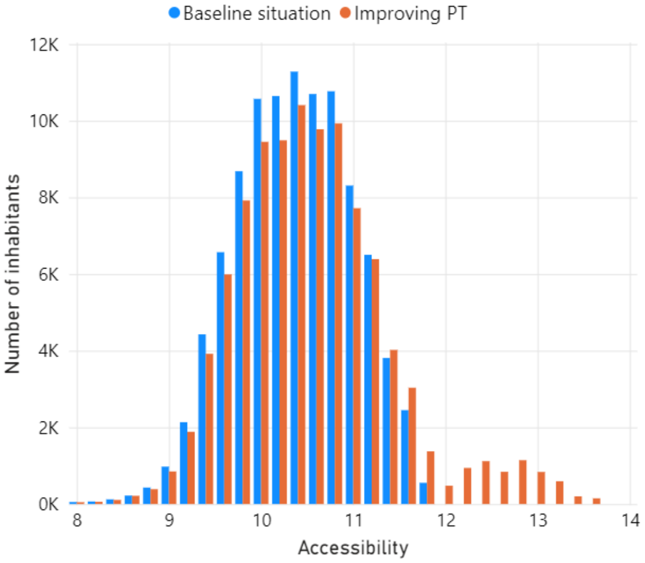


Figure 54: Frequency distributions of accessibility by PT to work according to the logsum approach in the fifth scenario

Next, equivalent figures have been prepared related to the total accessibility. Figure 55 shows the total accessibility of the three initial segments in the baseline and improved situation. Figure 56 shows the frequency distribution of the total accessibility considering all people in the municipality of Zwolle. Figure 55 firstly demonstrates that the accessibility considering all modalities has increased significantly for the targeted population group. As a result, their average accessibility is higher compared to the segment "no car" and approaches that for people who have a car. Subsequently, Figure 56 shows that the number of people with accessibility lower than four has decreased considerably. Instead, the target population has an accessibility of about four to five. This is around the average accessibility in Zwolle. Moreover, the number of people with accessibility higher than 5 has remained similar. Thus, it can be stated that improving public transportation for people without driver's licenses will improve accessibility for many people who are the worst off to an average level.

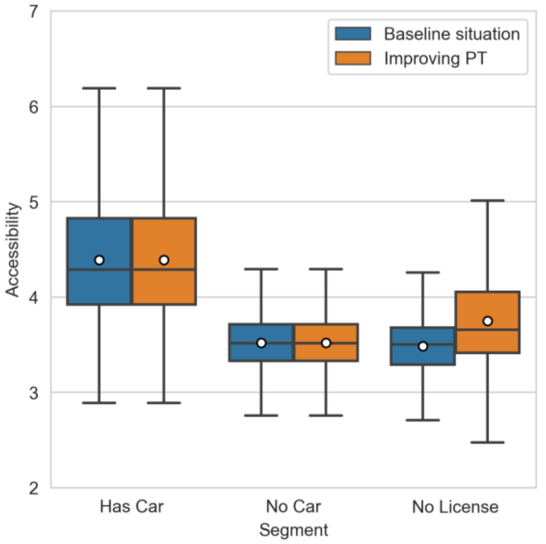


Figure 55: Total accessibility to work according to the logsum approach in the fifth scenario

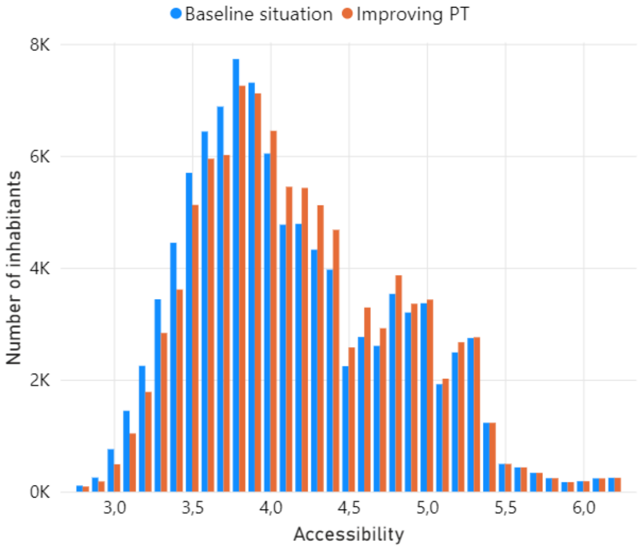


Figure 56: Frequency distribution of the total accessibility to work according to the logsum approach in the fifth scenario

6.6.2 Accessibility according to the IKOB approach.

Next, Figure 57 shows the accessibility by public transport of the four segments according to the IKOB approach in the fifth scenario. Similar to Figure 53, only the accessibility of those with no driver’s license is improved as planned beforehand. Consequently, this segment has the highest accessibility by public transport on average in the municipality of Zwolle. Further, Figure 58 shows the accessibility considering all modalities according to IKOB. The figure shows that the accessibility of the targeted segment has not changed compared to the baseline situation. The main reason is that public transport is not an important modality according to IKOB. Therefore, it does have a small effect on the total accessibility. It could therefore be concluded that improving public transport will not reduce inequalities in accessibility significantly.

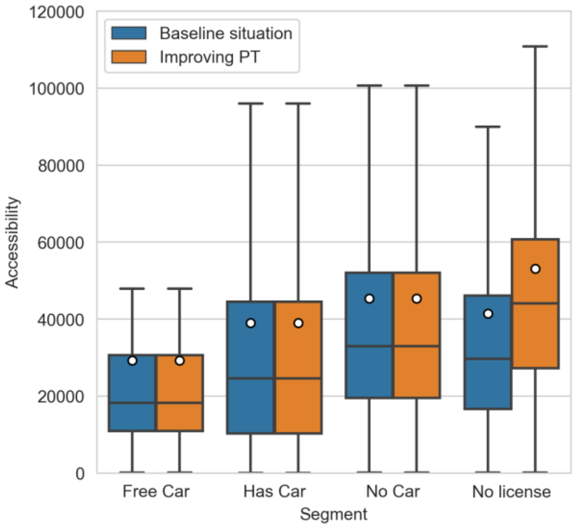


Figure 57: Accessibility by public transport to work according to IKOB in the fifth scenario

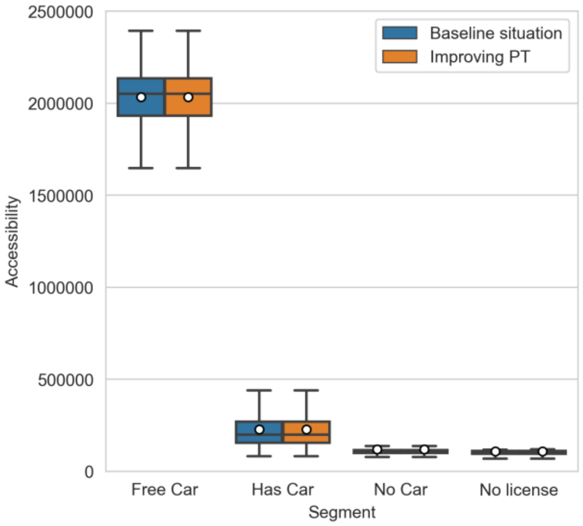


Figure 58: total accessibility to work according to IKOB in the fifth scenario

Next, Figure 59 shows the distribution of accessibility by public transport of all people in Zwolle in more detail. It could first be observed that the distribution of accessibility according to the IKOB approach is predicted differently compared to the logsum approach. That is, the logsum approach presents a normal distribution, as shown in Figure 56, while the IKOB predicts a more exponential-like distribution. Further, Figure 59 demonstrates that the number of people with accessibility lower than 40,000 has decreased. These are the people who do not have a driver's license. Instead, the target population after the proposed measure are among those with relatively high accessibility.

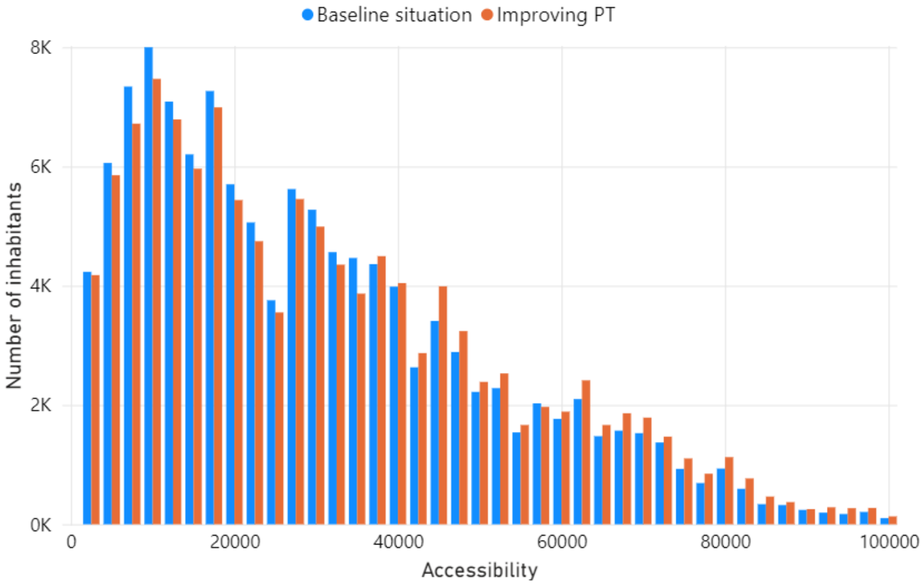


Figure 59: Frequency distribution of the accessibility by public transport to work according to IKOB in the fifth scenario.

6.7 Relative changes

Further, normalisation has been applied using the average accessibility of each zone calculated in both the baseline and a scenario. To do so, results from the baseline and a scenario are taken together. The highest value subsequently receives a value of one and the lowest zero. Following this, the differences between the baseline situation and the scenario are calculated. For instance, the normalised accessibility in the baseline scenario for some zone is 0.84 whilst it is 0.80 in the first scenario. This is thus a difference of 0.04. The discussed method is applied for the logsum as well as the IKOB approach.

The idea of this method is to set the results from both accessibility approaches on the same scale so that they can be compared. The normalised differences are subsequently ordered. Results from the first scenario have been presented in Figure 60 and those of the second scenario in Figure 61. It should be noted that the order according to the IKOB and logsum approaches are different. Therefore, a zone may have different rankings between the two approaches. The figures show first that accessibility has proportionally decreased more sharply according to the IKOB approach in both scenarios compared to the logsum one. These findings show that the IKOB approach is more sensitive to any alterations in the model compared to the logsum approach. The cause may be due to the logarithm in the logsum, which makes differences seem less apparent. However, equivalent conclusions can be made when the logarithm is ignored.

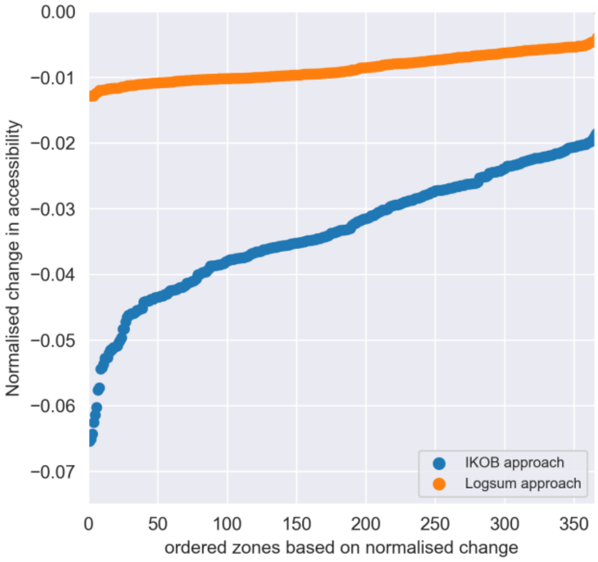


Figure 60: Ranked normalized differences between the baseline situation and the first scenario

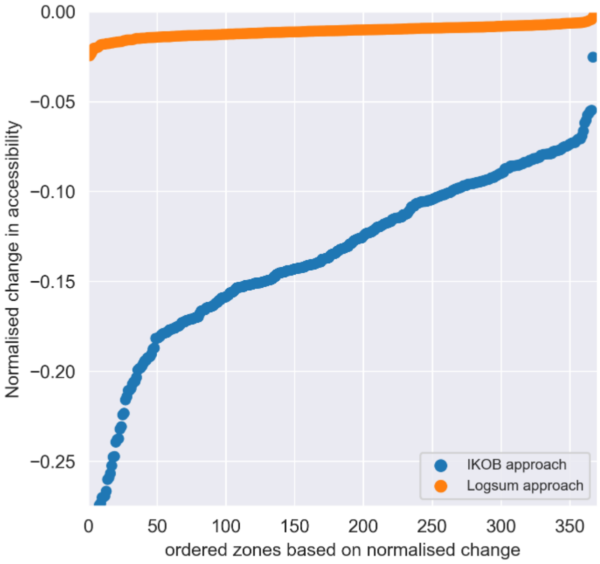


Figure 61: Ranked normalized differences between the baseline situation and the second scenario

6.8 Accessibility and inequalities

Furthermore, several indicators to determine the degree of inequality in accessibility were introduced in Section 3.6. It has been concluded that the Gini coefficient and 10/40 ratio will be applied in this study. The Gini coefficient ranges from 0 to 1, where 0 is a perfectly equal distribution and 1 is an extremely unequal distribution. With the 10/40 ratio, it can be determined to what extent the 10% of the population with the highest accessibility is better off compared to the 40% with the lowest accessibility.

6.8.1 Inequalities in the baseline situation

The two equality measures are subsequently calculated for each transport modality for the IKOB and logsum approaches. For the accessibility by car, the statistics are calculated twofold. One for the complete population, which includes those who do not have a driver's license and/or a car. The second group only consists of people who do have a car (and may use it for 'free'). The results are presented in the Figure below. Furthermore, it was recommended to not only show the Gini coefficient but also to visualise the corresponding Lorenz curves. These have therefore been plotted in Figure 62 for the IKOB approach and in Figure 63 for the logsum one.

