'Pay-Per-Use' vehicle tax in the Netherlands: a spatial accessibility perspective

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Abstract

Instead of paying taxes for car ownership, a Pay-Per-Use policy has been proposed in which Dutch car owners would have to pay taxes for the number of kilometres they drive their car. Attention for available mobility alternatives to the car in different areas of the Netherlands lacks in research commissioned by the government so far. The objective of this thesis is to identify whether people living in either urban, suburban, or rural areas will be most financially affected by this potential new policy, while assessing the spatial equity aspect of accessibility for public transit and cycling.

An multi-part accessibility equality method has been developed following the iterative Research through Design approach for the Groningen-Assen region as a case study area. Representing various scale levels, accessibility has been measured for bakeries, HEMAs, McDonald's, and IKEA based on network analysis using Geographic Information Systems (GIS). Using origin-destination cost analysis, the final method offers insight in travel time inequalities for public transit and bike as opposed to the car and connects resulting equality scores to the different degrees of urbanisation and population density. Due to the complex nature of tax effects, the final method offers insight in possible financial effects of the PPU policy for three fictional personas living in respectively urban, suburban, and rural areas.

Rural residents in the RGA face high travel times for public transit and cycling, compared to car travel times. Spatial patterns of accessibility equality scores – representing differences in travel time for public transit and bike as opposed to the car – differ per scale level of the destinations. Low scores and thus high inequalities are mainly observed in rural areas. Depending largely on the type of car and the annual mileage of a person, the PPU tax will be disadvantageous as opposed to the current MVT for two out of three personas. Overall MVT and PPU tax expenses for the rural persona are much higher compared to the urban and suburban personas, while accessibility equality scores are low, indicating that public transit and bike are no valid alternatives.

This thesis underlines the importance of addressing the sufficing or lacking presence of alternative modalities among regions to account for spatial equity in the potential PPU. Car dependency is probably overlooked by current research commissioned by the government. The PPU policy could actually be beneficial when the car is left parked a little more often, which appears possible in areas with high accessibility equality scores such as the cities Groningen and Assen and big villages.

Limitations of this research include lacking statistical inequality measures and relying mainly on travel time. Future research could consider implementing multi-modal trips as well as costs of alternative modes of transport.

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1 Introduction

1.1 Background

Dutch car owners will no longer pay taxes for car ownership from 2030, but for the number of kilometres they drive their car, according to the currently outgoing cabinet of the Netherlands[1] (Rutte et al., 2021). The aim is to maintain car tax revenues and reduce CO_2 emissions. This measure is called '*Betalen naar Gebruik'* (BnG), referring to the concept of 'Pay-Per-Use' (PPU). The rate is not differentiated by time and place. This means that it does not matter where the car drives: both the distance travelled in the Netherlands and abroad are taxed. Due to the fall of the cabinet in July 2023, the development of the PPU plans has temporarily stopped (Van Rij, 2023). The next cabinet will decide whether this reform of the motor vehicle tax will be continued and if so, how.

The principle of PPU for car mobility is not new on the Dutch political agenda. There have been plans to introduce such a system before. Between 1999 and 2001, a proposal for the '*Wet op het rekeningrijden*' was discussed in the parliament for a fixed amount during the morning rush hour in the Randstad - the urban agglomeration of the Netherlands (Tweede Kamer der Staten-Generaal, 1999). A few years later, the proposal for the '*Wet kilometerprijs*' was discussed, in which a kilometre tax was proposed instead of a motor vehicle tax. The kilometre price then depended on where a motorist drove and at what time (Tweede Kamer der Staten-Generaal, 2009).

Although these previous proposals were unsuccessful, it seemed that – before the fall of the cabinet – the current PPU plans would be adopted into law. The Council of Ministers agreed in 2022 to send a letter to the House of Representatives (*Tweede Kamer*) with the first elaboration of these plans (Van Rij & Harbers, 2022). Since then, various research has been conducted to be able to make choices regarding the elaboration of PPU.

One of these studies, conducted by the Ministry of Infrastructure and Water Management (I&W) and the Ministry of Finance (2023), focuses on effects on car taxes and income. The ministries have calculated the cost differences between the current Motor Vehicle Tax (MVT) (*motorrijtuigenbelasting*) and the future PPU policy per province, with a distinction between rural and urban regions. Although the low population density in rural areas would imply large driving distances, the Ministries found that the annual mileage of cars in the Netherlands is higher in urban areas compared to rural areas. This finding is based on data from Statistics Netherlands (*Centraal Bureau voor de Statistiek*) (CBS), taking into account behavioural effects. These effects include that people are expected to drive less kilometres after the implementation of the PPU policy. Due to the higher annual mileage in urban areas compared to rural areas, the cost increase of owner-occupied cars will be greatest in urban areas.

1.2 Problem statement

Although people in urban areas will have to pay the most according to this research of the Ministry of I&W and the Ministry of Finance (2023), people's access to alternative mobility options - such as public transit and cycling - is not being considered in research commissioned by the government. According to Breukelman (2023), as long as this is a voluntary decision, the fact that some people use their cars more frequently than others does not necessarily constitute an issue with the adoption of a kilometre tax: "Paying [PPU vehicle tax] for use, and therefore literally the burden on roads and the environment, is basically a fair starting point. Only then must everyone have access to sufficient alternatives to the car" (Breukelman, 2023). Research by Netherlands Knowledge Institute for Mobility Policy Making (*Kennisinstituut voor Mobiliteitsbeleid*) shows that residents of rural areas therefore have higher chances of forced car ownership and eventually of transport poverty (Jorritsma et al., 2018).

In the House of Representatives, this inequity has also been discussed. Wybren van Haga asked questions about rural residents who are disproportionately affected by the PPU policy, as public transit in rural areas is 'miserably poorly' organised, leaving no alternative to the car. Mark Harbers, the minister of I&W, refers in his answers to Van Haga to the research of the Ministry of I&W and the Ministry of

[1] Written in accordance with situation on 22 May 2024.

Finance (2023), stating that given the higher annual mileage in urban areas compared to rural areas, it is not expected that the introduction of PPU will result in a burden shift from drivers in urban areas to drivers in rural areas (Harbers, 2023). However, the fear of an excessive accumulation of negative consequences in rural areas is still a topic of discussion among political parties (NOS, 2023).

Although the Ministry of I&W and the Ministry of Finance (2023) are taking into account people's behavioural effects in terms of driving less kilometres, they do not consider whether people in different areas of the Netherlands actually have the possibility to drive less kilometres to access valued destinations. Population density and the availability of public transit in rural areas of the Netherlands usually differ considerably from the Randstad, which could lead to car dependence.

In conclusion, attention for available mobility alternatives in different areas of the Netherlands lacks in research commissioned by the government regarding the elaboration of PPU. Spatial accessibility differences should therefore be considered when determining how the PPU kilometre charge can be applied in a fair manner.

1.3 Research objectives

1.3.1 Main research objective and central question

Therefore, the objective of this thesis is to identify whether people living in either urban, suburban, or rural areas will be most financially affected by this new policy, taking into account alternative mobility options. The focus of this thesis therefore is not only on annual car mileage, but on assessing the spatial equity of accessibility by also considering alternative mobility options to the car. The accessibility of certain valued destinations – which are determined during this research – thus has been measured for different modes of transport and subsequently compared for regions with a different degree of urbanisation. An accessibility method is developed following the iterative Research through Design (RtD) approach for a case study area which is determined during the research. Regions where the costs of the future PPU policy will increase the most compared to the current MVT policy could in this manner be identified. As this objective has a highly spatial aspect, Geographic Information Systems (GIS) has been used in this research.

To reach this objective, the central question of this research is: "*To what extent will people living in urban, suburban and rural areas be financially affected by the upcoming 'Pay-Per-Use' motor vehicle tax policy, taking into account alternative mobility options?*"

1.3.2 Sub-objectives and sub-questions

To answer the central question and thus reach the research objective, multiple sub-objectives have been set up that should be achieved. To reach these sub-objectives, accompanying sub-questions have been answered during the research.

The first sub-objective is to clarify the societal problem that drives this research, which include spatial effects formed by unequal transport mode accessibility. This has been achieved by answering the following sub-question (SQ1): Which possible effects of the upcoming PPU motor vehicle tax for the society are yet unexplored from an accessibility perspective?

Subsequently, the second sub-objective is to ascertain how to quantitively research these unexplored possible effects on accessibility. As the main objective is highly spatially oriented, GIS is included in the second sub-question (SQ2): How can accessibility quantitatively be measured for different modes of transport using GIS?

Thirdly, it should be determined whether the possible accessibility effects can actually be measured with existing data for different degrees of urbanisation. To that end, regions in the Netherlands with different degrees of urbanisation have been studied and compared with each other. Therefore, the third question (SQ3) is: Is it feasible to use existing data for comparing geographical differences in accessibility and costs for different modes of transport using GIS?

1.4 Scope

It is important to emphasise that the development of the PPU plans has temporarily stopped due to the fall of the cabinet. It is not known yet whether the reform of the motor vehicle tax will be continued by the new cabinet and if so, how. Despite this uncertainty, this thesis remains relevant as it offers a new spatial perspective on the principle of PPU. When the next cabinet might continue the motor vehicle tax reform, this perspective could be useful. It is worth noting that the results of this study cannot be seen as a comprehensive financial calculation of the effects of the PPU, but that it serves more to illustrate the importance of considering geographical differences. Other vehicle taxes such as excise duties, energy tax, and purchase tax are not considered in this research. Additionally, as this research only focusses on a – to be determined – study region in the Netherlands, no claims can be made for the whole country. Finally, accessibility is measured in a general sense in this research: no differentiation will be made for specific users, ages, and mobility groups.

1.5 Reading guide

Firstly, a theoretical background is provided in which SQ1 and SQ2 are aimed to be answered (Chapter 2). The selection of the study area, destinations, and data are discussed in the methodology chapter (Chapter 3). Subsequently, the development of the accessibility method is explained by means of iterative cycles (Chapter 4). The results of the final method are presented in Chapter 5. Finally, the results and methodology of this thesis are discussed (Chapter 6), which is followed by a conclusion to answer the central question of this research (Chapter 7).