Table 9: Equality measures for the IKOB and Logsum approach

	IKOB approach		Logsum approach	
	Gini	**10/40 ratio**	**Gini**	**10/40 ratio**
Cycling	0.098	0.367	0.062	0.324
Car (all people)	0.625	8.169	0.346	1.714
Car (have car)	0.490	5.109	0.050	0.305
Public transport	0.377	4.534	0.137	0.462
Total	0.520	4.751	0.174	0.559

From the displayed results, it can first be observed that accessibility for cycling is the most equal. The extent of which is also similar between the IKOB and Logsum approach. By contrast, it can be seen that the inequalities for the other two modalities are estimated to be more substantial by IKOB compared to the logsum approach. One reason for this contradiction is that 3% of the population is allowed to use PT for 'free' in the IKOB approach. The accessibility of people who do not have to pay is a lot higher compared to those who do. This can also be deduced from the Lorenz curve in Figure 62, which increases rapidly in the last part. The same effect accounts for the large inequalities in accessibility by car. That is, a certain percentage of people can drive it for 'free'. The accessibility of this segment is up to nine times greater relative to those who have to pay, as discussed in Section 6.1.4. Although, the share of people who have a 'free' car is larger relative to those who have 'free' public transport making inequalities greater. Further, Figure 63 shows that the Lorenz curves predicted by the logsum approach remain close to the "equal distribution" line. Only the one for the car considering all people is distinctive. This is because a substantial portion of people do not have a car causing the accessibility to be 0. Hence, the straight initial line. The inequalities by car are entirely removed when only people are considered who do have one. This thus contrasts with the results predicted by the IKOB approach as it predicts substantial differences between people because of the "free" car segment and the effect of the income parameter.

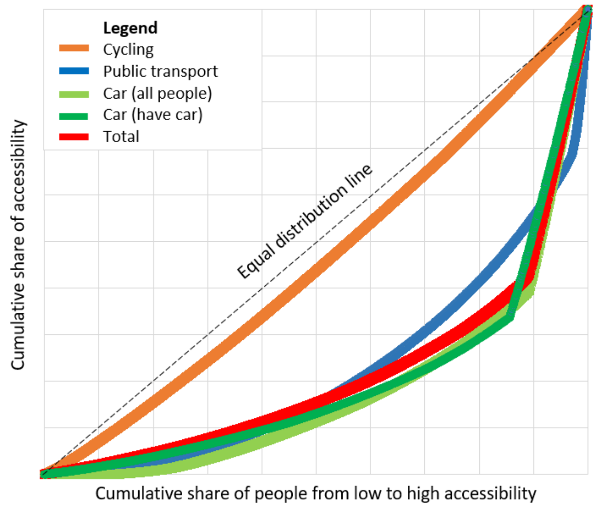


Figure 62: Lorenz curves according to the IKOB approach

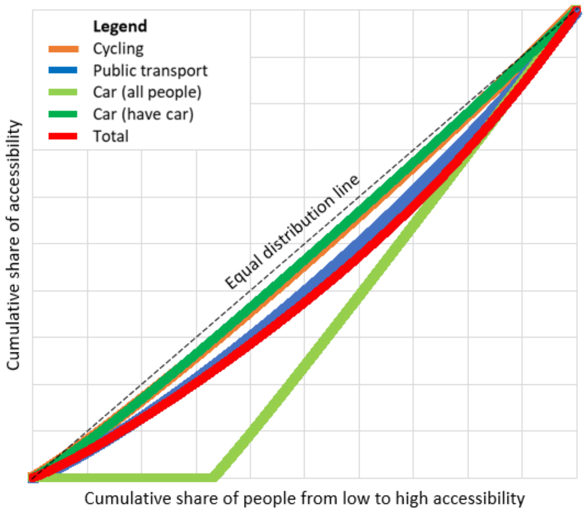


Figure 63: Lorenz curves according to the Logsum approach

6.8.2 Inequalities in the scenarios

Lastly, the inequality indices resulting from the five scenarios are presented in Table 10. The table shows the differences compared to the standard situation. Those for cycling and public transport are not shown for the first and second ones, as these scenarios do not affect them. Besides, the group car (have car) also includes those who can use it for 'free'. For the IKOB approach, two kinds of observations were made concerning inequalities in the first scenario. First, inequalities have become larger considering the complete population. The reason for this is that the advantage of people who have a ‘free’ car has increased even further. The other finding is that the inequalities between people who do have a car but not for ‘free’ have decreased. These two effects counteract each other. The table shows however that inequalities have become bigger. It can thus be concluded that the increased benefit of people who have a ‘free’ car is the superior effect. Furthermore, the inequality indices have remained the same according to the logsum approach. This is because every person is impacted exactly the same by the measure as modelled in Octavius, as explained before. As a result, differences between individuals stay the same so the indices remain unchanged.

Table 10 Inequality indices in the scenarios

Baseline situation				
	IKOB approach		**Logsum approach**	
	Gini	10/40 ratio	Gini	10/40 ratio
Cycling	0.098	0.367	0.062	0.324
Public transport	0.377	4.534	0.137	0.462
Car (all people)	0.625	8.169	0.346	1.714
Car (have car)	0.490	5.109	0.050	0.305
Total	0.520	4.751	0.174	0.559
The first scenario: increasing the costs of using the car				
Car (all people)	+0.015	+0.994	0	0
Car (have car)	+0.015	+0.461	0	0
Total	+0.016	+0.308	0	0
The second scenario: closing two bridges across the IJssel				
Car (all people)	-0.026	-2.657	-0.002	-0.012
Car (have car)	-0.028	-1.091	-0.003	-0.003
Total	-0.058	-1.509	-0.002	-0.004
The third scenario: Reduce car ownership				
Cycling	+0.005	-0.002	0	0
Public transport	-0.009	-0.380	0	0
Car (all people)	+0.038	+7.601	+0.099	n/a
Car (have car)	-0.003	-0.044	-0.003	-0.003
Total	-0.008	+0.066	+0.001	+0.014
The fourth scenario: Increasing job opportunities in a zone				
Cycling	-0.005	-0.006	-0.003	-0.004
Public transport	-0.017	-0.450	-0.002	-0.007
Car (all people)	-0.006	-0.472	-0.005	-0.008
Car (have car)	-0.003	-0.161	-0.001	-0.001
Total	-0.013	-0.349	-0.004	-0.008
The fifth scenario: Improving PT for those with no license				
Public transport	-0.014	-0.174	+0.032	+0.096
Total	0	-0.002	-0.008	-0.020

Furthermore, Table 10 shows that all the indices in the second scenario in which the two bridges have been closed have decreased compared to the baseline situation. The differences are estimated to be larger according to the IKOB approach. Especially the 10/40 ratios have been reduced significantly. The main reason for the great inequalities according to IKOB is that the accessibility of people who can use a "free" car is so much greater compared to those who cannot use one "for free." This advantageous situation has been reduced in the second scenario, making the distributions fairer. On the contrary, the changes are thus much smaller according to the logsum approach. The primary reason is that the variance in behaviour of people is estimated to be smaller. The proposed measure will therefore have a more similar effect on the accessibility of everyone.

Table 10 shows that the coefficients in the third scenario change for the accessibility by cycling and public transport according to the IKOB approach but not the logsum one. The reason has been elaborated before in Section 6.4.2. Namely, accessibility by these two modalities will increase according to IKOB when car ownership is reduced. Second, the coefficients considering the accessibility by car about the complete population have increased according to both approaches. This is because more people will have an accessibility of (close to) zero compared to the baseline situation. Besides, the 10/40 coefficient cannot be calculated for this group by the logsum approach. The reason is that more than 40% will not have a car in this scenario. The total accessibility of the “40” part in this coefficient is thus zero. Dividing zero by something is not meaningful. This does not happen in the IKOB approach as it is assumed that people who do not have a car have some accessibility (close to zero) as they could take a taxi or a shared car. Lastly, the distribution of the accessibility of people who do have a car has not much as the accessibilities themselves have not been altered. Only the size of the group itself is reduced.

In the fourth scenario, 10,000 job opportunities have been added in an area that originally had poor accessibility compared to other parts of Zwolle. The table shows that both approaches predict that inequalities by each modality will decrease. The reason is that more people from the segments “no car” and “no license” live close to the targeted zone compared to those who have a car. As a result, they can assess the additional jobs with less travel resistance on average increasing accessibility. The stated effect is predicted to be more substantial by the IKOB approach compared to the logsum one. This is especially prevalent according to the 10/40 indices. The main cause is that the number of jobs is transformed by a logarithm within the discrete choice models in Octavius. The relative effect of adding one job therefore reduces as the number of total available jobs increases. The effect of the proposed measure is therefore lower.

Furthermore, additional public transport services are provided to those with no driver’s license in the fifth scenario. Since this scenario does not affect accessibility by bicycle and car, related inequality indices are not presented. Only those for public transport and the total accessibility are shown. These indices firstly demonstrate that inequalities in accessibility by public transport have decreased according to IKOB. The reason is that the number of people with relatively poor accessibility has been decreased by the measure, as also shown in Figure 59. By contrast, the logsum approach predicts that inequality in accessibility by public transport will increase. The reason is that the accessibility of the targeted population has been improved so much that several of them have the best accessibility in the study area. This is also illustrated in Figure 54. What both measures do agree on is that the inequality in the total accessibility will be reduced. The total effect however is larger according to the logsum approach. The main reason is that the Octavius model considers public transport to be a more important modality. Improving public transport will therefore have an important impact on the total accessibility. However, according to the IKOB model, cycling and taking the car are more important, so improving public transportation does little to improve people's overall accessibility.

In conclusion, the logsum approach based on Octavius predicts less inequality in accessibility in the baseline situation compared to IKOB, as visualized in Figure 62 and Figure 63. The primary reason is that the Octavius model predicts smaller differences in the behaviour of people in the transport system. The subsequent scenarios analyzed in this research therefore have a smaller effect on the initial inequalities according to the Gini and 10/40 coefficients. The concept that several people can use the car and public transportation "for free" according to the IKOB approach specially creates differences compared to the logsum approach. In particular since the accessibility of those that can use these two modalities for free can be up to nine times higher compared to those that cannot. Furthermore, results show that the car modality is much more important compared to cycling and public transport according to IKOB. The logsum approach based on Octavius estimates the importance of the three modalities more similarly.

7. Discussion

The IKOB approach is an upcoming method of determining accessibility in the Netherlands. In addition, the company Goudappel have developed a microscopic strategic transport demand model called Octavius. Octavius is one of the most extensive models in the Netherlands to predict the behaviour of people in the transport system. Next, it is possible to apply the valuable information from the Octavius model with the logsum measure to calculate accessibility. In this way, one of the most detailed accessibility approaches based on the introduced logsum measure is created, which could be a viable alternative to the IKOB approach. It is however uncertain how the introduced accessibility approaches relate to each other. Therefore, this research aims to determine the extent of application and the additional benefits in assessing accessibility to work and related disparities using the devised logsum-metric grounded on the microscopic transport model Octavius compared to the IKOB approach. To do so, both are applied in the municipality of Zwolle.

Next, accessibility as calculated in this study cannot directly be “measured” as it is not a tangible asset. For example, it is not possible like with a transport model to compare the modelled traffic intensities to real traffic counts and make corresponding conclusions. This makes it difficult to verify whether the outcomes from both accessibility approaches are correct. Nevertheless, it has been attempted in this study to investigate both methods through an assessment framework. Multiple criteria about how a proper accessibility approach should behave are established in Chapter 5 which are subsequently compiled in said framework. The criteria are investigated by introducing five scenarios, the results of which have been discussed in the previous chapter. In this chapter, the framework will be evaluated based on the discussed results. Found differences between the two approaches can arise in three stages as schematized in Figure 64. First of all, both approaches consider different accessibility measures which cause the first variations based on theory alone. Then, both models consist of a structure to partition the population into several segments and to determine the accessibility of each one. This structure consists of multiple parameters whose values should be estimated with data to determine accessibility in a study area in practice. In this study, this is the municipality of Zwolle. The same data has been used for both accessibility approaches. So, differences do not arise from the data but from the other three introduced stages; theory, model structure and parameters & assumptions.

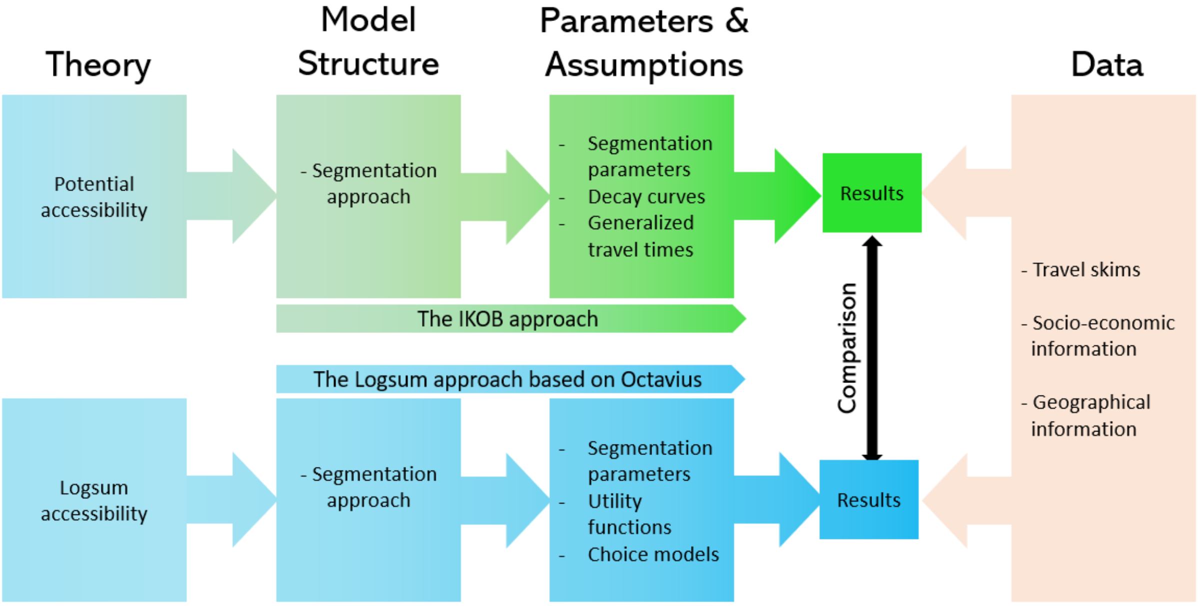


Figure 64: The stages of both accessibility approaches

7.1 The framework

First of all, the framework is presented below. How the logsum and IKOB comply with each criterion according to the results in this research is shortly discussed. It is then demonstrated whether these findings are caused by the input data (D), theory (T), model structure (MS) and/or the parameters & assumptions (P&A). Each stage will be elaborated upon in the following sections.

Table 11: Assessment framework

The framework							
Number	Criterion	Accessibility approach		Caused in stage:			
1	**The land-use component**	**The logsum approach**	**The IKOB approach**	**D**	**T**	**MS**	**P&A**
1.1	Increasing (reducing) the number of opportunities should have a positive (negative) effect on the accessibility.	The number of jobs is the fundamental part of the utility function. Increasing the number of jobs somewhere will increase accessibility. Due to the disutility of travel, the smaller the travel time and costs, the bigger the effect on accessibility. This is however the transport component.	The number of jobs is weighed by the disutility of travel. Increasing the number of jobs somewhere will increase accessibility as long as the weight is not zero. Jobs that can be reached by a smaller (generalized) travel time will have a bigger impact on accessibility. This is however the transport component.			✓	✓
1.2	Increasing (reducing) the demand for opportunities for an activity with capacity restrictions should decrease (increase) the accessibility to that activity.	This effect is also called competition. Competition is important for accessibility to job opportunities but is not considered in the model.	This effect is also called competition. There is an IKOB module for competition. It has not been applied in this study.			✓	
1.3	Increasing (reducing) the availability of remote working opportunities should increase (reduce) accessibility	Remote working is not considered in the Octavius model.	Remote working is not considered in the IKOB model.			✓	
2	**The transport component**						
2.1	An increase (decrease) in the number of opportunities in an area 'close' to people should have	"Close" is about the disutility to travel. In IKOB, the disutility is defined by the travel time as well as costs. Indeed, accessibility	"Close" is about the disutility to travel. In IKOB, the disutility is defined by the travel time as well as costs. Indeed, accessibility				✓

	a greater effect on their accessibility compared to a situation where the same number of opportunities are added (removed) in a zone further away.	reduces when the costs and/or travel time are increased.	reduces when the costs and/or travel time are increased.				
2.2	Reducing (increasing) the speed of a modality should have a negative (positive) effect on accessibility.	The travel time is considered as disutility to travel. Reducing the speed of a modality will therefore reduce accessibility.	The travel time is considered as disutility to travel. Reducing the speed of a modality will therefore reduce accessibility.				✓
2.3	Increasing (reducing) the service level of a transport modality should increase (decrease) the accessibility of that specific modality.	The service level is reduced by closing two important bridges. Results show that accessibility is reduced.	The service level is reduced by closing two important bridges. Results show that accessibility is reduced.				✓
2.4	Increasing (reducing) the cost of a transport modality should decrease (increase) the accessibility of that specific modality.	The cost of using the car has been increased in Scenario 1. Results show that accessibility is reduced for all people who do have a car	The cost of using the car has been increased in Scenario 1. Results show that accessibility is reduced for all people except those who can use a car for 'free'.				✓
3	**The individual component**						
3.1	Improving (decreasing) the service of a transport modality should not increase (reduce) the accessibility of those with insufficient abilities or capacities (e.g., driver's licence) to use that mode.	Results from the second scenario show that the accessibility of those who do not have a car and/or driver's license is not affected by closing the two bridges. Not having a car/ driver's license are the first two factors that are considered. Parameters like not having enough money or being disabled are not taken into account.	Everyone is able to use every mode. It is assumed that people who do not have a car but have a license rent a shared car. Someone who has neither takes a taxi. Other parameters are not considered.				✓
3.2	Increasing (decreasing) the number of	Everybody is able to apply to all jobs. No restrictions related to	In the considered IKOB approach, everybody is able to				✓

	opportunities should not increase (reduce) the accessibility of those with insufficient abilities or capacities to participate in them.	individual abilities or capacities are considered.	apply to all jobs. No restrictions related to individual abilities or capacities are considered.				
3.3	Increasing (decreasing) the cost of transportation should reduce (increase) the accessibility for those with less to spend to a greater degree compared to those with more to spend.	First, the income parameter is not considered. However, it may be approximated by other ones such as age. Results from the first scenario however show that every person is affected exactly the same, regardless of individual characteristics. This criterion is therefore not upheld.	The TVOM parameter is considered in IKOB. In this way, it is modelled that a euro of extra cost is perceived more severely by someone with a lower income compared to someone with a higher income. The model therefore complies with this criterion.				✓
4	**The temporal component**						
4.1	Increasing (decreasing) the number of opportunities should not increase (reduce) the accessibility of those who do not have time to participate (meaningful) in them because of their specific time schedules.	The temporal component is not considered in the Octavius model. This criterion could therefore not be studied.	The temporal component is not considered in the IKOB model. This criterion could therefore not be studied.			✓	
4.2	Increasing (decreasing) the number of opportunities should only increase (reduce) the accessibility during its opening hours.	The temporal component is not considered in the Octavius model. This criterion could therefore not be studied.	The temporal component is not considered in the IKOB model. This criterion could therefore not be studied.			✓	
5	**Additional criteria**						
5.1	Is the measure consistent with the transport demand model on which it is based?	Yes. The segments as well as their behaviour are directly derived from the demand model.	No, post hoc segmentation. Decay functions are not consistent with those in the demand model.			✓	✓

5.2	Is the unit of the measure an understandable term?	Some people that the unit of the potential accessibility measure is “the number of jobs”. In theory, this is false. Still, the outcomes are understandable for decision-makers.	It is comprehensive what the unit of “utility” means. Also, the logsum is a relative measure. It is only meaningful when compared to some baseline situation or the accessibility of an other segment. This makes it more difficult to interpret results.		✓		

7.2 The theory stage.

The first stage is about the theoretical foundations of both accessibility approaches. Many methods exist to turn the abstract concept of accessibility into measurable observations. This study focuses on two measures to do so. The first one is the potential accessibility measure which is the core of the IKOB approach. Second, the so-called logsum measure is applied as first devised by Ben-Akiva & Lerman (1985) to apply information from Octavius to calculate accessibility. Interestingly, mathematicians have proven that the logsum and potential accessibility measures are identical when equivalently specified (e.g., Anas 1983). It has been demonstrated that if both measures are equally implemented, they predict the same ranking when ordering individuals or zones according to accessibility. An example has also been provided in Section 3.5. Still, the logsum measure has a couple of peculiarities to consider. Firstly, the theoretical background takes a certain knowledge about discrete choice models and general mathematics to fully understand why the equation about the logsum is the way it is. Second, the logsum, as its name suggests, considers a logarithm. As a result, equal improvements will impact the accessibility differently depending on the original accessibility. Third, the logsum is a relative measure. It is only meaningful when compared to some other logsum. For instance, by comparing the accessibility of person y to person x, or the accessibility of a person z in situation one compared to situation two. Next, the logsum is the result of one particular discrete choice model. It is therefore not possible to compare values directly between different specifications of the same model or other discrete choice models. Beyond that, it is not even possible to compare the logsums of two modalities because a different choice model is used for each modality. The discussed reasons make working with the measure more complex compared to the potential accessibility one.

7.3 The model structure stage

Next, both the IKOB and Octavius models consist of a structure to divide the population into various segments and model the behaviour of each of those segments. This model structure is the foundation of the accessibility approaches and is the same regardless of practical application. The objective is to identify differences at this stage since they are caused by the structure itself and not by the circumstances in one practical application.

Next, most of the differences in the model structure between the two approaches are caused by the fact that they are created based on divergent principles, as explained in Section 4.3.4.2. On the one hand, parameters that create variations in the decisions people make when travelling are included in Octavius when two conditions are met. First, their effect has been demonstrated by literature. Second, such parameters are proven statistically significant from observed travel behaviour in the Netherlands.

This is verified when the behavioural parameters for the different multinomial choice models in Octavius are estimated. Policymakers may request one specific particular parameter to be included. It will not be added if its effect has not been found statistically significant. The parameters that are considered in the IKOB approach are determined by a group of researchers. They choose what to include based on current literature, data availability, feasible computation times and demand from policymakers.

The considered principles cause differences in the segregation approach in which the groups of people are created that are considered further in the model. The IKOB approach considers a stepwise approach similar to creating a decision tree in which every step the population is divided into smaller groups according to a condition. For instance, does this person have a car are not? There are several points to note about this approach. First, the steps should be linked by all kinds of varying datasets and assumptions which causes inconsistency between each step. In addition, there is no verification at the end of the segmentation to check whether the created segments are still consistent with the real population. The accuracy of the created segments is therefore uncertain. In contrast, Octavius considers microsimulation in which a population is created that represents the real one as accurately as possible using statistical procedures. This population consists of agents that each have a set of particular characteristics. The statistical procedures ensure more accurate results compared to the IKOB approach.

Only accessibility to work is considered in this study. For accessibility to work, it holds that one job can only be occupied by one (qualified) worker. Therefore, a situation occurs in which people compete for a limited number of opportunities which is called competition (Shen, 1998). An IKOB model is available in which competition is considered. Still, it is not taken into account in this research. The reason is that a suitable method to do so in conjunction with the logsum measure must also be established. It is out of scope for this research to create such a method. Only having one model with competition creates an unequal comparison and the IKOB module is therefore not considered. By not taking into account competition, the applied accessibility measures only consider the supply side for opportunities whilst the demand side is ignored (Shen, 1998). Shen also states that this is only valid if the demand for opportunities is uniformly distributed across space and when there are no capacity limitations. The first condition is not upheld for the Netherlands as population densities are higher in cities compared to the countryside. The second condition does not hold for accessibility to work as earlier stated. Not considering competition is therefore especially a weakness of the logsum approach.

Furthermore, the presence of remote working has accelerated rapidly during the Covid-19 pandemic. This involves both completely working remotely or a hybrid approach where physical presence is only required on certain days. Virtual access is therefore provided to opportunities that are normally located in space. Accessibility to job opportunities therefore consists of an online and physical component. Neither the IKOB nor the Octavius approach takes this into account. For instance, an accessibility approach that considers remote working has been introduced by Cavallaro & Dianin (2022) and van Lent (2023). Moreover, the framework shows that the availability of opportunities at different times as well as the time availability of people to participate in them is not considered in both approaches. Therefore, the temporal component according to Geurs & van Wee (2004) is not taken into account. This is because the current structure of the models does not allow for modelling this particular mechanism. It is therefore assumed that everyone has time to go to work.

7.4 Data & application in Zwolle

The aim is to create the most suitable comparison between the IKOB approach and the created logsum approach based on Octavius. To do so, several aspects have been taken into account. First of all, they are both applied in the same study area with identical datasets. The Municipality of Zwolle has been chosen for this. The reason is that this is the only municipality for which an Octavius model is created (at the start of this assignment) which is allowed to be used for this research. The vast majority of datasets applied in this study area for both approaches are the same. This first includes skims about travel times, distances and costs for each modality to travel between any two zones in the study area. These have been calculated by using a transport demand model which only provides free flow travel times. However, most go to work during rush hours when travel times are longer. For instance, it was found in a study that on average people could reach 12.5% fewer jobs by car during rush hours (CBS et al., 2020) Therefore, accessibility is overestimated in this study compared to reality. This is the same for both accessibility approaches, so it poses no problem for the comparison. Also, this is not the 'fault' of the approaches themselves. This can simply be added by considering travel time skims with congestion. These were however not available for this research.

Next, the socio-economic information about each zone in the study area is provided by the municipality of Zwolle. However, this did not include data about the distribution of income categories, necessary for the IKOB approach. For this, the population should be divided into four income groups. Therefore, an estimation has been made using interpolation with two datasets from the CBS. Moreover, the income distribution is estimated with more aggregate data causing adjacent zones to have the same income distribution. Because of the discussed method to calculate the income distribution in each zone, there will be some inaccuracies compared to the real situation. However, differences are expected to be only a few percent. In addition, the idea of this study is to compare the two accessibility approaches, not to calculate the accessibility itself in Zwolle as accurately as possible. The discussed variations should therefore not be a problem.

7.5 Parameters & assumptions

The following step is to shape the model structures with the necessary parameters and assumptions to apply both accessibility approaches in a practical situation. For instance, to decide what parameters to consider, how travel impedance is modelled and who can make use of what modalities. This information is mostly made available by the creators of the models themselves. The outcomes of the final step of this research are specific to the considered models and circumstances of the chosen study area. They are not caused in earlier stages such as the theory, the model structure and the data. Conclusions may be different if other decisions were made or if a different study area was chosen. For example, the Randstad area. In this section, the effects of the specific models applied in Zwolle are examined. It is first discussed how the segmentation approaches are implemented. Then, the accuracy of the results is addressed. Lastly, it is elaborated upon how both approaches comply with the components of accessibility in a practical situation according to Geurs & van Wee (2004).

7.5.1 Segmentation

First of all, the segmentation is finalized with assumptions and estimated parameters. The subsequent segments are vastly different between both approaches. This is because both use (a) different (number of) parameters to distribute the population. For instance, IKOB considers income categories whilst Octavius considers age categories. The resulting number of segments in IKOB is 60 segments whilst Octavius takes into account 4320 of them. Ideally, the segments in both methods are equalized to make comparing them more accurate. However, this is not desirable because the various parameters are correlated in some way. This makes it difficult for instance to establish how the four income categories from IKOB are distributed within the four age categories in Octavius. It seems likely that older people will have higher incomes on average, but the question is how exactly. To answer this, some data must be collected and assumptions made. Differences will then arise in the comparison because of the chosen assumptions and data rather than the approaches themselves. The segments are therefore kept as they were.