2 Theoretical background

This chapter provides an overview of conducted research, by providing insight in possible accessibility effects of the PPU policy (Section 2.1) and accessibility measures (Section 2.2).

2.1 Possible accessibility effects PPU policy

Based on literature, the unexplored possible societal effects of the upcoming PPU vehicle tax on accessibility are explored in this sub-section. Therefore, this sub-section aims to clarify the problem statement (see Section 1.2) on a theoretical basis by answering sub-question 1 of this thesis: *Which possible effects of the upcoming PPU motor vehicle tax for the society are yet unexplored from an accessibility perspective?* To answer this question, this sub-section starts with defining the accessibility perspective from a transport perspective (Section 2.1.1), followed by highlighting its spatial equity aspect (Section 2.1.2). Finally, the role of accessibility in research commissioned by the Dutch government on the upcoming PPU policy research is discussed (Section 2.1.3). Combining knowledge derived from the literature on spatial accessibility inequity, it is concluded which possible accessibility effects are not covered by the Dutch government.

2.1.1 Accessibility

According to Di Ciommo & Shiftan (2017), the equal distribution of accessibility is a main topic in the literature on transport and equity. The concept of accessibility has become central to planning during the last sixty years: improving accessibility is a goal that is being included into mainstream transportation planning and policy-making (Geurs et al., 2012). In (international) literature, many references are made to the study by Hansen (1959), who defines accessibility as the potential opportunities for interaction. Besides opportunities for interaction, other – more specific – definitions of accessibility include the ease of reaching activities or destinations (Hamersma et al., 2023).

While accessibility measures the ability to *access* a place, mobility measures the ability to *move* from one place to another (El-Geneidy & Levinson, 2006). Despite this difference in definition, mobility and accessibility are often used interchangeably. It is important to note the difference here. The main distinction between the terms is that accessibility is about the ease of reaching destinations or activities, rather than the ease of traveling along the network itself (El-Geneidy & Levinson, 2006). Therefore, the focus in mobility is mainly on the movement as an end in itself. High levels of mobility can, but do not necessarily reflect high levels of accessibility.

Geurs & Ritsema van Eck (2001, p. 34) identified four different components of accessibility, of which the *transport component* and the *land use* (or *spatial*) *component* recur in many studies on accessibility. To illustrate, these components overlap largely with the two core concepts that accessibility relies on according to Handy & Niemeier (1997) (*transportation* and *activity*) and according to Rodrigue (2020) (*distance* and *location*).

The transport component expresses - in terms of time, cost, and/or effort – the disutility that people encounter when attempting to travel a certain distance from their origin to their destination (Geurs & Ritsema van Eck, 2001). Rodrigue (2020) refers to this disutility as 'friction': the location with the least friction relative to others is likely to be the most accessible. Therefore, this transportation element is largely determined by the service provided by the transport system (Handy & Niemeier, 1997). The ease of travel can be measured by travel distance, time, cost (Handy & Niemeier, 1997; Rodrigue, 2020), or effort (Geurs & Ritsema van Eck, 2001). In conclusion, the transport component reflects the ease of reaching destinations.

Accessibility is therefore greatly dependent on travel costs: the less time and money that must be spent on travel, the more destinations that can be visited within a certain budget, the greater the accessibility (Handy & Niemeier, 1997). 'Costs' are not solely monetary costs: other measures, such as distance and time, are often used as impedances as well in transport research.

These costs vary for different modes of transport. Therefore, travel choice is of equal importance: “the wider the variety of modes for getting to a particular destination, the greater the choice and the greater the accessibility” (Handy & Niemeier, 1997, p. 1175). Accessibility could be measured for a single transportation mode or for a combination of different transportation modes, such as cars, public transit and bicycles (El-Geneidy & Levinson, 2006; Hamersma et al., 2023).

On the other hand, the land use (or spatial) component captures the amount and quality of activities present at each location, as well as how these activities are distributed throughout space (Geurs & Ritsema van Eck, 2001). Hence, this component reflects on the spatial distribution and characteristics of potential activities or destinations, e.g. jobs, homes, or shopping facilities. This spatial distribution of activities can determine the attractiveness of traveling to particular locations (Handy & Niemeier, 1997).

Therefore, destination choice is also a central aspect in accessibility: “The more destinations, and the greater the variety, the higher the level of accessibility” (Handy & Niemeier, 1997, p. 1175). According to Handy & Niemeier (1997) and El-Geneidy & Levinson (2022), the first step in explaining accessibility is to measure access to jobs. This is because employment serves as an indicator of overall activity. Besides jobs, examples of other destinations are healthcare facilities (Abd Jalil et al., 2018), cultural facilities (Park & Lee, 2015), shopping facilities (Li et al., 2020), and green spaces (Comber et al., 2008). Depending on the aim of the research, even more specific destination types could be identified, since accessibility levels of different types of destinations may differ notably for particular origin areas (Handy & Niemeier, 1997). The accessibility of key destinations and access to transport are often strongly shaped by a person’s residential location (Di Ciommo & Shiftan, 2017).

The chosen destination(s) could also depend on the spatial scale level of the research. ‘Local accessibility’ concerns reaching (basic) facilities in one’s own environment (e.g. general practitioners, local supermarkets, and primary schools), while ‘regional accessibility’ concerns the accessibility of activities in a larger area (e.g. hospitals, large shops, and jobs) (Hamersma et al., 2023). ‘National’ and ‘international accessibility’ is more about maintaining connections between regions and countries and the activities that take place there (e.g. amusement parks and economic prime locations).

Although accessibility may be evaluated differently, there seems to be consensus in academic literature that accessibility is determined both by the transportation system and by patterns of land use. Besides these two components, Geurs & Ritsema van Eck (2001) identified the temporal and individual components of accessibility. The former reflects the availability of activities throughout the day, while the latter reflects the individual valuations of the components based on people’s characteristics.

2.1.2 Accessibility and equity

Since accessibility takes into consideration locations as well as the distance to other locations, accessibility is a considered a good indicator for inequalities (Di Ciommo & Shiftan, 2017; Rodrigue, 2020). Insufficient accessibility can lead to transport poverty: the concept and its possible effects are explained in this sub-section.

Transport poverty: social exclusion and transport justice

Inadequate accessibility of destinations and inadequate travel options, in combination with limited personal capabilities or skills, increases the chance that some groups of people will be able to participate in the mobility system to a lesser extent, or in other words, would suffer from transport poverty (Jorritsma et al., 2018). Lucas et al. (2016) state that transport poverty is a multidimensional concept, consisting of various dimensions: mobility poverty, accessibility poverty, and transport affordability. Jorritsma et al. (2018, p. 9) explain the differences between these dimensions:

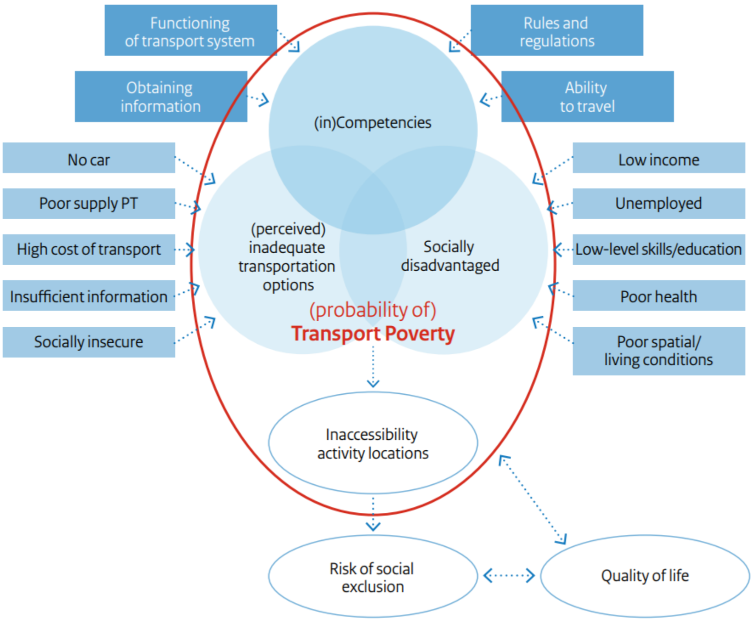
> “The concept of 'mobility poverty' refers to the lack of access to transport or modes of transport. This is in fact about inadequate transport options. The concept of 'accessibility poverty' focuses on the effort (money, ease and time) that someone has to make to reach certain activity locations that are important to participate in social life. The lack of financial resources refers to people

with a low income, but can also indicate car dependence (*forced car ownership*), as a result of which low-income households spend a large part of their income on traveling by car due to the lack of alternative forms of transport."[2]

As the upcoming PPU policy is considered from an accessible perspective in this thesis, the main focus in this thesis is on the 'accessibility poverty' dimension. However, from the explanation of the three dimensions by Jorritsma et al. (2018) it becomes clear that accessibility poverty is not an isolated concept as it is imbedded within transport poverty.

Based on an extensive literature review, Jorritsma et al. (2018) developed a conceptual model to map the relationships and effects of several factors that contribute to (the probability of) transport poverty (see Figure 1). The model shows that transport poverty consists of the interplay between three main dimensions, which are caused by various aspects. A relevant part of this model for this thesis is that the inaccessibility of activity locations concerns the inability or difficulty to reach work locations, medical services, education, and social networks. Relevant causes for this inaccessibility in this thesis include poor supply public transit, high cost of transport, and poor spatial conditions.

Figure 1 *Conceptual model of transport poverty by Jorritsma et al. (2018)*



Source: Jorritsma et al. (2018)

Overall, a possible effect of transport poverty is the creation of a risk of social exclusion, which in turn has an effect on the quality of life (Jorritsma et al., 2018). Di Ciommo & Shiftan (2017) also state that a lack of access to transport limits accessibility of key activities and opportunities, which in turn increases the risk of social exclusion. More specific, the place of residency – such as rural areas – can limit access to transportation options: this is called geographic exclusion (Church et al., 2000). Partly overlapping with this social exclusion perspective, transport poverty could be reviewed from a transport justice perspective. Accessibility could be regarded a primary social good: every citizen should have an adequate level of accessibility to avoid social exclusion (Jorritsma et al., 2018). This ethical perspective holds on to a basic accessibility, which serves as threshold.