One of the considered parameters in the segmentation approach in IKOB is that some people can make use of a ‘free’ car. The idea of the ‘free’ car is to model the behaviour of people who get a car from the company. This has been modelled by setting the variable cost per kilometre to use the car to zero. Because the variable cost is the only cost component for accessibility to work, they can really use the car for free. Whether the car is ‘free’ in reality depends. Firstly, because there are diverse ways someone can get a car from the company. The first way is the situation in which a person only uses a shared car from the company for commuting to work. The costs for this situation are indeed close to zero for the employee. On the contrary, there is also a group who can use a car from the company for private use. The tax authorities consider this as additional wages which are not taxed yet. Therefore, a certain percentage is added to someone’s salary, increasing taxes (“bijtelling” in Dutch). Another possibility is for the employee to pay an additional monthly fee for the use of a car. So having a "free" car is most of the time not the case. In addition, people who cannot use the car for free often receive driving reimbursement from the company which lowers the costs. Because of the discussed reasons, the "free car" and "have car" groups will be closer in reality than modelled. Further, having a free car is a condition of working at a certain company. Considering that someone with a free car can reach all jobs indirectly means that each company will offer the opportunity to do so, which is not the case.

7.5.2 Accuracy

Another point to consider is that several parameters in IKOB are (partly) estimated using expert judgment. Firstly, to define what the TVOM (inverted value of time) is for each income group. It is difficult to determine how much money an hour is worth for each specific segment of the population. Therefore, certain values for the TVOM are estimated by experts in the IKOB approach. The TVOM values are subsequently applied to determine generalized travel times. Then, the potential accessibility is found by weighting the number of jobs according to the generalized travel times with decay curves. These curves are not consistent with those in the used transport demand model. Instead, separate ones are estimated based on the preference of an individual. The parameters to shape these functions are also partially estimated by experts. Because expert judgment is applied twice to determine accessibility, there will be uncertainty in the results. In Octavius, the choices of all agents like to what location they are going to travel with what modality is modelled with multinomial choice models as discussed in Section 4.3.2. The structure of the utility functions in these and the corresponding parameters are estimated using statistical procedures. Only those parameters that have a statistically significant effect on the behaviour of people are included. No expert judgment like in IKOB is considered. It is therefore expected that results from the Octavius model are more trustworthy.

7.5.3 The components of accessibility

Based on the assessment framework presented in Table 11, it can be concluded that most of the differences between the accessibility approaches are not caused by theory, model structure and data, but by the parameters and assumptions in the practical situation in Zwolle. This section discusses to what degree the two accessibility approaches in the practical application in Zwolle consider each component of accessibility according to Geurs & van Wee (2004).

The first component is the transport one which describes the disutility of travelling between a given origin and destination through the network. Both accessibility approaches include travel times as well as travel expenses. The input skims about both are calculated by the same traffic demand model, as stated before. The skims are incorporated differently, but fundamentally similar. That is, the higher the times and costs become, the less attractive an opportunity becomes. Results show that the extent to which this occurs varies. Namely, the first minutes of the (generalized) travel time are shown to have little effect according to IKOB. In addition, there is a cut-off after which the accessibility will be zero. The logsum approach assumes a higher disutility initially and a larger "tail", meaning that opportunities further away still have some effect on the accessibility. Another difference is that some kind of comfort parameter is implemented in Octavius by modelling that each component of the travel time by public transport are perceived differently. For example, a minute of waiting time is perceived as more severe than a minute on the train itself. In short, whilst the behaviour differs between the two approaches, they both comply with the four criteria as discussed in the framework. Furthermore, additional public transport services were provided to those who do not have a driver's license in the fifth scenario. With the proposed measure, those with no driver's license have the best accessibility by public transport. As a result, inequalities are reduced according to IKOB. Moreover, the accessibility by public transport of the targeted segment is improved so much in the logsum approach that inequalities have actually increased. Ultimately, the accessibility considering all modalities has become fairer in the logsum approach. In IKOB however, there is no significant impact of the measure on the total accessibility. This shows that IKOB assumes that the car and cycling are much more important than PT. The Octavius model assumes a more equal effect between the three.

The second component is the land-use one. At the start, the same input data regarding job opportunities has been used for both approaches. This concerns the number of jobs in each subdivided region in the Netherlands. Also, the way the data is applied in the model is fairly similar. Namely, the higher the number of jobs at a location becomes, the bigger the impact on accessibility. This has also been demonstrated in scenario four by adding 10,000 jobs to one zone. It was also found that this impact is strongest around the zone in which the zones were added and diminishes as distance increases. However, this is related to the transportation component, as jobs that can be reached with more travel resistance have a smaller impact on accessibility. Furthermore, the framework shows that both models do not consider competition, which has already been discussed in Section 7.3.

The next component is the individual one about which there are a number of conflicting views. First, only those who have a car and a driver's license can use the car in the Octavius model. On the contrary, each person can make use of the car modality because of the taxi and shared car assumption in IKOB. Essentially, two new motives are introduced by doing so. However, the costs of these two are a lot higher, making them not attractive alternatives. The impact of the assumption is therefore limited. In addition, it is assumed in the considered approaches that everybody can reach every job opportunity. This may not be realistic as certain education is often required. There are IKOB modules that consider this. However, since this is not included in Octavius, it was chosen not to apply it to keep the comparison between the two more similar. Besides, other limitations caused by the abilities of individuals are not considered in both. Another distinction between the two is how the cost component is related to individual and household characteristics. Population segments with different incomes experience costs differently in the IKOB approach. In this way, it is modelled that a person with a low income experiences a euro cost more severely relative to someone with a high income. Results from the first scenario show that increasing the cost of travelling will impact those with less income to a greater extent. In Octavius however, everyone perceives a euro of travel cost the same. The results from the first scenario therefore show that every person is impacted similarly when the cost of travelling is increased. This has also been proven mathematically in Appendix C.4. Several studies have shown that income is to some degree related to how costs are perceived. For instance, Fournier & Christofa (2021) found that the value of time of a 55-year-old is three times higher compared to an 18-year-old. The IKOB therefore incorporate the costs more appropriately. The question that remains is how accurate this approach is, as the exact parameters to do so are based on expert judgment. Lastly, the temporal component is not considered at all in both approaches, as stated in Section 7.3.

7.6 Investigating inequalities

This research aims not only to determine the appropriateness of the two approaches to analyse accessibility but also their ability to examine inequalities in the distribution of accessibility. This has first been accomplished by creating so-called Lorenz curves. These curves demonstrate a great difference between both approaches. That is, the IKOB predicts that inequalities are much higher compared to the logsum approach. The primary cause is that some people can use public transport and/or the car for ‘free’ in the IKOB approach whose accessibility is so much higher than those who cannot. Second, inequalities are further investigated by introducing the Gini coefficient and 10/40 index. A fairly similar study was conducted by Pritchard et al. (2019) who applied the potential accessibility measure in three areas including the Randstad in the Netherlands. Furthermore, the Gini coefficient, among others, was applied to determine inequality in accessibility. It was found in this study that the Gini for the accessibility by car in the Randstad is 0.09. This coefficient more closely matches with those predicted by the logsum one compared to IKOB. Further, it is found by Pritchard et al. that the Gini for public transportation is 0.35 which is more consistent with IKOB. Still, comparing results is complicated because the accessibility approach applied are substantially dissimilar. Furthermore, the Randstad has different characteristics to Zwolle. That is, a lot of cities in which many jobs are available are situated close to each other in the Randstad while Zwolle is a medium-sized city surrounded mainly by sparsely populated areas. Another similar research was performed by Lucas et al. (2016) who investigated the inequalities in accessibility to basic services such as bakers, drugstores, doctors and pharmacies. They used among others the potential accessibility to assess inequalities in three municipalities in the Netherlands. It was found that inequalities were the highest in Dongeradeel, which is a (former) rural municipality in the north of Friesland, with a Gini of 0.65. Inequalities were estimated less prevalent in The Hague and Delft with Gini’s of 0.27 and 0.13. Moreover, Neutens et al. (2010) applied the Gini coefficient to several people- and location-based measures to find inequalities in accessibility to government offices in the city of Ghent, Belgium. Neutens et al. (2010) conclude that people-based measures predict a more unequal distribution (0.63) compared to location-based measures (0.26). The same has thus not been found in this study as the coefficients are higher according to the IKOB approach compared to the logsum one. The reason is that the coefficients according to IKOB are heavily inflated because of the ‘free’ modalities, as touched upon before.

Next, five scenarios have been introduced and their effect on inequalities investigated. Table 10 discussed in Section 6.8 has shown that the Gini coefficients according to both accessibility approaches have not been altered that much by the considered scenarios. The largest found difference is a 0.06 reduction to the baseline situation. The 10/40 index shows larger differences. The first reason is that the Gini coefficient is particularly sensitive to the middle of a distribution. The created equity scenarios primarily cause differences in the bottom and top of the distribution. So, the Gini cannot capture the effects appropriately. Second, the Gini coefficient ranges from one to zero making numerical differences smaller. The 10/40 index finds the ratio between the accessibility of the 10% with the best accessibility combined compared to the 40% with the lowest accessibility combined. This index is therefore only sensitive to the bottom and top of the distribution. The 10/40 index would therefore be more appropriate for analyzing equity scenarios as it provides insight into the people who are the best and the worst of, who are especially relevant for equity studies. Still, the Gini coefficient still holds valuable information. The reason is that both measures capture a different part of the inequality distribution making them work together instead of having the same purpose. It is therefore valuable to present them both nonetheless.

8. Conclusions & Recommendations

Aggregated measures for the complete population are considered most of the time in Dutch transport policy (Hoen et al., 2019). As a result, differences between people may remain unnoticed. Introduced policy measures could thus negatively impact certain groups or increase inequality. Moreover, it is more difficult to predict whether the proposed measure will benefit the targeted population segment. To combat this, a different approach is proposed. In this approach, mobility should not be seen as the objective in itself, but as a way for *everyone* to reach sufficient destinations in a reasonable time (Hoen et al., 2019). In the Netherlands, accessibility analyses are often founded on aggregated transport demand models. Such models have several limitations causing that the demand to examine differences in accessibility cannot be adequately addressed. To respond to the emerging demand, the "Integrale kijk op bereikbaarheid", or IKOB (Voerknecht, 2021) has been devised. Moreover, the microscopic strategic transport demand model Octavius has just been completed by Goudappel. The model can be applied to estimate traffic volumes in the transport network, among other purposes. There is also the possibility to calculate accessibility by applying data from Octavius. In this way, the differences between various segments of the population are incorporated from the start. The two divergent approaches for calculating accessibility are implemented in this research. For the IKOB approach, an existing iteration of the model is considered. In addition, a method to calculate accessibility based on Octavius has been created, described and implemented in this study.

The IKOB approach thus connects to current demand and is therefore an upcoming way of determining accessibility in the Netherlands. Its implementation is also encouraged by politicians. For instance, a resolution was passed in Dutch parliament that called for current policy to be adapted to IKOB's insights[5]. There are however a few aspects to consider. First, how the variable 'free' car is modelled is questionable. The first reason is that the segments "have car" and "free car" are closer to each other in reality than modelled due to factors such as "bijtelling", monthly fees and travel reimbursements. Second, IKOB predicts that the accessibility of someone with a 'free' car and/or 'free' public transport is up to nine times higher compared to those who cannot use it for free. Such major differences are not realistic. Nevertheless, the IKOB itself and most steps within it are logical and understandable. Moreover, proper insights can be created to demonstrate the general effect of a particular measure as concluded with the assessment framework created in this study. For instance, when will accessibility increase, when does it decrease, when are inequalities increased and which segment of the population will be more affected. Whether the exact quantitative results from the model are accurate is more questionable. The primary reason is that several parameters to calculate the potential accessibility such as the TVOM[6] and to shape the decay curves are (partly) estimated using expert judgment. Furthermore, all kinds of datasets are combined which may cause inconsistency. There will be uncertainty in the results caused by the stated procedures. In addition, because accessibility is not an observable entity, it is difficult to validate what the accuracy of the model will be. The IKOB approach is therefore an appropriate method to get an *initial* estimation of what a policy measure will do. However, to base actual policy decisions on IKOB does not seem appropriate. It would therefore be recommended to primarily use the IKOB in the initial research phase of a measure. After that, more research on the precise effects should be conducted using other approaches and models.

Furthermore, an approach to calculate accessibility with the logsum measure is introduced in this research. Many other approaches to do so have been performed in the past (E.g., Beria et al., 2018; Dixit & Sivakumar, 2020; Tillema et al., 2011). A separate discrete choice model is created in each of these studies. An advantage of the logsum approach is precisely that it can be applied based on existing

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[5] Kamerstukken II 2022/23, 35925, nr. 59, p. 1.

[6] Time value of money. Represents how much minutes each euro is worth for a person. Inverted value of time.

transport models that employ discrete choice models. This has been accomplished in this research by applying data from the microscopic strategic transport demand model Octavius. Because Octavius is a highly detailed model, this study contributes to the current literature by introducing one of the most detailed accessibility analyses based on the logsum approach. Still, the Octavius model is foremost an approach to estimate traffic intensities as stated before. It is found in this study that the information from the model study can be applied to calculate accessibility. This provides the opportunity to quickly prepare an accessibility study for regions for which an Octavius model is already provided. For example, there is no further need to gather additional data sources and estimate parameters in another model. Being able to collectively offer a traffic model and an accessibility study together may also increase the market opportunity of the Octavius model. The downside is that the accessibility approach cannot be conducted for regions for which an Octavius application has not yet been established.

In addition, the distinction to IKOB is that each behavioural parameter in Octavius is estimated from statistical information about the daily mobility of the Dutch population. So, no expert judgment is performed. It is therefore expected that the calculated accessibilities will be more reliable. There are however a few elements to consider about the logsum approach based on Octavius. Firstly, it has been concluded that the cost of travelling is perceived the same by every agent in Octavius. The reason is that the travel cost is a separate part of the utility functions. It is therefore recommended to implement the travel costs in the same way in these functions as the travel time. That is, by connecting it to several individual parameters. The logit models should thereafter be re-estimated to identify if one or more parameters have a statistically significant effect on how the costs are perceived. Secondly, the model predicts fewer inequalities in accessibility compared to the IKOB approach. The considered scenarios in this study have subsequently a small influence on inequalities according to the logsum approach. Because of these small deviations, it is difficult to confidently conclude whether a situation has in fact improved or not. The approach is therefore less appropriate for investigating inequalities. Thirdly, the logsum measure by itself is more complicated compared to the potential accessibility one. The reasons are that results are only meaningful in comparison to other logsums, that it is not possible to compare values from different specifications of the same model or other discrete choice models and that it considers a logarithm by which the effect of a measure depends on the original accessibility.

Moreover, the IKOB model is specially created to investigate accessibility. It therefore incorporates more aspects of accessibility compared to the logsum approach. For instance, there are modules to incorporate competition as well as a method to relate how many jobs are available in each region for each income group. A method to calculate competition for the logsum approach was out of the scope for this research. Still, it is worthwhile to investigate if there is an opportunity to do so with the logsum measure in the future. Lastly, both models do not consider the effect of remote working on accessibility. They therefore assume an outdated worldview which means they cannot fully reflect current behavior. It is therefore worthwhile for the creators of both approaches to investigate creating an online component. In conclusion, a valuable first step is taken to establish a new accessibility approach based on the logsum metric in this study that can contribute to current and future demand in the Netherlands. Following this, the approach should be further developed to make it more appropriate.

Appendix A: Discrete choice models

In life, every person is faced with a situation in which they must choose between several finite alternatives. For instance, am I going to take the car, train, or bicycle to work? The alternative whichever seems most advantageous is chosen. In other words, the alternative that provides the highest utility in a choice set is selected. The decision to choose between alternatives with a certain utility could be modelled through discrete choice models. The theory discussed in this section is based on Train (2001) and Ben-Akiva & Lerman (1985).

Appendix A.1 The logit model

For the application of this methodological framework, several assumptions should be made. First, the alternatives must be mutually exclusive from the decision maker's perspective. This means that choosing one alternative automatically implies that the others are not chosen. So, the decision maker only selects one alternative. Second, the choice set consists of all alternatives that are feasible and known to the decision maker. The choice set should be exhaustive, meaning that all possible alternatives are considered. Third, the number of alternatives must be finite. This assumption distinguishes discrete choice models from regression models. Fourth, discrete choice models are normally derived by assuming so-called "utility-maximizing behaviour" by decision-makers. With this, it is implied that decision-makers assess alternatives with the aim of attaining the highest possible level of satisfaction from their financial means.

The reasons and arguments for choosing between alternatives are known to the decision-maker and can be indicated by "U_{it}" . These are however unknown and cannot be observed by a researcher. Instead, this researcher may observe some characteristics of the alternatives faced by the decision maker (x_{nj}) and characteristics of the decision maker itself (s_t). These characteristics are used to estimate the representative utility through a vector of attribute values: $V_{it} = V(x_{nj}, s_t)$. There will be a difference between the actual utility U_{it} and representative utility V_{it}, called the error ε_{it}. In other words:

$$U_{it} = V_{it} + \varepsilon_{it} \tag{25}$$

The researcher does not know ε_{it} and considers it random. Multiple theoretical models could be applied, based on how the error term is handled. The most common one is the Logit, for which it is assumed that each ε_{it} is an independently, identically distributed extreme value. Or ε_{it} is characterized by the Gumbel distribution. This implies that the unobserved portion of utility is unrelated to the alternatives. In doing so, it is assumed that the representative utility V_{it} has been defined sufficiently enough. Next, utility does not have an absolute zero and is therefore interval scaled. This will have consequences when calculations are going to be made.

A decision maker t chooses alternative i over j if $U_{it} > U_{jt}$. Using Equation 25, this can be transformed into: $V_{it} + \varepsilon_{it} > V_{jt} + \varepsilon_{jt}$, or $\varepsilon_{jt} - \varepsilon_{it} < V_{it} - V_{jt}$. Whether this is the case depends on the random error terms. Therefore, which alternative is chosen is inherently probabilistic.

Using the fact that the error terms are characterized by the Gumbel distribution, the probability that alternative i is chosen from a choice set consisting of n alternatives is calculated by Equation 26.

$$P_{it} = \frac{e^{V_{it}}}{\sum_{j=1}^{n} e^{V_{jt}}} \tag{26}$$

EXAMPLE

Consider a situation in which a decision maker should decide between taking the bus (U_{bus}) or car (U_{car}) to work. The representative utility of taking the bus (V_{bus}) is perceived to be equal to 3 and for taking the car (V_{car}) equal to 4. This means that taking the car is the most beneficial alternative only when $\varepsilon_{car} - \varepsilon_{it}$ is bigger than -1, as shown in the equation below.

$$V_{car} + \varepsilon_{car} > V_{bus} + \varepsilon_{bus} \quad to \quad \varepsilon_{car} - \varepsilon_{bus} > V_{bus} - V_{car} \quad to \quad \varepsilon_{car} - \varepsilon_{bus} > -1$$

Whether this is the case depends on the randomly generated error terms. Figure 2 shows the joint probability distribution of ε_{car} and ε_{bus}. The individual distributions are shown on the sides by the purple and blue curves, the joint distribution is visualized by the level curves with yellow, orange and red. The green line indicates where $\varepsilon_{car} - \varepsilon_{bus} = -1$ and splits the volume into two. The volume above the line $A(V_{bus})$ represents the likelihood that alternative V_{bus} is chosen and below the line $A(V_{car})$ that V_{car} is chosen. The probability that an alternative is chosen is found by dividing $A(V_{car})$ or $A(V_{bus})$ by the total volume.

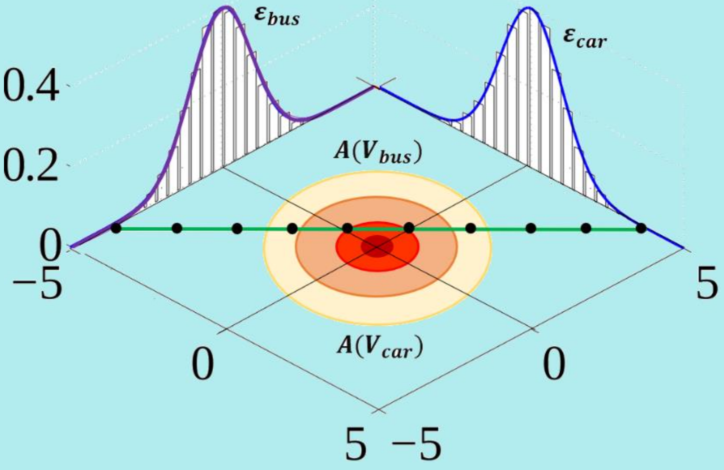


Figure 65: The joint probability function for two error terms

In this case, the probability that taking the car is the best alternative is 73%. The same principles as discussed could be performed for decision sets with more than two alternatives. This could however not be visualized in a 3D space.

The absolute levels of utility are irrelevant in a logit model. Instead, the probability that a certain alternative is chosen only depends on the relative differences to the others. This means that the same value could be added to each utility function, or each utility multiplied by a certain constant without effect. The implication of this is that only parameters can be included that reflect differences between alternatives. Moreover, the absolute values of certain parameters cannot be estimated. One parameter is instead normalized to zero and only the differences to it are included. This holds for example for sociodemographic variables, as the attributes of the decision-maker do not change. They can however create differences in utility over alternatives. Next, the average effect on the utility of unincluded variables is often considered by alternative-specific constants. By doing so, the mean of the error term is zero. Again, only the differences between alterative-specific constants are important due to the reasons discussed before.

The relation between the probability from the logit model and the representative utility is shown in Figure 66. It could be observed that it follows an S-shape. This implies that an increase in utility has the greatest effect when the probability is close to 0.5. Conversely, the same increase in utility will have a smaller effect when differences are higher. In this way, it can be argued that it is more worthwhile to improve the train service within cities compared to the countryside.

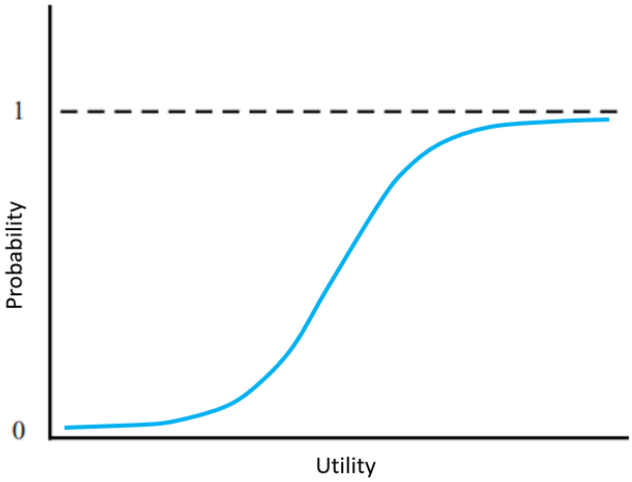


Figure 66: The logit curve (Train, 2001)

Next, the odds of choosing alternative i over j $(e^{V_{it}}/e^{V_{jt}})$ in a logit model does not depend on other alternatives. In other words, it exhibits independence from irrelevant alternatives (IIA). This assumption may not be accurate in some circumstances. For instance, in a situation in which a new transit mode is created that is very similar to a train service. The probability of choosing a train will likely be reduced by a greater proportion compared to the car. So, the ratio between the odds of choosing the car and train does not remain constant. The IIA assumption is breached. In these cases, it may be convenient to introduce a different model. For instance, generalized extreme value models (GEV). GEV models constitute a large class of models with varying patterns. The unifying attribute is that the unobserved patterns are jointly distributed as a generalized extreme value allowing correlation between alternatives. A Logit model is a type of GEV in which no correlation occurs between any alternatives.

Appendix A.2 The Nested logit

A different kind of GEV model is the nested logit, which is appropriate when the set of alternatives can be portioned into subsets, represented by different levels. In the decision to choose a certain alternative in a nested logit, two properties should hold. First, IIA should hold in the same nest. So, each nest is equal to a Logit. Second, IIA is not required for any two alternatives from different nests. The utility is then modelled as follows:

$$U_{itd} = V_{it} + V_{id} + V_{itd} + \varepsilon_{it} + \varepsilon_{id} + \varepsilon_{dm} \tag{30}$$

The error terms ε_{it} and ε_{id} represent the unobserved components in the first and second level, respectively. The term ε_{dm} is the remaining unobserved component of the total utility. To be able to create a nested logit, it should be assumed that either ε_{it} or ε_{it} is equal to 0. Calculating the probability that an alternative is chosen in one go may be complicated. It is more convenient to write it as a product of x standard logit probabilities where x is the number of levels. The equation that finds the probability that alternative i from nest B_k is chosen is a two-level nested logit is presented in Equation 31. The upper level is represented by the marginal probability P_{nB_k} of choosing an alternative in nest

B_k. The lower model is represented by the conditional probability $P_{it|\,B_k}$ that alternative i is selected by person t given that nest B_k is chosen.

$$P_{it} = P_{it|\,B_k} * P_{nB_k} \tag{31}$$

The probability of choosing nest B_k depends on the expected maximum utility that a person receives from the alternatives in that nest. Therefore, the upper and lower models should be linked in some way. This is achieved by including some parameter I_{B_k}. It attempts to describe the utility of the best alternative in a subset as a summary of this subset to the decision maker. It has been defined in such a way that it can be inserted into the utility function in the upper logit model.

Appendix A.3 The logsum

Next, an individual chooses the alternative from a choice set that maximizes their utility (U_{it}). Which alternative maximizes the utility and to what extent is probabilistic, as the utility of each alternative cannot be determined with certainty, as discussed in Section A.2. In other words, a decision is made so that $Max_{i\in C_t}U_{it}$. It may occur that alternative j in choice set C_t maximizes utility with a value of 5 or that alternative i does so with a value of 4.5. A deterministic answer is found by calculating the expected value of $Max_{i\in C_t}U_{it}$. This measure represents the average value of the alternative with the highest utility from the choice set. The discussed process is visualised in Figure 67. The utilities of taking the bike, train and car to some location in one hypothetical situation are indicated by the blue dots. The individual chooses the alternative that has the greatest utility. In this case, taking the car. As discussed, the values and with it the location of these dots on the x axis is probabilistic. The probability of each location is characterized by the Gumbel distribution. The one for the bicycle is presented in blue for demonstration purposes. The maximum value of the three alternatives is therefore also probabilistic and follows the Gumbel distribution as shown in red. The expected value of this distribution is represented by the dashed black line.

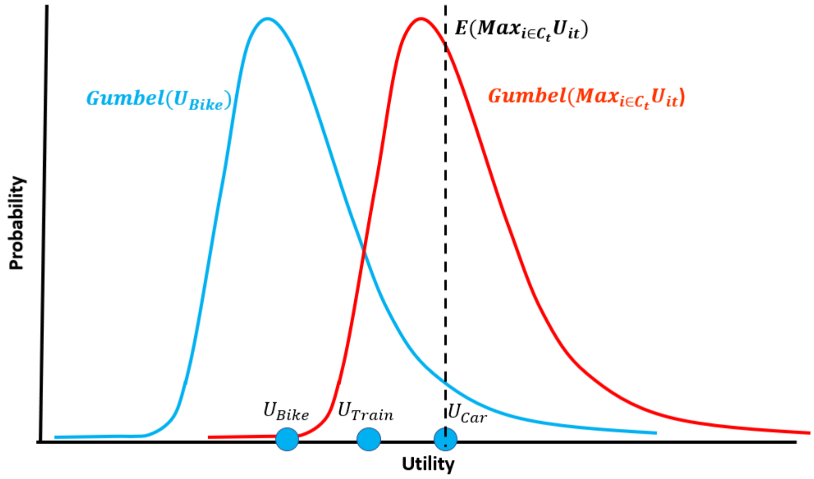


Figure 67: Representation of the logsum

With this in mind, an equation for $E(Max_{i\in C_t}U_{it})$ can be formulated. First, a Gumbel distribution has a location parameter η and scale parameter μ. In short: $Gumbel(\eta, \mu)$. The maximum of n Gumbel distributed values e_i is characterized as follows:

$$Gumbel\left(\frac{1}{u}\ln\left(\sum_{j\in B_k} e^{u*V_{jt}}\right), u\right) \tag{32}$$

Lastly, the expected value of this distribution is calculated by using the next equation:

$$E(Max_{i\in C_t}U_{it}) = \frac{1}{\mu}\ln\left(\sum\nolimits_{j\in B_k} e^{\mu * V_{jt}}\right) + C \tag{33}$$

The resulting expression is often referred to as the "logsum". It has been defined most of the time in such a way that $u = 1$.