Transport modes: car dependency

From both environmental and equity perspectives, it is relevant to compare different transport modes (Benenson et al., 2011). A reason for this is that cars tend to provide substantially higher levels of accessibility. If car accessibility is indeed considerably higher than public transit accessibility, an area

[2] Translated from Dutch.

can be considered car dependent (Benenson et al., 2011). It should be noted that some people living in rural areas value the rural lifestyle and are willing to accept compromises and make trade-offs and choices to have a simplified life, sometimes at the expense of less mobility (Cooper & Vanoutrive, 2022).

2.1.3 Role of accessibility in Dutch PPU research

To make choices for the development of PPU policy, the Dutch government has commissioned research into a number of topics (Van Rij, 2023). Table 1 provides an overview of these studies. In the rightmost column, it is stated whether possible accessibility effects of the upcoming PPU policy are studied in the corresponding research in the form of quotes.

From the comparison it appears that half of the conducted studies - to a greater or lesser extent - touch upon the concept of accessibility and alternative mobility options for the car. Especially in research on citizens and their understanding and the attitudes towards the PPU policy, the aspect of transport justice arises (Dialogic, TwynstraGudde, & Decisio 2022; Motivaction, 2022; Arup & KPMG, 2023). Car dependency and a lack of access to alternative mobility options seem to be principal concerns of Dutch residents. MuConsult, Revnext, & 4Cast (2022) and Knoope et al. (2022) both highlight that (financial) effects of the PPU policy for residents living in various regions are not being considered in their effect studies. As stated in the introduction of this thesis, the Ministry of I&W and the Ministry of Finances (2023) did differentiate between costs for rural and urban regions: the Ministries found that due to the higher annual mileage in urban areas compared to rural areas, the cost increase of owner-occupied cars will be greatest in urban areas. However, no attention is paid to the previously revealed concerns of car dependency and lacking mobility alternatives.

Based on this sub-section, an answer can be given on the first sub-question of this thesis: *Which possible effects of the upcoming PPU motor vehicle tax for the society are yet unexplored from an accessibility perspective?* Spatial inequalities can be measured by the level of accessibility, since it combines components of transport and land use. To avoid social exclusion, everyone should have equal access to opportunities according to transport justice theory. However, aspects such as high costs of transport and poor spatial living conditions can lead to transport poverty, which in turn can lead to social exclusion. From research commissioned by the government it appears that possible rising costs caused by car dependency and lacking mobility alternatives are concerns of residents of rural areas, but are not yet quantitatively researched among regions from an accessibility perspective.

Table 1 *Comparison PPU research commissioned by the Dutch government*

Author	**Name report**	**Aim**[3]	**Spatial accessibility equity**[3]
MuConsult, Revnext, & 4Cast. (2022, October)	Varianten voor tariefstructuur Betalen naar Gebruik - Onderzoek naar doelbereik en enkele neveneffecten	Elaboration of three main variants for a rate structure with mapping of the resulting effects.	“Other (financial) effects for residents of a province or the provinces themselves, such as increased use of public transit as an alternative to the car, are not taken into account.” (p. 81)
Knoope et al. (KiM) (2022, November)	Verwachte effecten van betalen naar gebruik - Inzichten vanuit de literatuur en een expertsessie.	Exploratory research into the behavioural and social effects of the introduction of PPU.	“Due to the different partial effects, it cannot be concluded whether people in the city are better or worse off than people in the countryside if PPU is introduced. It would be good to conduct more research into the effects of PPU across different regions, taking into account the alternatives that people have available.” (p. 58)
Ministry of Finance (2022, November)	Verkenning opcenten onder Betalen naar Gebruik	Official exploration into the possible design and associated policy effects of the provincial surcharges under a PPU system.	-
Dialogic, TwynstraGudde, & Decisio (2022, December)	Onderzoek kilometerregistratiesysteem voor betalen naar gebruik	Visualising three possible solutions for mileage registration with PPU.	“In regions where there is no good alternative to the car, the understanding of PPU may be lower. This can be nuanced somewhat since car ownership and thus access to mobility 'often becomes cheaper.'” (p. 29)
Motivaction (2022, December)	Betalen naar gebruik - Resultaten kwalitatief en kwantitatief onderzoek	Mapping the attitudes and preferences of citizens with regard to PPU.	“Not everyone has the choice to leave their car at home: some (older) people have difficulty walking, others are really dependent on their car for their work and there are people who have little or no access to public transit.” (p. 14) “The degree of urbanisation has a slight influence on attitudes towards PPU. Only Dutch people who do not live in an urban area at all are less likely to be positive (...) and less likely to consider PPU a fair form of road tax (...). They therefore more often own a car (...) and say to a greater extent that they cannot leave the car at home more often (...). In addition, this group often mentions the disadvantage that PPU will result in more traffic through villages and on local roads because people will take the shortest routes (...).” (p. 47)
Landsadvocaat (2023, March)	Advies Betalen naar Gebruik – buitenlandse kilometers	Advice on the question of whether EU law and free movement rights preclude a PPU design in which tax must also be paid on kilometres driven abroad.	-
MuConsult, Revnext, & 4Cast (2023, May)	Effectstudie Betalen naar Gebruik fase 2 - Tabellenrapport	Follow-up research into the effects of different variants for the rate structure, including indicative policy effects in 2040 and distribution effects between regions and provinces.	-

[3] Translated from Dutch.

Author	Name report	Aim[3]	Spatial accessibility equity[3]
Ministry of I&W & Ministry of Finance (2023, May)	Betalen naar Gebruik – Effecten op autobelastingen en inkomenseffecten	Research into cost developments per car and the income effects of PPU.	"The average mileage per car also plays an important role in the differences in effects according to degree of urbanization. In highly urban areas, the annual mileage of cars is higher compared to rural areas. That is why the cost increase of owner-occupied cars is the greatest in urban areas." (p. 5)
Arup & KPMG (2023, May)	Verdiepend onderzoek nalevingsgedrag en keteninrichting Betalen naar Gebruik	Follow-up research into compliance behaviour and possible measures to strengthen the existing kilometre registration as a basis for PPU and elaboration on how the public implementation organisations involved can divide the tasks that arise within the implementation chain.	"(...) PPU can be seen as unfair to taxpayers for various reasons. For example, (...) because car use is becoming more expensive while motorists do not always have the option to use alternative transport." (p. 6)
Knoope (KiM) (2023, June)	Verkenning van de gevolgen van betalen naar gebruik voor autoreizen naar het buitenland	Exploration of the consequences of PPU for car travel abroad.	-
Van den Bossche & Jansen (Ecorys) (2023, September)	Quickscan Grenseffecten Betalen naar Gebruik	Making an inventory of possible cross-border effects when introducing PPU.	-
Wijermars et al. (SWOV) (2023, September)	Verkeersveiligheidseffecten van 'Betalen naar Gebruik' - Effecten van een BnG-variant op de verwachte aantallen slachtoffers in 2030.	Mapping the road safety effects of a variant of PPU.	-

2.2 Accessibility measures

The second sub-objective of this thesis is to ascertain how to quantitively research the identified unexplored possible effects on accessibility with GIS. Section 2.2.1 shows a general overview of accessibility measures. Subsequently, more specific measures on how to measure inequalities in accessibility for different modes of transport are identified (Section 2.2.2). This section therefore aims to answer the second sub-question of this thesis: *How can accessibility quantitatively be measured for different modes of transport using GIS?*

2.2.1 Accessibility measures

Geurs & Ritsema van Eck (2001) identified three basic perspectives on measuring accessibility. Firstly, *infrastructure-based measures* analyse the performance of the transport infrastructure. Measures such as "level of congestion" and "travel speed" are mostly used in transport planning. Although the infrastructure-based type is easiest to measure and interpret, it does not take into consideration the interplay of land use and transport infrastructure (Scheurer & Curtis, 2007). This type of measure is hardly used for measuring accessibility, as it mainly focuses on the quality of the transport network instead of providing insight into accessibility between different areas (Benenson et al., 2011).

Secondly, conversely, *activity-based measures* analyse the distribution of activities in space and time and are mostly used in urban planning and geographical research (Geurs & Ritsema van Eck, 2001). This perspective has later been divided into two perspectives: *location-based* and *person-based measures* (Geurs & Van Wee, 2004). The former describes the level of accessibility to spatially distributed activities (e.g. "number of jobs within 10 minute travel time from origin locations"), while the latter focuses more on individuals and time (e.g. "number of activities in which a person can participate at a given time"). Such activity-based measures therefore also include the land use component (see Section 2.1.1), but are typically more complex and harder to understand (Scheurer & Curtis, 2007). Most research that compare accessibility by car and public transit use location-based measures (Benenson et al., 2011). The high dependence on detailed data input makes person-based measures difficult to apply at a regional level (Benenson et al., 2011).

Finally, *utility-based measures* analyse the (financial) advantages that individuals obtain from participating in spatially distributed activities (Geurs & Ritsema van Eck, 2001). As accessibility is a complex idea that is difficult to summarise in a single indicator or index that applies to everyone. This final measure crosses over into the fields of economics and social science and still needs significant research and development (Scheurer & Curtis, 2007). Similarly to person-based measures, utility-based measures are hard to apply on a regional scale due to their high dependence on detailed data (Benenson et al., 2011).

Another distinction that is often made in comparing accessibility measures is between the *cumulative opportunities measure* and the *gravity-based measure* (Handy & Niemeier, 1997; Geurs & Ritsema van Eck, 2001; El-Geneidy & Levinson, 2006; Scheurer & Curtis, 2007). Both measures can be classified as activity-based measures. The cumulative opportunities measure is the simplest method and is referred to as the *contour* or *isochoric measure* by Geurs & Ritsema van Eck (2001). This method counts the number of potential opportunities that can be reached within a predetermined travel time (or distance) (Handy & Niemeier, 1997; El-Geneidy & Levinson, 2006). While in this measure all potential destinations within the cutoff time are weighted equally, the gravity-based measure takes distance decay into account: closer destinations are given more weight (Hamersma et al., 2023). This measure is sometimes called 'Hansen's measure', referring to the early developing of the model by Hansen (1959). Although the gravity-based measure is frequently employed in the literature, planners typically find it easier to comprehend and evaluate simpler indicators such as the cumulative opportunities measure (El-Geneidy & Levinson, 2006). Benenson et al. (2011, p. 503) also argue that simple measures are to be preferred over more complex measures in identifying inequalities between different areas: "It is by no means certain that more comprehensive measures provide better estimates of these disparities or result in the identification of different areas or neighbourhoods that experience substantial disparities". While simple indicators can be just as useful for planners as more complex measures, scientists occasionally criticise these for their lack of solid theoretical basis (Handy, 2020).

Measuring accessibility is often based on network analysis, which in turn is based on graph theory (Stentzel et al. 2016). A road network consists of edges (roads) and nodes (crossings) and a set of connections between these nodes and edges. Costs are defined to the edges, so that algorithms – such as the classical Dijkstra algorithm (Dijkstra, 1959) – can determine routes with the least costs (Stentzel et al., 2016).

Since most research that compare accessibility by car and public transit use location-based measures, the location-based (part of the activity-based) measure is most relevant for this thesis. Although gravity-based measures can give more insight in the valuation of destinations, this valuation is not the main relevance of this thesis. Therefore, with the focus of this thesis is on cumulative opportunities measures, based on network analysis.

2.2.2 Measuring inequalities in accessibility

Spatial equity can be evaluated by measuring accessibility and many methods employ accessibility in equity assessment. Statistical methods and spatial-based approaches are the most applied measures of spatial equity in literature (Azmoodeh, 2021). Examples of the former are the Gini coefficient and comparing variances of equity level for social groups. The next sub-section gives a practical example on how to measure inequalities in accessibility from a location-based approach, comparing different modes of transport in GIS.

Inequalities car versus public transit

Benenson et al. (2011) developed a location-based accessibility measure which is able to identify inequalities by comparing two transport modes: the car and public transit. They developed a tool named Urban.Access, which is a GIS application based on the Network Analyst extension of Esri's ArcGIS. Their mode-based accessibility measure is based on the estimate of the travel time between origin (O) and destination (D). To be able to compare different transport modes, the travel time (τ) is measured for both the bus (B) and private car (C). Besides the actual travel time within the vehicles, Benenson et al. (2011) take walking time (from/to bus stop or parking spot), waiting time, and transfer time into consideration. Subsequently, Benenson et al. (2011) define the calculation of both the 'access area' and the 'service area'. The area computation is fundamentally the same: the reachable area is calculated for a specific mode within a certain travel time. However, the former calculates the area containing all destinations that can be reached from a certain origin, while the latter calculates the area containing all origins from which a certain destination can be reached. When analysing the equity component of accessibility, the access area is especially relevant (Benenson et al., 2011).

Based on these areas, Benenson et al. (2011) developed two comparative accessibility measures: the 'Access Area (AA) ratio' and the 'Service Area (SA) ratio'. These measures define accessibility levels "in terms of the *gap* between transit-based and car-based accessibility" (p. 506), in which the gap represents the inequalities. Given an origin O, the Bus to Car (B/C) access area ratio can be defined as:

$$AA_O(\tau) = BAA_O(\tau) / CAA_O(\tau) \qquad (1)$$

The formula of the Service Area ratio is comparable, but measures the accessibility gap with a given destination instead of a given origin. The ratios can be expanded with particular types (k) of destinations or origins and eventually capacities (e.g. number of jobs or number of apartments). The B/C Access Area ratio to destinations of type k can be defined as the sum of capacities of the destinations that can be accessed during time τ with bus and car:

$$AA_{O,k}(\tau) = \Sigma_{Dk}\ \{D_{k,\,Capacity} \mid D_k \in BAA(\tau)\} \ / \ \Sigma_{Dk} \\ x\ \{D_{k,\,Capacity} \mid D_k \in CAA(\tau)\} \qquad (2)$$

The formula of the B/C Service Area ratio is comparable, but again measures the ratio with origins as input. These measures (Formulae 1 and 2) result in an index, varying between 0 and 1. As an example of interpretation of this result, Benenson et al. (2011, p. 506) show that for destinations of type j (job), an outcome like $AA_{O,\,j}$(60 min)=0.3 means that "within 60 minutes of travel, bus users have access to 30% of jobs compared to car users".

3 Methodology

Building on the literature review, this chapter shows the methodological choices that have been made to eventually answer the central question of this research: *To what extent will people living in urban, suburban and rural areas be financially affected by the upcoming 'Pay-Per-Use' motor vehicle tax policy, taking into account alternative mobility options?* In Section 3.1, the Research through Design approach is introduced and a visual representation of the analysis scheme of this thesis is presented. Section 3.2, 3.3, and 3.4 show the selection of the case study area, transport modes, and destinations that are being studied in this thesis. Finally, Section 3.5 and Section 3.6 show the choices made in software and the preparation of the network data.

3.1 Research through Design

The third sub-objective of this thesis is to develop an accessibility method that is able to compare geographical differences in accessibility for different modes of transport and car tax costs, using existing data and GIS. To reach this sub-objective, a Research through Design (RtD) methodology has been adopted in this thesis for developing an accessibility method.

Research and design have traditionally been seen as separate activities. However, despite their differences, research and design activities both aim to create something new by expanding upon previously existing knowledge (Stappers & Giaccardi, 2017). In the past decades, design activities have become more widespread in the academic world. Consequently, the RtD approach is quickly gaining in popularity and an increasingly recognised methodology in research (Godin & Zahedi, 2014). Zimmerman et al. (2010, p. 310) define RtD as "a research approach that employs methods and processes from design practice as a legitimate method of inquiry". Godin & Zahedi (2014) add to this that the insights that are gained throughout the design process provide a better understanding of complex issues. In other words, the RtD approach builds upon previous design contributions to create new knowledge.

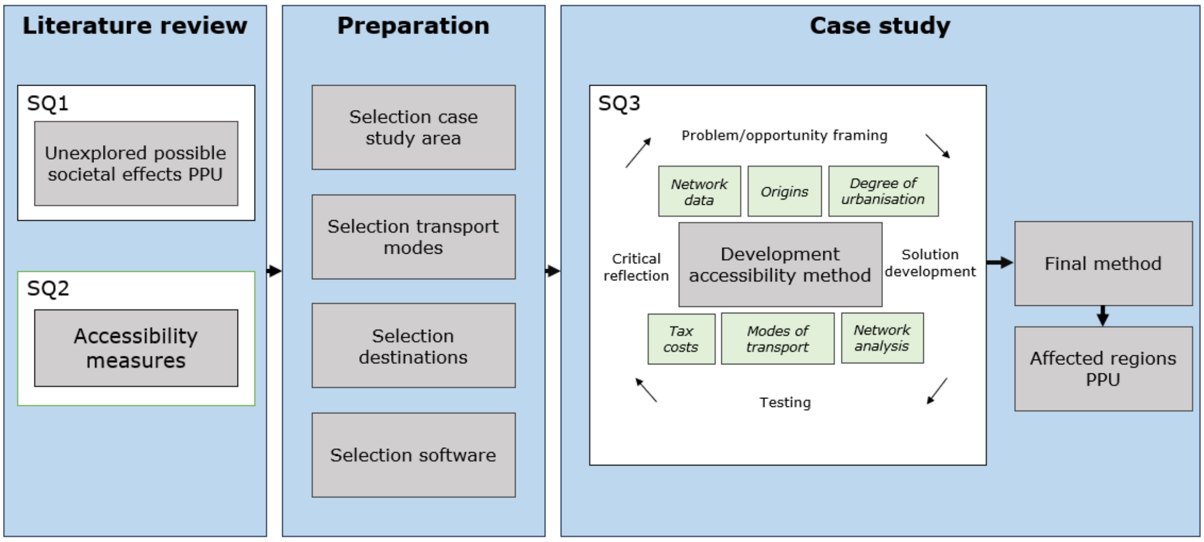
There is no clearly defined singular methodology by which RtD is carried out (Stappers & Giaccardi, 2017). There is a great variety in activities, methods, and processes used during RtD. One way to conduct RtD is by 'iterative prototyping'. In this approach, an RtD project starts on a basis of background knowledge, which consists of consulted literature and experiences of involved people (Stappers & Giaccardi, 2017). Subsequently, a prototype or piece of theory is created, which iteratively is being improved throughout the research (Stappers, 2007). This improvement can be reached by adding and leaving knowledge after each conducted experiment. This agile process of RtD involves many feedback loops, which are considered as a cycle of four activities by Maher et al. (2018): (a) problem/opportunity framing, (b) solution development, (c) testing, and (d) critical reflection. These activities do not have to be strictly predefined: the aim after all is to build upon the knowledge gained from the previous steps during the process. Zimmerman et al. (2010) define a different but relatively similar action research sequence of such an iterative RtD: (a) planning, (b) acting, (c) observing, and (d) reflecting. Ideally, all steps of the iterative process are documented as they may include valuable and crucial lessons (Stappers & Giaccardi, 2017). RtD has been adopted as research methodology in multiple previous accessibility studies for various case study areas. For instance, Li et al. (2018) applied the RtD methodology to model and visualise neighbourhood accessibility and walkability in Washington DC. Based on existing walkability tools, literature, their own experience, and qualitative studies, they designed two prototypes of geo-visualisations.

In this thesis, an RtD methodology has been adopted that follows this 'iterative prototyping' to design and develop an accessibility method that can measure geographical differences of the upcoming PPU policy. The iterative cycles in this thesis are derived from the action sequences considered by Maher et al. (2018): (a) problem/opportunity framing, (b) solution development, (c) testing, and (d) critical reflection. In the critical reflection of each cycle, only the quality of the method is assessed, not the content of the results of the analysis. Due to time constraints, three iterations have been carried out during this research.

Figure 2 shows an overview of the methodology of this thesis. The background knowledge (referred to by Stappers & Giaccardi, 2017) of the method is comparable with the performed literature review (Chapter 2). Therefore, besides answering the first two sub questions (SQ1 and SQ2), the literature review serves as input for the first prototype in the first cycle. Prior to creating a first prototype, some selections are discussed in the following sections in this chapter.