The alternative with the highest representative utility (V_{it}) will have the strongest effect on the logsum because it is most likely to be the best alternative. On the contrary, a change in the utility of taking the bike in the example will not have a great impact, as it has the lowest representative utility. Even more, the effect of taking the bike on the logsum is neglectable if the difference to the best alternative is big enough. Next, C is an unknown constant, as it is only possible to measure relative differences in utility and not absolute ones, as discussed in Section A.1. In addition, adding a random constant to all utility functions does not affect the choice probabilities. However, it does affect the logsum value as shown in the example below.

EXAMPLE

First, let's add a constant C to the utility function for every alternative, creating:

$$U_{it} = V_{it} + \varepsilon_{it} + C \tag{34}$$

The logsum is then defined as follows:

$$E(Max_{i\in C_t}U_{it}) = \ln\left(\sum\nolimits_{j\in B_k} e^{V_{jt}+c}\right) \tag{35}$$

Considering that $e^{x+y} = e^x * e^y$, this can be rewritten as:

$$= \ln\left(\sum\nolimits_{j\in B_k} e^{V_{jt}} * e^c\right) = \ln\left(e^c \sum\nolimits_{j\in B_k} e^{V_{jt}}\right) \tag{36}$$

Lastly, by taking $\ln(x * y) = \ln(x) + \ln(y)$ and $\ln(e^c) = c$, the result is:

$$= \ln\left(\sum\nolimits_{j\in B_k} e^{V_{jt}}\right) + \ln(e^c) = \ln\left(\sum\nolimits_{j\in B_k} e^{V_{jt}}\right) + C \tag{37}$$

It can be concluded that adding a parameter C to the utility of every alternative will increase the logsum by the same amount. Because of this, one must be careful when processing the resulting values from the logsum. For instance, it is not appropriate to directly compare logsums as shown in the equation below. The ratio between the logsums of any two random persons x and y is much different when C is 1 compared to 1000. It is also not possible to compare different model specifications. The measure is only meaningful if a benchmark has been established.

$$\frac{\ln_x\left(\sum_{j\in B_k} e^{V_{jt}}\right) + C}{\ln_y\left(\sum_{j\in B_k} e^{V_{jt}}\right) + C} \tag{38}$$

Appendix B Results about the baseline situation.

Appendix B.1. Scatterplot about ranked accessibility according to IKOB and the logsum approach.

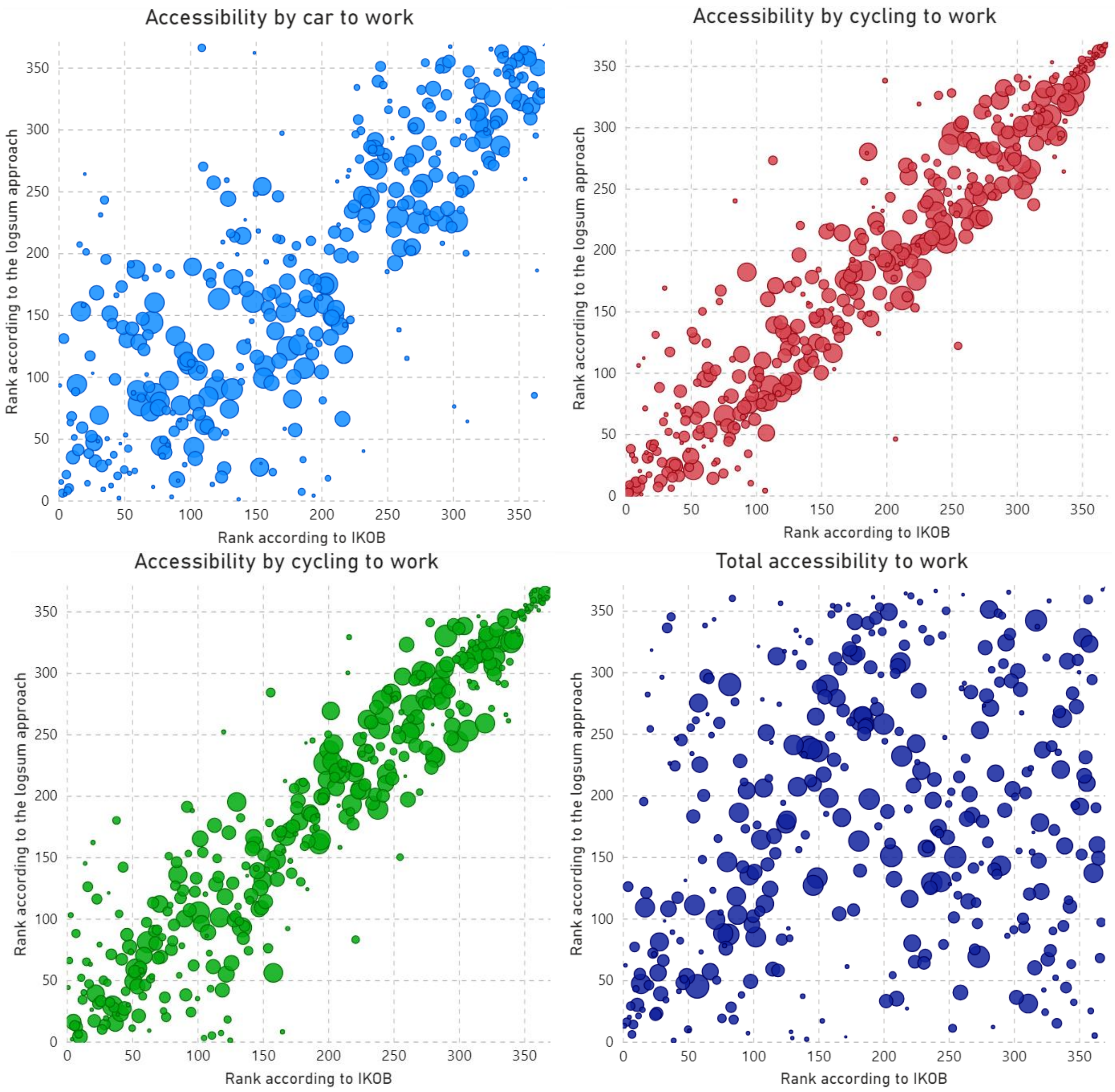
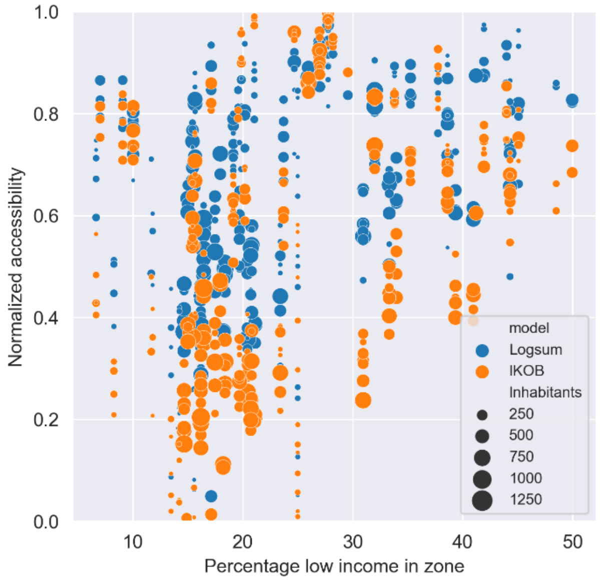


Figure 68: Scatterplots showing the relationships between ranked zonal accessibility according to IKOB and the logsum approach.

The visualized scatterplots show the correlation between the ranking of the average zonal accessibility to work according to the IKOB and Logsum approaches. Each zone is represented by a dot. The larger the dot, the more inhabitants in the represented zone. The figure in the top left shows the accessibility by car to work, the top right the accessibility by public transport to work and the bottom left the accessibility by cycling to work. Lastly, the figure in the bottom right shows the accessibility to work considering all modalities.

Appendix B.2: Relation between income categories and accessibility by PT



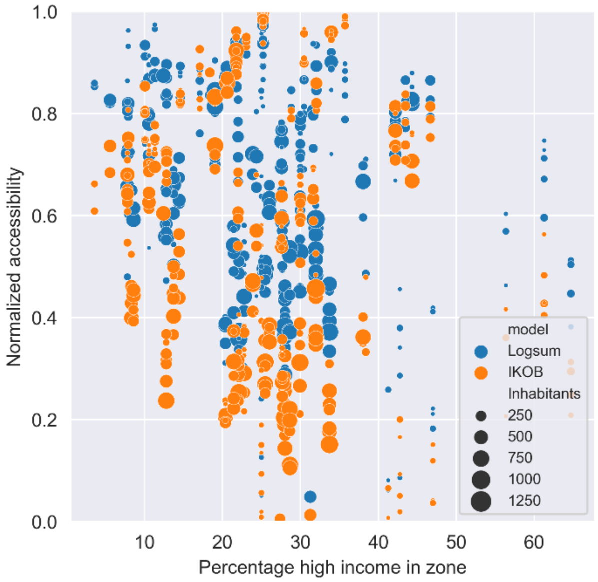


Figure 70: Relation between low income and accessibility by PT

Figure 69: Relation between high income and accessibility by PT

Appendix B.3 The advantage of having a free car.

People who can use the car for ‘free’ have a big advantage over those who cannot do so according to IKOB. Take for example the city of Utrecht where around 250,000 jobs are available. The travel time to Utrecht is 52 minutes over 91 kilometres. Someone who has a ‘free’ car will have a generalized travel time of 52. According to the decay curve, this corresponds with a coefficient of 0.5. This person will thus have accessibility of around 125,000 to Utrecht. Next, the generalized travel time of someone with a high income who does not have a car for ‘free’ is 110[7]. With the decay curve, 110 results in a weight of around 0.001. In conclusion, Figure 71 illustrates how the accessibility of a person who has access to a ‘free’ car and a person with a high income but cannot use the car for ‘free’ are built up. The three northern provinces are Friesland, Groningen and Drenthe, the western ones are Utrecht, North- and South Holland and the southern ones are Zeeland, Noord-Brabant and Limburg. The figure shows that the accessibility of the person with a high income depends more on opportunities in the study area itself and the rest of the province of Overijssel, which are relatively close by. In addition, this person is not able to reach any opportunities in the west of the country while the person with the ‘free’ car does so, as explained before.

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[7] See Equation 20: generalized travel time = travel time + TVOM*distance*cost per distance. In this case: 52+4*90.6*0.16 = 110.

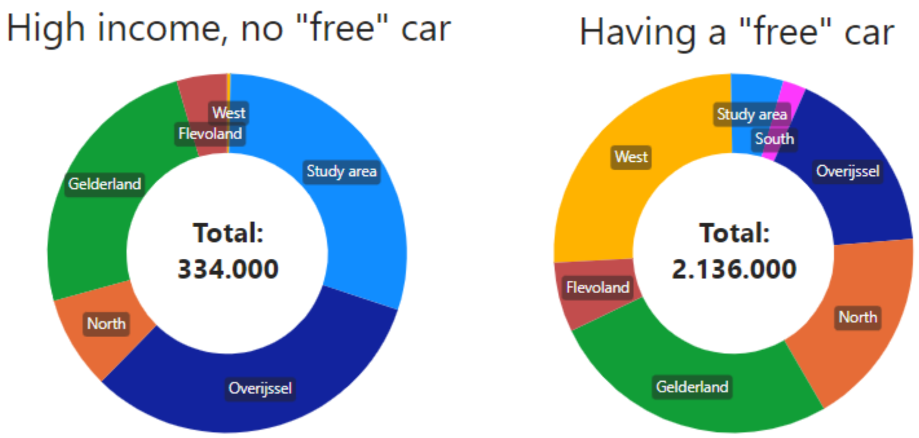

Figure 71: Breakdown of the accessibility of two segments in IKOB

Appendix B.4. Segments in the logsum approach and accessibility

The average total accessibility in relation to how many cars there are in a household is visualized in Figure 73. It can be observed that the more cars people have, the higher the accessibility becomes. Although, there is also a lot of variety within each category. Next, Figure 72 shows the total accessibility and distribution therein for each gender. It can be seen that the accessibility of males is fractionally higher compared to females whilst the variations within the categories are high among both segments.

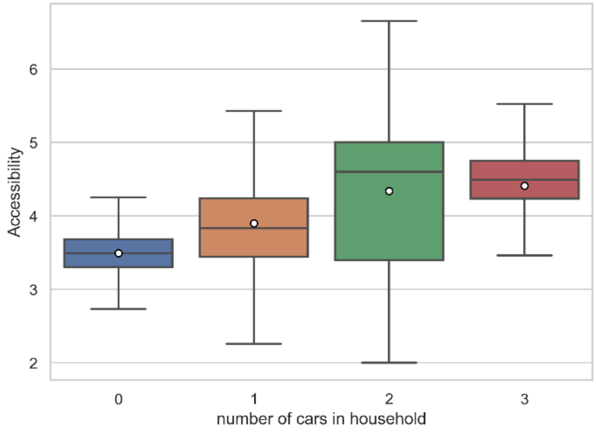

Figure 73: Total accessibility and number of cars in household

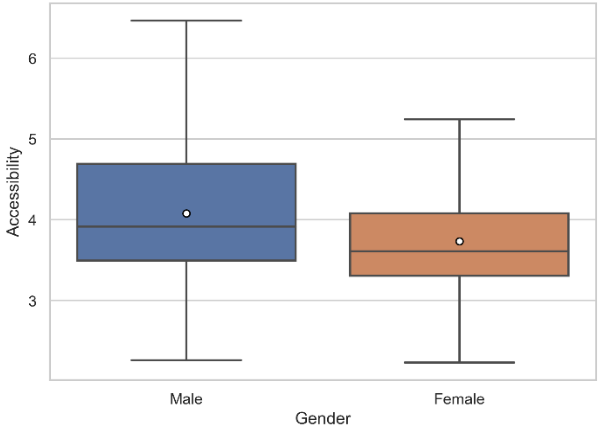

Figure 72: Total accessibility across gender

Appendix C Travel costs and inequalities

To test the effect of travel costs on (inequalities in) accessibility, it has been decided to increase travel costs for using the car by 30% in the first scenario. This has been implemented by changing the input data. The stated scenario is also relevant in the Dutch context, as it is often proposed to make driving a car more expensive as a measure to combat climate change (de Rooy, 2023). The two accessibility approaches have been re-applied using the new input data. The subsequent results will be elaborated upon in this section.