Chapter 4 shows the design process of the accessibility method in the form of a case study. Chapter 5 shows the results of the analysis that has been conducted with the final method. Overall, the case study aims to answer the third sub-question of this thesis: *Is it feasible to use existing data for comparing geographical differences in accessibility and costs for different modes of transport using GIS?*

***Figure 2** Analysis scheme*



3.2 Case study area

Prior to creating a first prototype, various input variables have been selected. As shown in Figure 2, one of these prior selections encompasses determining the case study area of the accessibility method. As the third sub-objective of this thesis is to develop an accessibility method that is able to compare geographical differences in accessibility for different modes of transport and car tax costs, regions with different degrees of urbanisation had to be studied and compared with each other. The following sub-section lists the requirements that the case study area should meet to be able to answer the third sub question and eventually the central question of this thesis. Subsequently, based on these requirements, the second sub-section shows the selected case study area in this thesis.

3.2.1 Requirements

Firstly, as the PPU policy is intended to be implemented in the Netherlands, (1) *the case study area should be located completely within the boundaries of the Netherlands*. Additionally, as adjacent regions of the case study area will be included in the accessibility method, (2) *the case study area cannot be located within 15 kilometres from the national border with Germany and Belgium*. A case study area is not an enclave: as people can travel through and to neighbouring regions, the road network, public transit availability, and destinations within fifteen kilometres are included in the accessibility method in this thesis. This threshold of fifteen kilometres is set based on an accessibility study in a rural region in Germany by Stentzel et al. (2016). In their analysis, they consider all relevant facilities in a 15-kilometre buffer around their study region. If a case study area is chosen close to the border with Germany and Belgium, cross-national data are required for creating the accessibility method. High cross-border mobility exists between the Netherlands with its neighbouring countries for jobs, education (CBS, 2020), shopping, and everyday life practices (Szytniewski et al., 2018). Due to data availability and data consistency considerations, it is required that the 15-kilometre buffer around the chosen case study area is completely located within the Netherlands – equivalent to the case study area itself.

Furthermore, (3) *the case study area should be a contiguous area which contains urban, suburban, and rural area(s)*. In this way, all three considered degrees of urbanisation can be studied in one overarching area. Subsequently, to represent a common area within the Netherlands, (4) *the case study area should contain at least one highway (A-road)* and *(5) the case study should include at least one hub of multiple train tracks*.

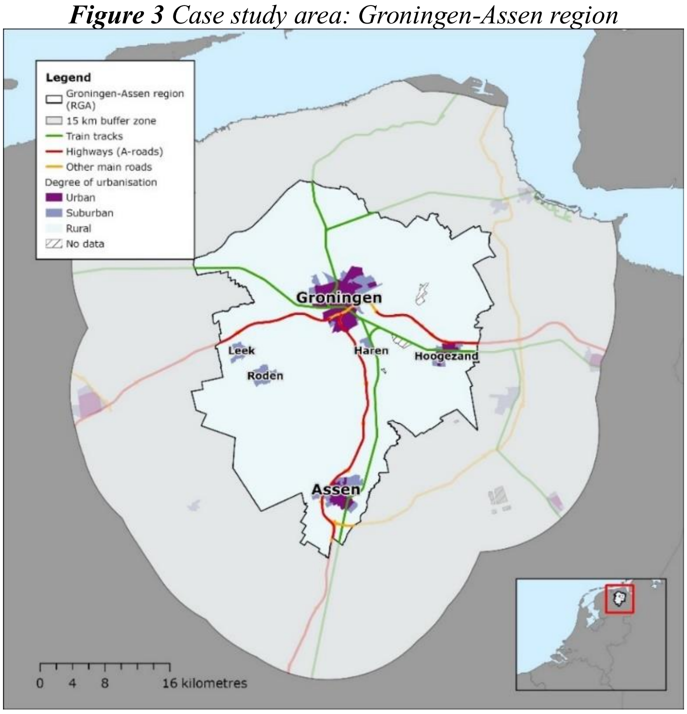
Besides these five requirements, the case study area could be chosen freely. The area does not have to comply with other location restrictions or certain area sizes. Although it is not a strict requirement, it has been preferred that the case study area complies with an existing area division (e.g. COROP area or safety region) or partnership. This would make the results of this thesis more applicable in practice.

3.2.2 Selection case study area: Groningen-Assen region

Appendix A provides an overview of the process of selecting a case study area. By visually comparing all spatial layers, the Groningen-Assen region (*Regio Groningen-Assen*) (RGA) has been selected as case study area in this thesis. The RGA is a voluntary partnership between the provinces of Drenthe and Groningen and the municipalities of Assen, Groningen, Het Hogeland, Midden-Groningen, Noordenveld, Tynaarlo, and Westerkwartier. These authorities have been working together in the RGA since 1996 on various themes, such as economy, mobility, spatial quality, and housing (CBS, 2023). There have been several municipal reorganisations in the area in recent years, which makes the current area demarcation of the RGA rather unclear. In this thesis, the NOVEX demarcation of the RGA is chosen as case study area.

Figure 3 shows that the RGA meets all requirements. The complete study area is located within the Netherlands and its fifteen kilometre buffer does not exceed the national border, implying that data from Germany are not required. All degrees of urbanisation are represented in the area, including differences in size (e.g. the urban areas Groningen and Assen). Suburban regions can mainly be identified at the edge of the cities and in villages. A large share of the region is rural. There are multiple highways (A7 and A28) and some main roads (N7 through Groningen connecting the A7 highway, and N33 connecting Assen with Eemshaven). Groningen can be identified as the main highway and train track hub, which connects to all cardinal directions.

Figure 3 *Case study area: Groningen-Assen region*



Source: Esri (2022c); Rijkswaterstaat (2023); ProRail (2022)

3.3 Case study transport modes

From environmental and equity perspectives, a comparison between accessibility for different transport modes is required. The focus of this thesis is on creating a multi modal accessibility, which is able to compare accessibility by car, public transit, and bike. These former two mode choices are in line with Benenson et al. (2011), since they explain that when car accessibility is substantially higher than public transit accessibility, an area can be defined as car dependent. It is also chosen to consider bike accessibility, since reasonable distances can be covered by bike and the Netherlands is strongly focused on cycling. Solely walking is not integrated as a transport mode, since the range is substantially smaller compared to the other considered modes. After calibrating, a next model could include cycling on an e-bike to improve the analysis when time allows. The e-bike especially has become increasingly popular and is considered a good alternative for certain car trips by policy makers and planners (De Haas et al., 2022).

It should be noted that comparing other modalities will bear different results. Therefore, other modes of transport could be considered in research on other scale levels (e.g. airplanes, boats, and international trains) or in other countries (e.g. focus on walking instead of cycling).

3.4 Case study destinations

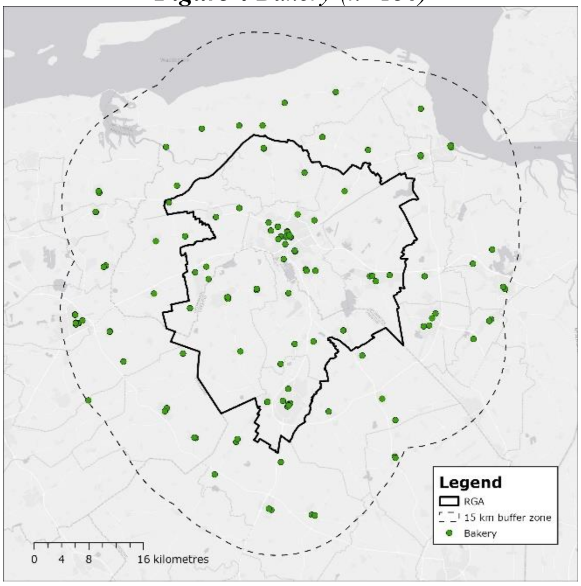
From the literature review it appears that measuring accessibility starts with calculating the access to jobs. Other examples included healthcare, cultural spaces, green spaces, and shopping. Handy & Niemeier (1997) pointed out that very specific destination types could be interesting, since that may show completely different accessibility levels for particular areas. Therefore, it has been decided that the accessibility method will aim to calculate accessibility for four different types of destinations. These destinations have been chosen based on their spatial scale, similar to the scale levels described by Hamersma et al. (2023)(see Section 2.1.1).

The first destination that has been considered is the bakery, of which 130 are located in the RGA, including its 15-kilometre buffer (see Figure 4). The bakery represents a facility that should be accessible on a local level. One scale level higher, the Dutch department store chain HEMA has been selected as destination: it is assumed that this facility should be accessible on sub regional (in between local and regional) level (see Figure 5). In total, 31 establishments of HEMA are located in the considered RGA region. The regional scale level is represented by the fast food chain McDonald's, which houses 13 locations within the case study area (see Figure 6). Finally, the furniture department store IKEA is selected to represent a destination that could be considered a national scale level (see Figure 7).

On first sight, these facilities show varying spatial distributions, allowing for varying accessibility scores throughout the case study area. HEMA, an originally Dutch department store chain, has over 500 locations in the Netherlands which are mainly located in centres of cities and villages. The fast food chain McDonald's has approximately half as many locations in the Netherlands and is not only located in city centres, but also often along highways. IKEA has less than fifteen establishments within the Netherlands, of which the largest branch in the Netherlands - and also the second largest branch in Europe - is located in Groningen.

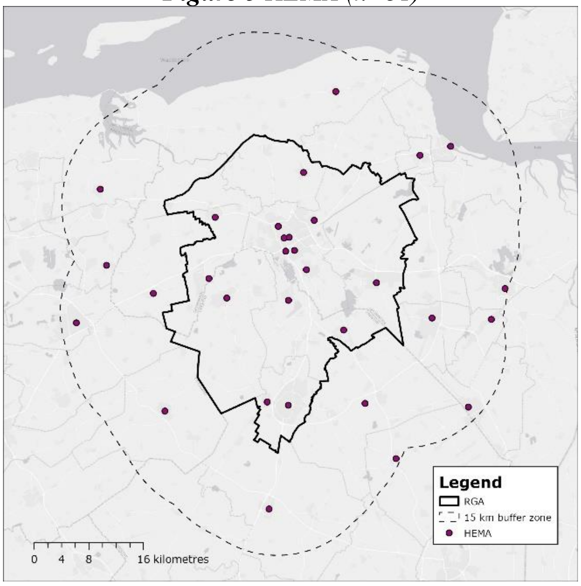
With these destinations, the aim is to show differences in local and regional functions. Spatial data of these destinations within the case study area have been retrieved by geocoding addresses which have been retrieved from the websites of the companies. The final accessibility method should be capable to easily measure accessibility and PPU effects for any other destination.

Figure 4 *Bakery (n=130)*



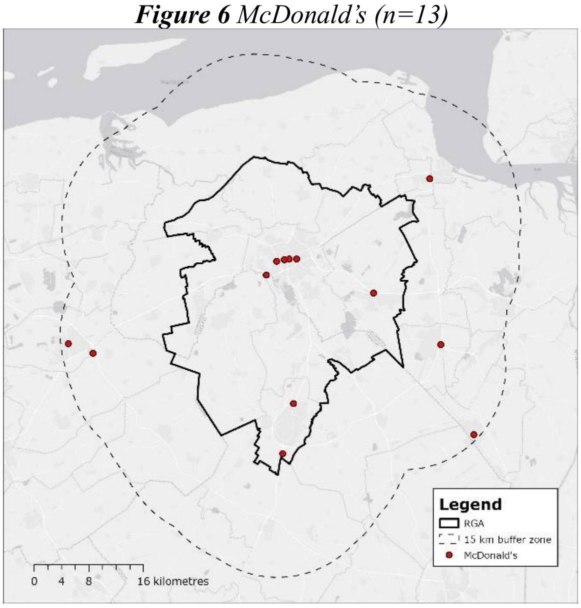
Source: Esri Nederland (2022c)

Figure 5 *HEMA (n=31)*



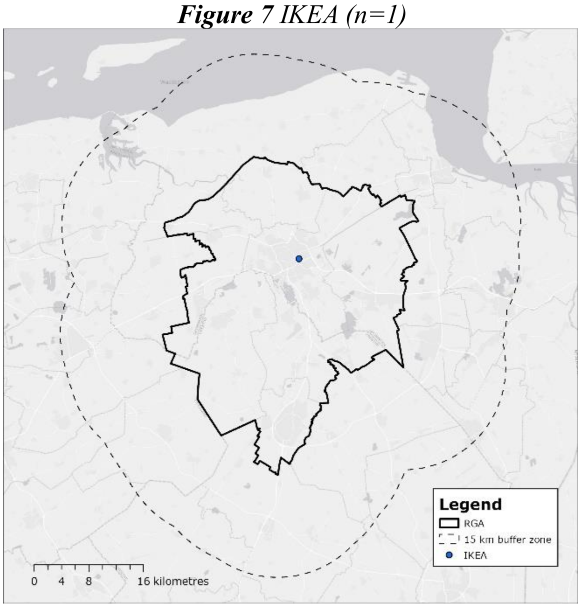
Source: HEMA (n.d.)

Figure 6 *McDonald's (n=13)*



Source: McDonald's (n.d.)

Figure 7 *IKEA (n=1)*



Source: IKEA (n.d.)

3.5 Software

Higgins et al. (2022) compared five software packages for multimodal routing to measure place-based accessibility: ArcGIS Pro, Emme 4.4, OpenTripPlanner in R and Python, and R[5] in R. It appeared that each tool offers its own strengths and weaknesses (Higgins et al., 2022). Based on the focus on minimising travel time – 'traditional foundation of accessibility analysis' according to Higgins et al. (2022, p. 112) –, the availability (university licence), and experience accumulated by previous research projects, it has been chosen to develop the accessibility method in this thesis with the Network Analyst in ArcGIS Pro. Despite some drawbacks (Higgins et al., 2022), ArcGIS's Network Analyst enables users to generate multi modal – including public transit – transportation networks which can be used for measuring accessibility. The Network Analyst works with an implementation of Dijkstra's algorithm (Dijkstra, 1959). Esri provides tutorials on how to perform network analysis for the car (Esri Nederland, 2021) and for public transit (Esri, n.d.; Esri Nederland 2022a; 2022b). As the RtD concept is based on continuously experimenting and improving the method, the ArcGIS software is no hard requirement. If it appears that certain core analyses cannot be performed with the Network Analyst, other software will be considered during the method development.

3.6 Network data

3.6.1 Road network

To evaluate accessibility with network analysis, a spatial representation of the road network is needed. Such a road network is necessary for modelling and analysing car or bike accessibility, but also for public transit since people need to travel to a stop or station. In Table 2, the advantages and disadvantages of three different road networks are evaluated.

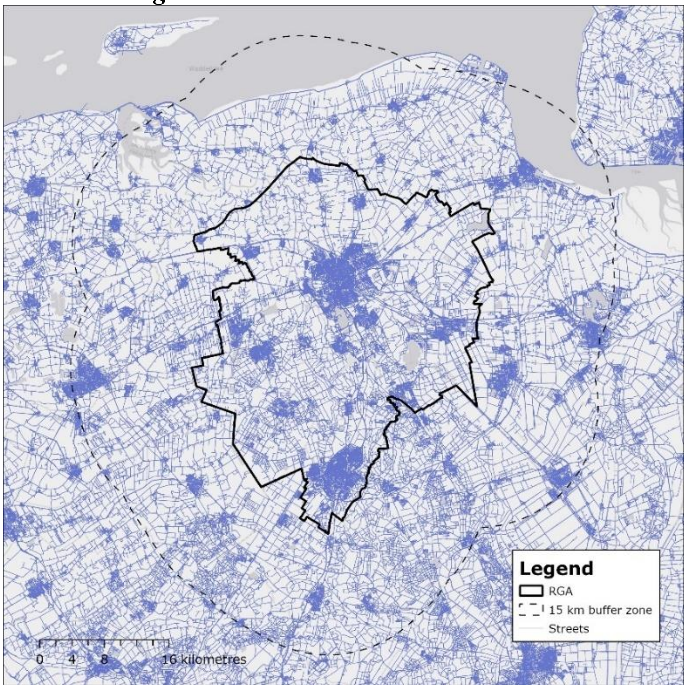
Table 2 *Comparison network data sets*

Data set	**Advantages**	**Disadvantages**
OpenStreetMap	• Open data: freely accessible • Easy download for provinces (via e.g. Geofabrik) • Open collaboration: everyone can add, which makes it up to date and detailed • Includes small walking paths • Includes topology	• Open collaboration: everyone can add, which makes mistakes probable • No clear documentation ArcGIS Pro on network properties (only for ArcGIS 10)
Dutch National Road Database (*Nationaal Wegenbestand*) (NWB)	• Open data: freely accessible • Easy download for the whole Netherlands • Maximum allowed speeds can be joined, which is needed for calculating travel time • Updated monthly • Includes topology	• Small walking paths are missing • No clear documentation ArcGIS Pro on network properties
Esri ArcGIS Online network service	• Built-in network in ArcGIS Pro: network properties already set • High quality data • No download needed • Can consider current traffic congestion • Includes topology	• Requires Esri credits (however: provided by university) • Cycling not an existing mode-option • No insight in data

From Table 2 it can be concluded that all data sets can be retrieved relatively easily and that they all include the main roads and consider topology. However, possibilities in mode choice and compatibility with the ArcGIS Pro software differ. The selection of the road network in this thesis has been performed during the creation of the accessibility model (see Chapter 4), but has been included as iteration section in Appendix B for readability purposes. In conclusion, an alternative compared to the compared network data sets has been acquired[4]. This is the OSM Premium Data network offered by Esri Nederland, in which the properties have already been set by Esri Nederland and which is suitable for different modes of transportation (car, fire truck, bus, bike, pedestrian, and truck). Figure 8 shows the input street layer on which the network data set is based for the case study area.

[4] The OSM Premium Data network data set from Esri Nederland and its manual have been retrieved via Utrecht University and have not been used for other purposes other than this thesis.

***Figure 8** Streets in and around the RGA*

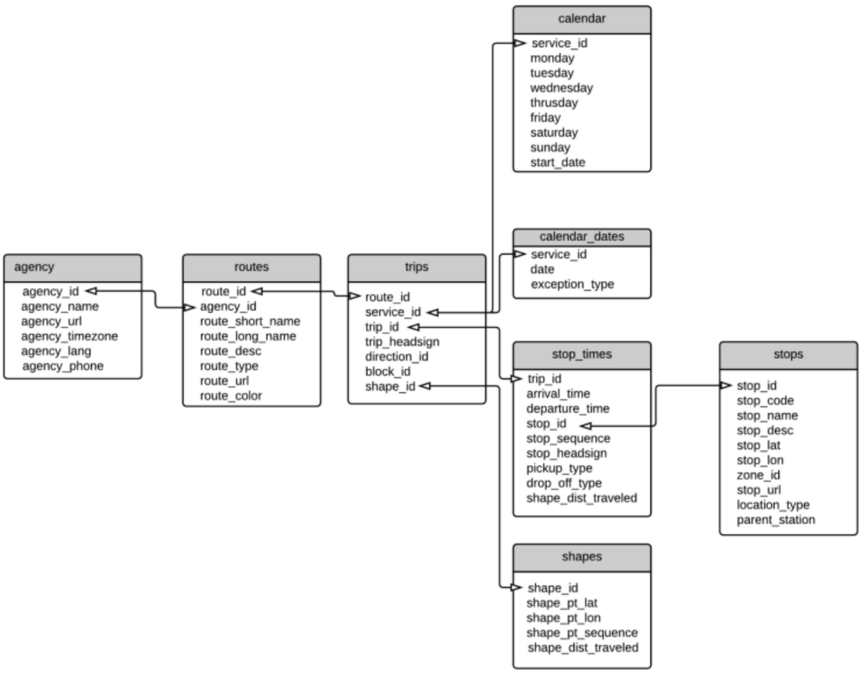


Source: Esri Nederland, 2023

3.6.2 Public transit network

Network analysis for public transit can be performed with General Transit Feed Specification (GTFS) data, which is a worldwide open standard for public transit data (see Figure 9). GTFS data for the Netherlands have been retrieved via OVapi, which offers a frequent-updated country-wide GTFS file containing data from all public transit operators (trains, buses, metros, and trams). ArcGIS Pro includes a standard toolbox to convert the GTFS data to a geodatabase in order for it to be used in Network Analyst (Esri, 2022). Esri offers multiple help pages and tutorials for preparing and analysing GTFS data with this toolbox (Esri, n.d.; Esri Nederland 2022a; 2022b).