Appendix C.1 Zonal accessibility

First of all, the average accessibility in each zone has been calculated in the first scenario. The normalised accessibilities according to the IKOB approach have been presented on the left side of Figure 74. Then, it has been calculated how the accessibilities have changed compared to the baseline situation. The right side of Figure 74 shows in which zones the accessibility changed relatively the most and the least. First, it could be observed that the zones in which the accessibility has decreased the most are mostly located at the borders and in an area in the north above the highway. The areas in which it has decreased the least are clustered in the northwest and around the city centre. The one in the northwest stands out, which is the Stadshagen neighbourhood. Mostly middle-income families live in this residential area, which have a relatively high accessibility in the baseline situation.

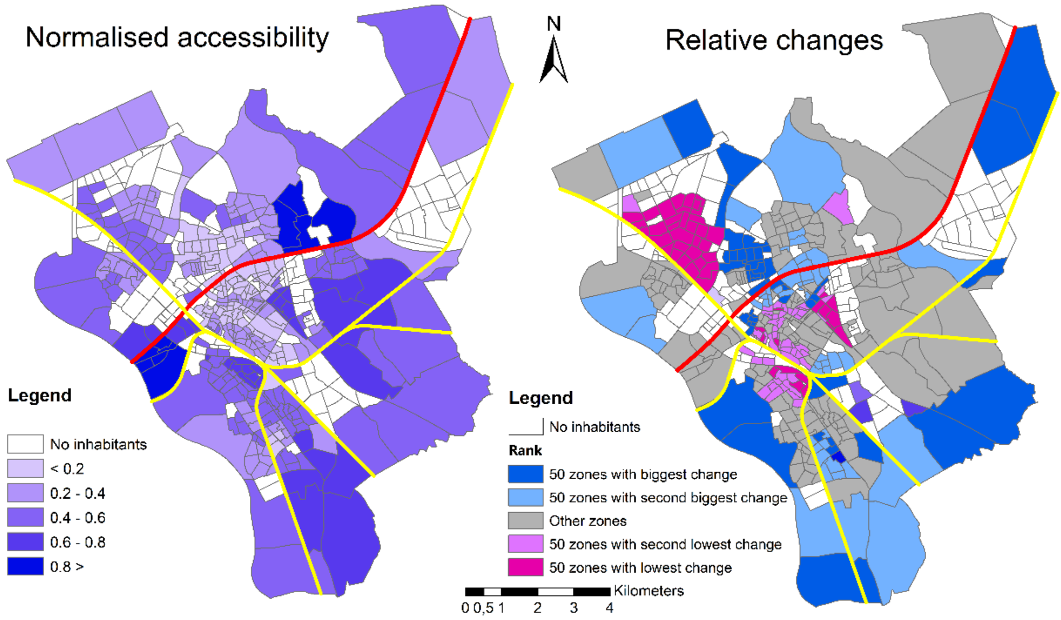

Figure 74: Accessibility by car in the first scenario according to IKOB

Next, the same figures have been created for the logsum approach, as shown in Figure 75. The figure on the right shows that accessibility has decreased the most at the borders of the study area. On the contrary, the accessibility has decreased relatively speaking the least in and around the city centre. The discussed pattern seems similar to the average car ownership, presented in Figure 13. This is caused by the fact that the accessibility by car is calculated based on all people in a zone. Thus, also those who do not have a car, which logically have an accessibility of zero. This group will not be affected by the measure as they do not have a car to begin with. The larger this share of people in a zone, the fewer people are affected which reduces the overall found change in that zone.

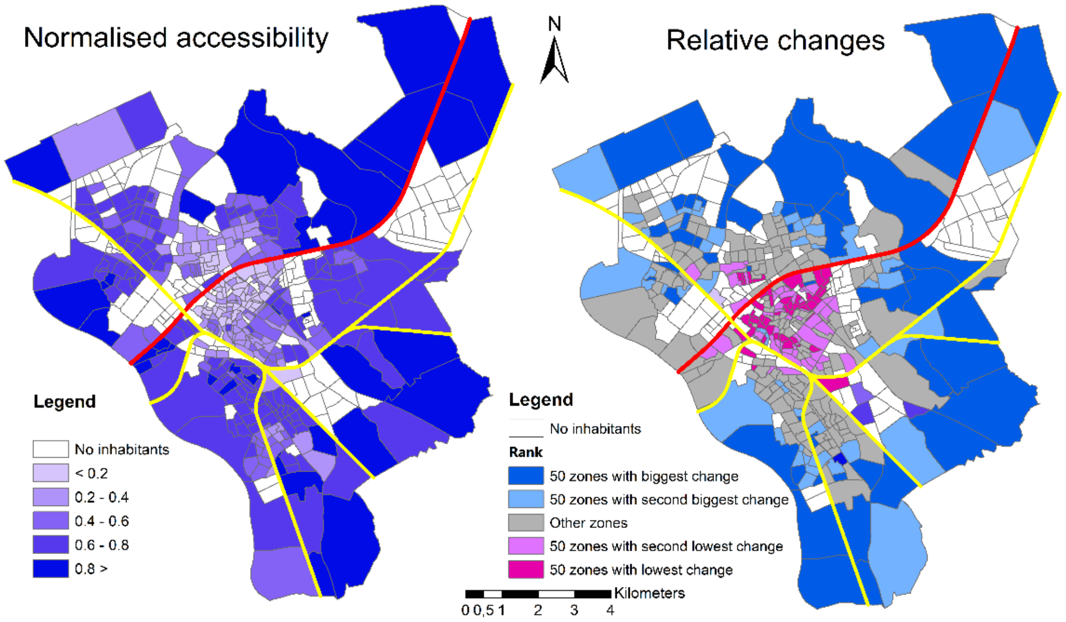

Figure 75: Accessibility by car in the first scenario according to the logsum approach

Appendix C.2 Accessibility of the initial segments.

Further, Figure 77 shows how the accessibility by car of the four initial segments are impacted by the measure according to the IKOB approach. Figure 76 shows the same information, only the range of the y axis has been altered. First, the accessibility of people who have a free car has not been impacted by the measure. This is logical, as the cost component is ignored in the travel impedance function for this segment. The people represented by this segment will therefore not be affected by increasing the cost of travelling. In contrast, the accessibility of people who do have to pay for their car has been reduced by 14% on average. With this, it can be stated that the advantage of people who can use the car for free has increased even further compared to the other segments.

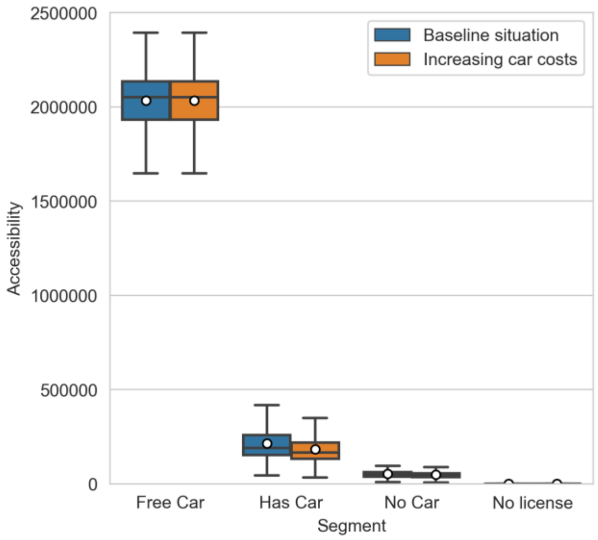

Figure 77: The accessibility by across segments according to IKOB in the first scenario.

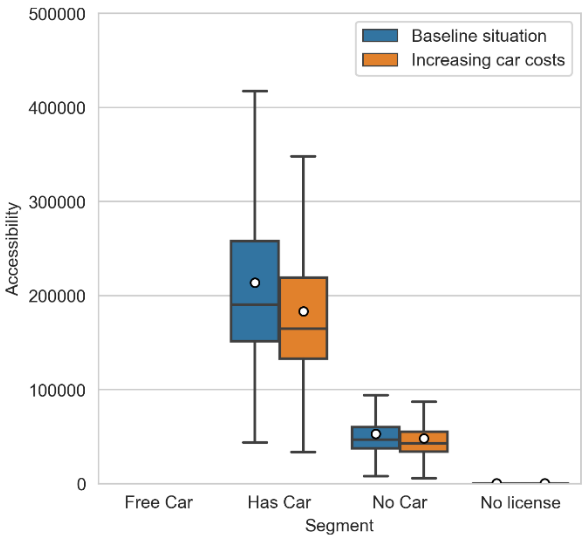

Figure 76: Figure 77, but with an altered y-axis

Appendix C.3 Accessibility of those who do have a car but not for ‘free’.

It was found that the high-income segment is relatively the most impacted (-15.6%) in the first scenario. On the other hand, the accessibility of the low (-11.3%) and medium-low (-12.6%) segments declined comparatively less rapidly. This is unanticipated, as the TVOM factor ensures that segments with a lower income experience the costs of travelling more harshly. To find a reason for the unanticipated results, we must look at the specific characteristics of the study area. Figure 78 shows the weights from the travel impedance function to which the number of jobs is weighted in the potential accessibility measure. The weights of the low and high-income groups for travelling to four locations in the baseline, as well as the first scenario are shown. It could be observed that the weight for “high” is for each destination bigger compared to “low”. Next, the figure shows how the weights are affected by increasing travel costs. It could be noted that the weight for someone with a low income is reduced more substantially compared to one with a high income for every destination. This shows that for travelling to each separate location, the hypothesis that the accessibility of the less well-off is impacted more harshly does hold. The same is thus not the case when considering the complete study area. It was explained in Section 6.1.4 that a large part of the accessibility of people with a higher income is defined by the opportunities in cities outside the municipality of Zwolle. A small difference in weight will therefore have a great impact on the number of overall opportunities this group could reach. People with a "low" or "medium low" level are mostly unable to reach these opportunities in the first place, so the discussed effect does not impact them. This causes differences between people with low and high incomes to become smaller.

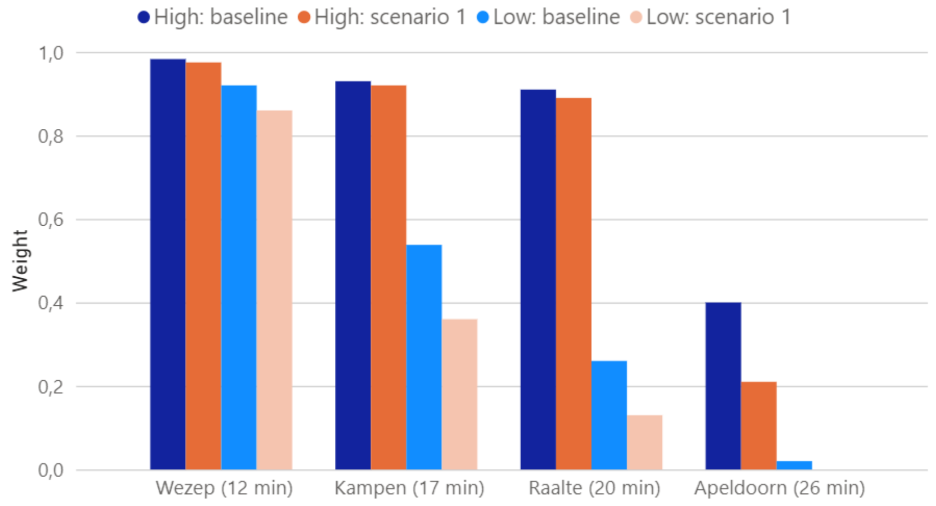

Figure 78: Differences in weights according to IKOB in the first scenario compared to the baseline.

Appendix C.4 Mathematical proof that every person is affected the same.

First of all, the logsum of agent p in home location h travelling with modality m for motive c is defined as:

$$A_{p,h,m,c} = E\left(Max_{j\in C_{sa}} U_{p,m,c,i\,|h,j}\right) = \ln\left(\sum_{i=1}^{n} e^{V_{p,m,c,i\,|h,j}}\right) \tag{40}$$

$V_{p,m,c,i\,|h,j}$ is the systematic utility as calculated with Equation 18 whilst $U_{p,m,c,i\,|h,j}$ represents the actual utility. n is the number of zones in the considered study area C_{sa}.