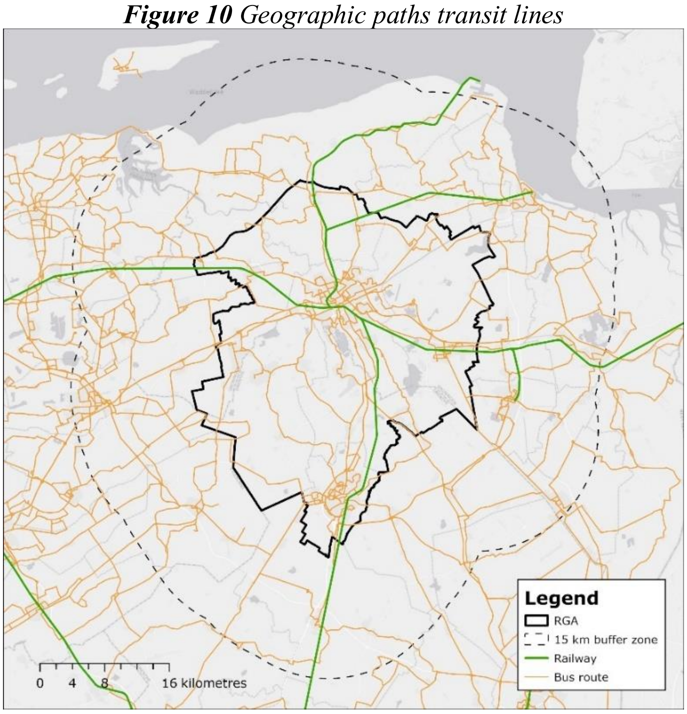
***Figure 9** Schema of the GTFS data format*



Source: Vieira et al. (2023)

GTFS data for the Netherlands have been retrieved from OVapi (2024). This GTFS data set includes data of all transit service providers that operate in the Netherlands (see Section 3.6.2). Figure 10 shows the actual paths taken by the vehicles in the public transit system. Trains and busses are active within the case study area.

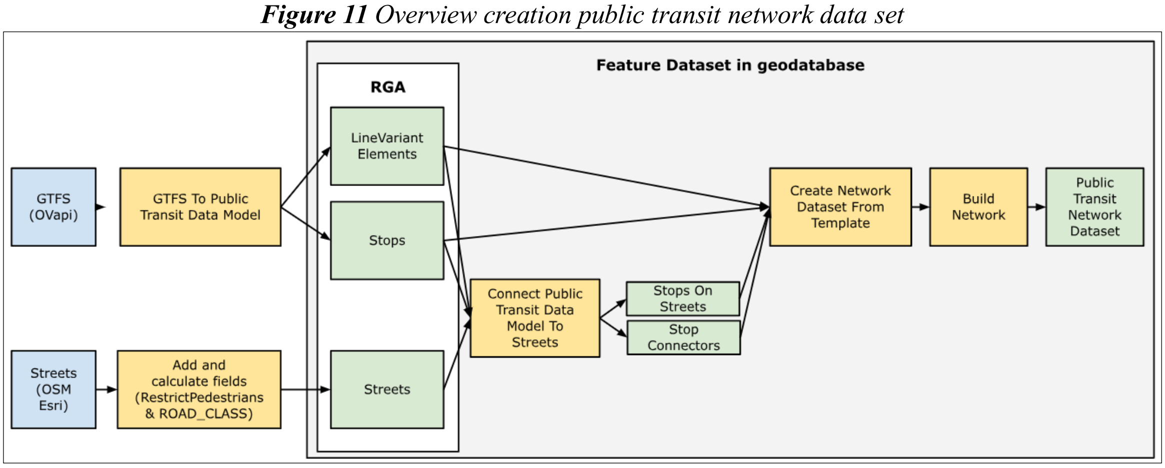
Figure 10 *Geographic paths transit lines*



Source: OVapi (2024)

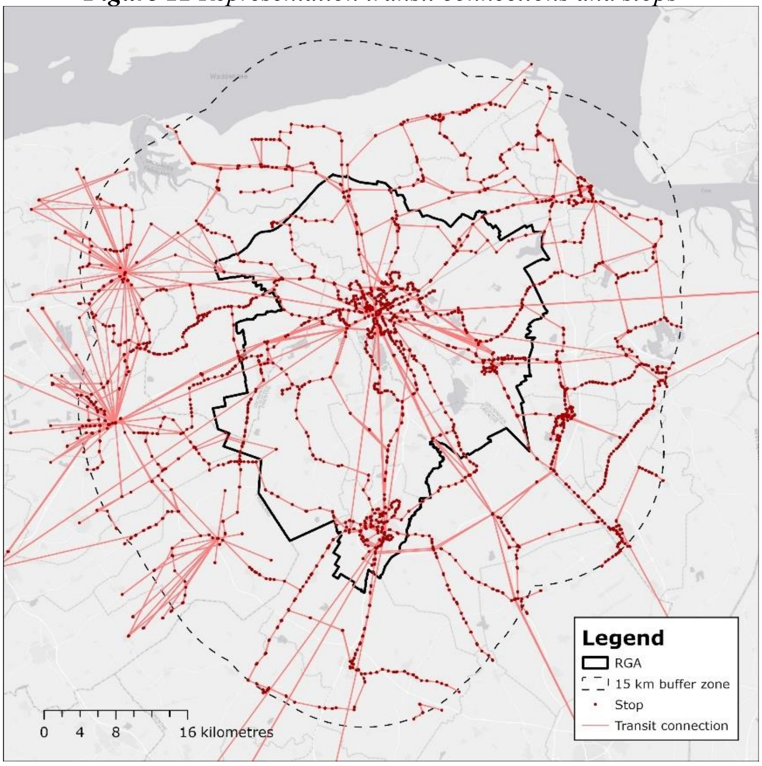
Various manuals have been consulted to create a network data set from GTFS data in ArcGIS Pro (Esri, n.d.; Esri Nederland 2022a; 2022b). Figure 11 shows an overview of the creation of the public transit network data set. Tools from the Public Transit toolbox have been combined with Network Analyst tools. All output has been generated in a Feature Data set within a geodatabase.

Figure 11 *Overview creation public transit network data set*



GTFS data have been converted to a set of feature classes and tables that represent the transit stops, lines, and schedules. For any pair of stops that are directly connected by a transit trip, the tool draws a straight line to generate the LineVariantElements features (see Figure 12). It should be noted that these straight lines are not intended to represent the actual geographical paths travelled as shown earlier in Figure 10. Instead, the lines show the linkages in the transit system calculated on the public transit schedules. Due to high computation times for the complete public transit network of the Netherlands, it has been chosen to only preserve the stops and connections within the RGA and its fifteen kilometre buffer. All intersecting stops and connections outside the region have been retained as well. In this manner, it is made sure that all considered destinations within the RGA and its fifteen kilometre buffer can be reached, while keeping computation times low.

Figure 12 *Representation transit connections and stops*



Source: OVapi (2024)

In order for a network data set to realistically model public transit, people should be able to travel towards transit stops and from the stops towards their destinations. Therefore, a multimodal network needed to be established which includes walking. The OSM Premium Data street feature class from Esri Nederland (2023) has been used as input for this multimodal network. Since pedestrians are not able to walk on every street (such as highways), a field had to be added that indicates whether pedestrians are allowed to travel on a certain street segment. This field has been calculated with the same Python script as the properties of the pedestrian restrictions in the OSM Premium Data road network data set. The transit stops have been linked to the streets to ensure such a connection (see Figure 13).

__Figure 13__ Example of connection of stops to street network

Source: Esri Nederland (2023); OVapi (2024)

The provided template in the manual by Esri (n.d.) has been used to create a network data set. Since the OSM Premium Data include long contiguous street features that are not split at each intersection, the streets connectivity policy of the network has been changed to Any Vertex. Finally, the network data set has been built to be able to perform analysis with it.

After running some simple Shortest Route analyses between random locations, it can be concluded that the GTFS-based public transit network data set returns realistic results, including travel and walking time. Strengths of this network data set are its up-to-datedness and its completeness. Some limitations are that the multimodal network only includes walking and no other means of transport, while in the Netherlands many people travel to a station by bike or car (multimodal trips). In addition, the waiting time cannot be consulted separately, since it is included in the travel time. Finally, within the Network Analyst, travel time is the only impedance that can be calculated: it is not an option to measure the actual travelled distance. However, despite these limitations, this network data set offers realistic and complete insights in travel times and therefore can be used for calculating accessibility for public transit.

4 Development of accessibility method

This chapter shows the iterative process of the creation of a method that measures the possible accessibility inequalities for the future PPU policy in the form of a case study. The chapter is divided into three cycles that are completed during the iterative process. For each iteration, the feedback loops are explained to show the process of improving the method. Overall, the case study contributes to answering the central question of this research: "*To what extent will people living in urban, suburban and rural areas be financially affected by the upcoming 'Pay-Per-Use' motor vehicle tax policy, taking into account alternative mobility options?*"

4.1 Cycle 1: Destination-based service areas

a) Problem/opportunity framing

From the literature review it appears that Dutch citizens worry that the new PPU policy will impose high costs for people living in rural areas who lack alternative mobility options besides the car. Such spatial inequalities can be quantitatively measured by the level of accessibility, since it combines both transport and land use aspects. Therefore, an accessibility method based on actual travel routes provides insight in how accessible certain areas are for different modes of transport. This method is able to show potential inequalities between regions within the RGA, which could indicate potential transport poverty and geographic exclusion for different degrees of urbanisation.

b) Solution development

In the first accessibility method prototype, service areas – visualised by isochrones – have been calculated using the ArcGIS Pro Network Analyst. This type of network analysis determines the region that encompasses all accessible streets that lie within a specified impedance. The prototype has been created by using bakeries as destinations. In the testing phase of this cycle (phase c), the other destination types are also considered.