The utility function for the car in the standard situation in Octavius from Equation 18 is abstractly shown below. In this equation, β is a parameter, c the travel cost per kilometre and x the distance between zone j and t.

$$V_{p,m,c,i\,|h,j} = \beta \ln\left(c * x_{jt}\right) + rest \tag{41}$$

Combining Equations 40 and 41 results in:

$$E\left(Max_{j \in C_{sa}} U_{p,m,c,i\,|h,j,Baseline}\right) = \ln\left(\sum_{i=1}^{n} e^{\beta \ln\left(c * x_{jt}\right) + rest}\right) + C \tag{42}$$

The utility function when increasing the cost by 30% becomes:

$$V_{p,m,c,i\,|h,j,scenario\ 1} = \beta \ln\left(c * x_{jt} * 1.3\right) + rest \tag{43}$$

Combining Equations 40 and 42 results in:

$$E\left(Max_{j \in C_{sa}} U_{p,m,c,i\,|h,j,scenario1}\right) = \ln\left(\sum_{i=1}^{n} e^{\beta \ln\left(c * x_{jt} * 1.3\right) + rest}\right) + C \tag{44}$$

Considering that $\beta \ln(a * d) = \beta \ln(a) + \beta \ln(d)$ results in:

$$= \ln\left(\sum_{i=1}^{n} e^{\beta \ln(1.3) + \beta \ln\left(x_{jt} * c\right) + rest}\right) + C \tag{45}$$

Considering that $e^{a+b} = e^{a} * e^{b}$:

$$= \ln\left(\sum_{i=1}^{n} e^{\beta \ln(1.3)} * e^{\beta \ln\left(x_{jt} * c\right) + rest}\right) + C \tag{46}$$

Next, $e^{\beta \ln(1.3)}$ is a number and is the same for travelling to each location n and can therefore be taken out of the sum. This results in:

$$= \ln\left(e^{\beta \ln(1.3)} \sum_{i=1}^{n} e^{\beta \ln\left(x_{jt} * c\right) + rest}\right) + C \tag{47}$$

Further, considering that $\ln(a * d) = \ln(a) + \ln(d)$ gives:

$$= \ln\left(e^{\beta \ln(1.3)}\right) + \ln\left(\sum_{i=1}^{n} e^{\beta \ln\left(x_{jt} * c\right) + rest}\right) + C \tag{48}$$

$\ln\left(e^{\beta \ln(1.3)}\right) \approx -0.097$. Therefore:

$$= \ln\left(\sum_{i=1}^{n} e^{\beta \ln\left(x_{jt} * c\right) + rest}\right) + C - 0.097 \tag{49}$$

It could be observed that $\ln\left(\sum_{j \in B_k} e^{\beta \ln\left(x_{jt} * c\right) + rest}\right)$ in Equation 49 is the same as the logsum in the baseline situation as shown in Equation 42. The only difference is thus the -0.097 compared to the baseline situation. As a result, every person will have an accessibility of -0.097 less when increasing the cost of using the car by 30%. Since the logsum is a relative value, only differences between segments are important. Increasing the logsum of every person in the same way will not influence the results.

Appendix D: Accessibility and closing roads.

In the second scenario, two important bridges to cross the river IJssel have been closed. Consequently, the river becomes a barrier in the west of the municipality. This results in a significant increase in travel times to locations from the study area to the west and southwest of the country. For example, travel time to cities such as Harderwijk, Amersfoort, Utrecht, Arnhem and Apeldoorn increased between 12 and 20 minutes from the study area. The travel times to the north and east have stayed the same. The resulting effects on accessibility have been calculated with both approaches.

All the results from this scenario are presented in the main report.

Appendix E: Accessibility and reducing car ownership.

In the third scenario, car ownership in the study area has been reduced by 30%. Consequently, fewer people are able to make use of the car modality, which is the most important modality in relation to accessibility. Some results will be elaborated upon in this section.

Appendix E.1 Zonal accessibility

Next, the differences in accessibility between the baseline situation and the third scenario are shown in Figure 79. The figure shows that the accessibility by car will decrease in each zone where people live according to the logsum approach. The reason is that fewer people will have a car because of the changed input data. This increases the number of agents who have an accessibility of zero bringing down the average. Figure 79 also shows that the IKOB approach predicts that accessibility decreases almost in every zone. However, there are a few zones where people do live where this is not happening. These zones are distinctly marked with a purple colour. To find the cause of this, it is required to explain some specific parts of the IKOB model.

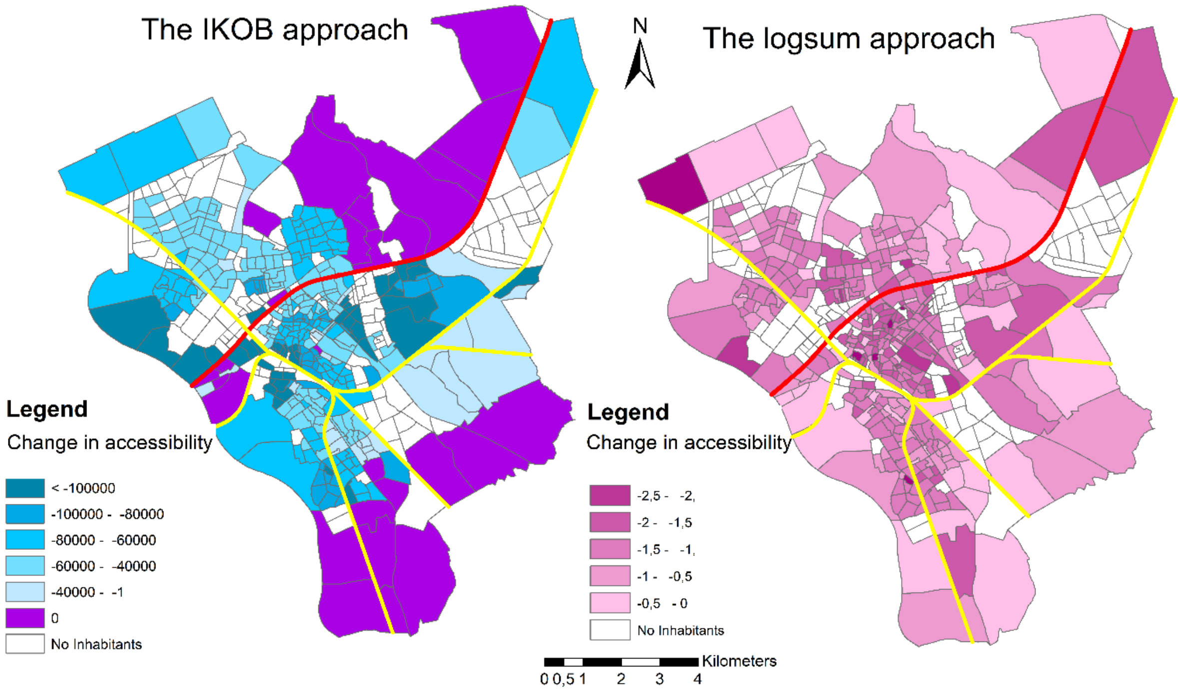

Figure 79: Changes in accessibility in the third scenario compared to the baseline situation.

The part this concerns is the segmentation step. In this step, the population in a zone is firstly divided into three groups; those who have a car, those who do not have a car but have a driver's license and those who have neither. The sizes of the three groups are initially estimated based on the degree of urban density and income distribution in that zone. The found results can subsequently be altered using data from the CBS. This is firstly achieved by comparing the estimated results about how many people have a car to data from the CBS. The contradiction is that in IKOB, car ownership is determined per person whilst the used data from the CBS deals with car ownership per household. To use it, it is assumed[8] that when the car ownership in a zone is less than one car/household, households who have more than one car are not present there. This assumption will be elaborated upon at a later stage in this section. Next, car ownership according to the CBS is directly adopted when the initial estimate was too high. On the contrary, the initial estimate is kept when it is lower. In the third scenario, car ownership has been reduced by 30% which acts as new CBS data. With this, three situations could occur as visualised in Figure 80 considering the discussed theory.

1) Car ownership is overestimated in both the baseline situation and the third scenario. Therefore, car ownership will be adjusted in both situations. A difference will occur between the results from the baseline situation and the third scenario.
2) Car ownership is underestimated in the baseline situation. It is overestimated in the third scenario and therefore adjusted. A difference will occur between the baseline situation and the third scenario.
3) Car ownership is underestimated in both the baseline situation and the third scenario. Therefore, car ownership does not change in both situations. There will be no difference between the baseline situation and the third scenario.

Figure 80: The three possible situations according to IKOB in the third scenario

The zones in which situation 3 occurs are thus marked in purple. In addition, it was stated before that the assumption is taken that households who do have more than one car are not present in zones in which the average number of cars per household is lower than 1. The available data for this research about car ownership in Zwolle is shown in Table 12. The dataset is divided into two groups; zones in which the car ownership per household is on average bigger than 1 and those in which it is smaller than one. For each group, it is calculated how many households have no cars, 1 car and more than 1 car. The table shows that 11.05 % of the households have more than 1 car in zones in which the average is lower than 1. This shows that the assumption made by IKOB is quite dubious.

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[8] Assumptions are made by the researchers that have created IKOB, not by me.

Table 12: Data about car ownership in the study area

	Number of cars in household		
	No car	1 car	More than 1
Cars/household < 1	38.01 %	50.94 %	11.05 %
Cars/household > 1	18.15 %	59.28 %	22.56 %

Appendix E.2 Accessibility by each Modality

Next, Figure 81 shows how the accessibility by each modality has changed compared to the baseline situation according to the Logsum approach. Each modality is shown in a separate graph, as the accessibility cannot be compared between them. Boxplots are presented for accessibility by public transport and cycling. The boxplot for the accessibility by car is rather wide. The reason is that more than 25% of the population does not have a car and whose accessibility is therefore zero. The value for the first quartile will then be zero. The averages in the figures are indicated by the white dot. These show that the accessibility by public transport and cycling has not changed at all. On the contrary, the accessibility by car has reduced. This is not surprising as fewer people will have a car in the third scenario. This increases the frequency of people who have accessibility of zero, which brings down the average.

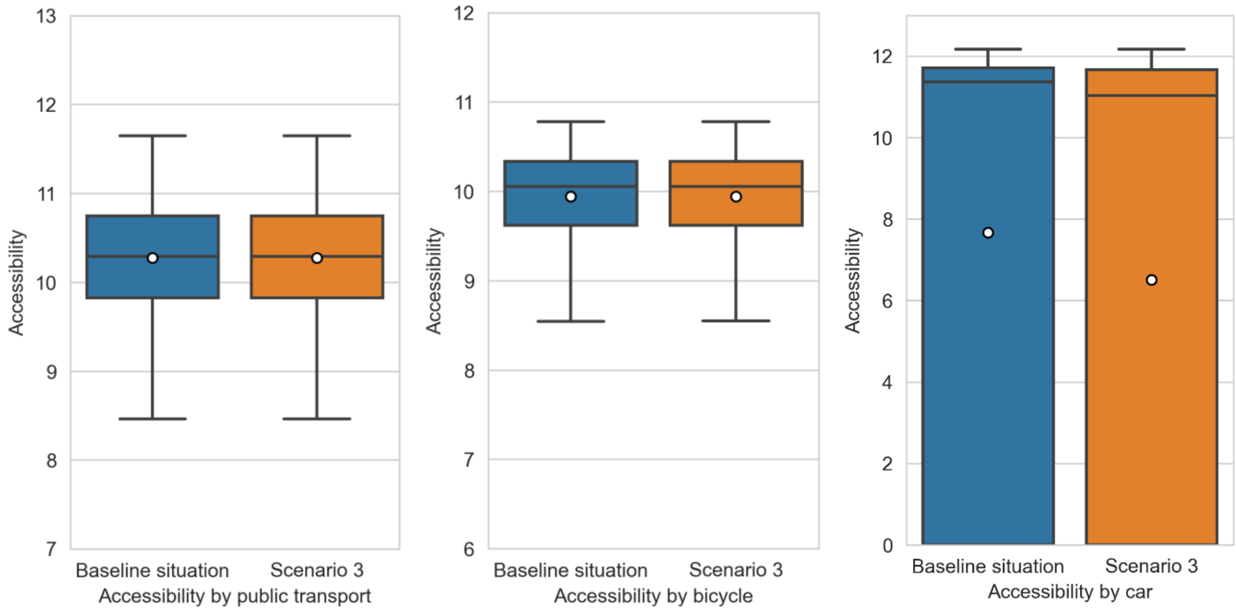

Figure 81: Accessibility by each modality in the third scenario according to the Logsum approach

Furthermore, a similar figure showing how the accessibility by each modality has changed compared to the baseline situation has been created for the IKOB approach. It has been presented in Figure 82. First, it could be observed that the accessibility by car has decreased as predicted by the Logsum approach. Besides, the average (identified by the white dot) is located relatively high since people who have the car for 'free' raises the average significantly. On the contrary, it seems that the accessibility by bicycle and public transport has increased. This is interesting as reducing the number of cars seems to have an effect on accessibility by the other two modalities, which conflicts with the logsum approach.

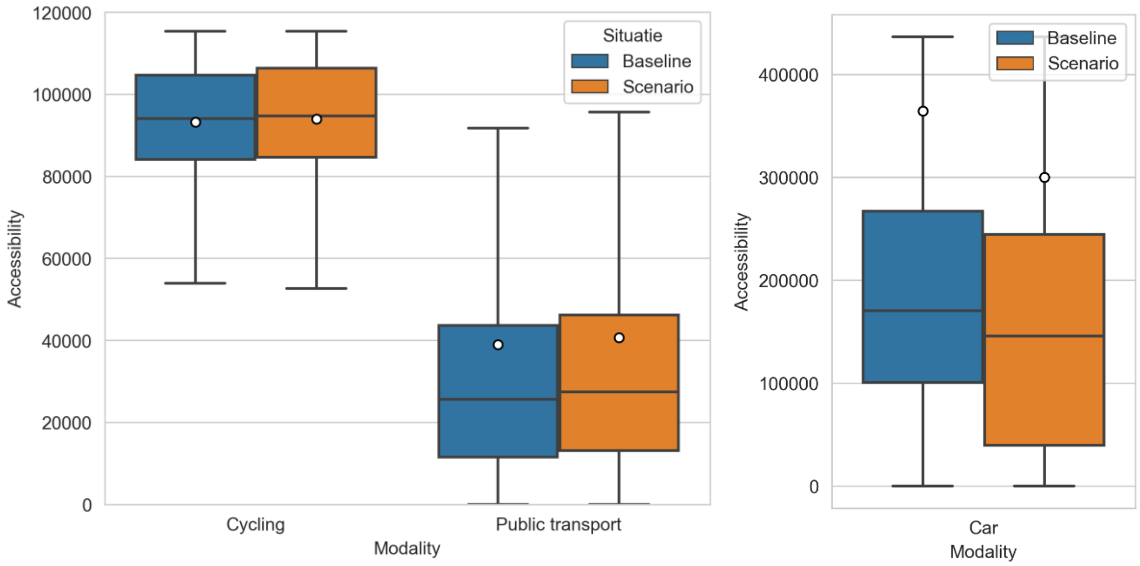

Figure 82: Accessibility by each modality in the third scenario according to the IKOB approach

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