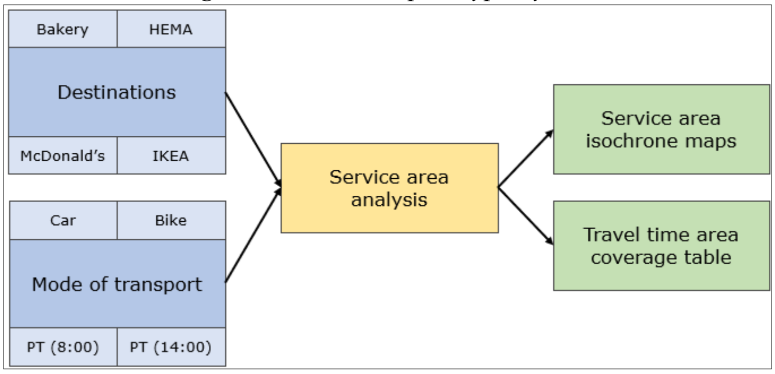
Within the OSM Premium Data network data set, the impedance can be either travel distance or travel time, which can be measured for different modes of transport. The GTFS network data set only offers the possibility of calculating travel times (see Section 3.6.2). To equally compare public transit to other modes of transport, travel time has been used as impedance. Hence, minimising travel times can also be seen as the traditional foundation of accessibility analysis (Higgins et al., 2022).

For each mode of transport (car, public transit, and bike), separate Service Area layers have been created per destination type. Table 3 shows an overview of the settings that have been implemented in these layers. One can choose to create a service area by accumulating travel time in the direction away from or toward the facilities. This would result in different service areas due to for instance one-way restrictions in the network. In this accessibility prototype, it has been chosen to calculate travel times toward facilities, since the objective is to measure how long people need to travel to reach a certain destination. For the public transit analysis, a specific date and time have to be specified. It has been chosen to analyse a random weekday (Friday 2 February 2024) and two times: one in the morning rush hour (8:00) and one in the afternoon outside peak hours (14:00). Besides visualising the results of the service areas as isochrones in maps, the spatial coverage has also been measured by calculating percentages of the area of the total area of the RGA.

Table 3 *Settings Service Area layers*

	Car	**Public transit (a)**	**Public transit (b)**	**Bike**
Facilities	Bakery, HEMA, McDonald's, and IKEA			
Mode	Car driving time	Public transit time		Bike driving time
Direction	Towards facilities			
Cutoff (in min.)	Until 40 (5 min. interval)	Until 160 (10 min. interval)	Until 160 (10 min. interval)	Until 150 (5 min. interval)
Date and time	Not using time	2-2-2024 08:00	2-2-2024 14:00	Not using time
Output geometry	Dissolved polygon rings			

Figure 14 *Flowchart prototype Cycle 1*



c) Testing

Figure 15 until 18 and Table 4 show the results of the service area analysis, with bakeries as facilities. The results of the service area analyses of the other destinations can be found in Appendix C. In all cities and villages – including their surrounding areas – people have to drive a maximum time of five minutes to reach a bakery. From each location within the RGA case study area, bakeries can be reached by car within fifteen minutes of driving (see Figure 15). 94.3% of the RGA area can reach a bakery within ten minutes (see Table 4). The areas with the highest car travel times are in the northern part of the RGA in Ezinge and around Slochteren.

Figure 17 and 18 show the public transit travel times to bakeries on the 2nd of February 2024 at respectively 8:00 and 14:00. The different departure times show similar results. Comparable to the car, people have to travel a maximum time of five minutes to reach a bakery within the cities and villages. It takes a few minutes longer to reach a bakery while departing from the edges of the urban areas. However, compared to car travel times, big differences in time could be observed outside the cities and villages. While the maximum car travel time in the area around Slochteren is fifteen minutes, people need to travel a maximum of 100 minutes (1 hour and 40 minutes) with public transit to reach the fastest reachable bakery. High travel times of over an hour can also be observed in other rural areas in between the cities and villages, such as in between Haren and Hoogezand, in between Groningen and Leek, and around Veenhuizen.

Although the total number of travel minutes differ, the resulting service areas of bakeries calculated by bike are from a spatial perspective relatively comparable with the service areas measured by public transit (see Figure 16). People living in and around the cities and villages can reach a bakery within five to ten minutes of cycling. The maximum cycling time within the RGA is 45 minutes, which is from the area around Slochteren. Besides Slochteren and Veenhuizen, the area of Ezinge stands out as a region with high cycling times.

Figure 15 *Service areas bakeries (car)*

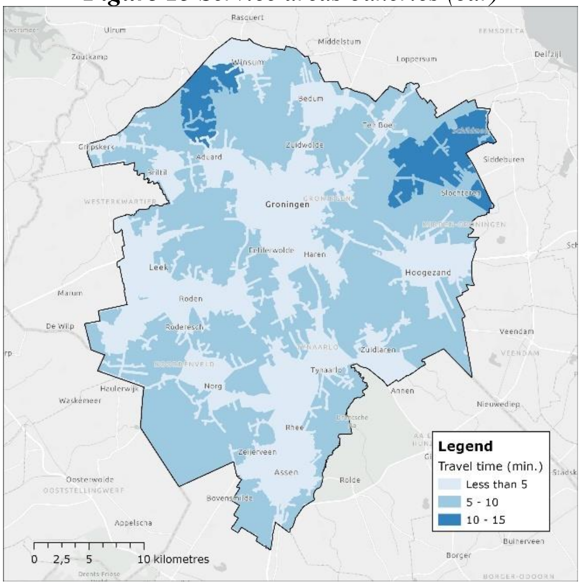


Figure 16 *Service areas bakeries (bike)*

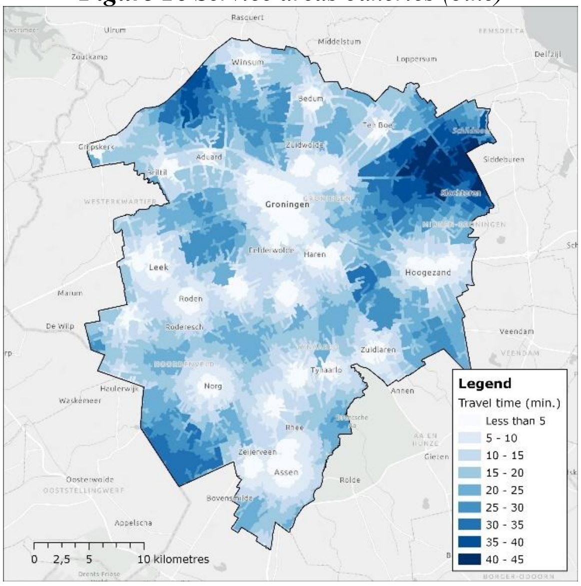


Figure 17 *Service areas bakeries (public transit 2-2-2024 8:00)*

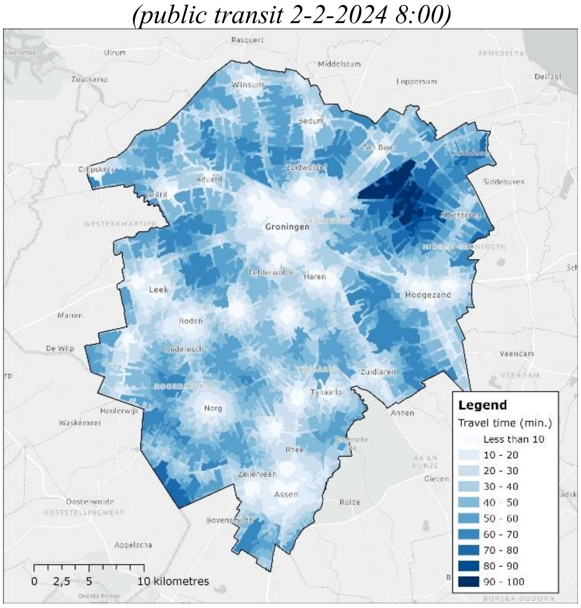


Figure 18 *Service areas bakeries (public transit 2-2-2024 14:00)*

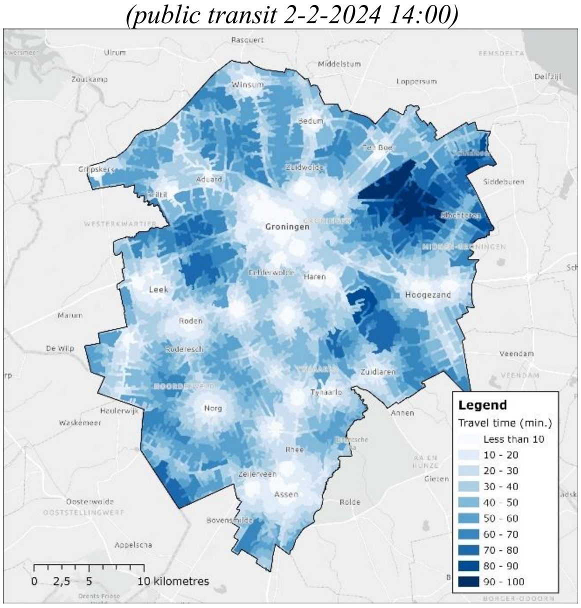


Table 4 *Travel time to bakery area coverage of the RGA by mode of transport*

	Car	**Public transit (a)**	**Public transit (b)**	**Bike**
0-10 min.	94.3 %	5.7 %	5.8 %	25.3 %
10-20 min.	5.7 %	11.6 %	11.3 %	40.4 %
20-30 min.		15.7 %	14.8 %	25,1 %
30-40 min.		18.0 %	17.5 %	7,5 %
40-50 min.		18.5 %	17.7 %	1,8 %
50-60 min.	0 %	17.0 %	16.0 %	
60-70 min.		9.4 %	8.8 %	
70-80 min.		2.3 %	4.6 %	0 %
80-90 min.		0.6 %	1.8 %	
90-100 min.		1.3 %	1.6 %	

d) *Critical reflection*

The isochrones resulting from the service area analyses show results that can be interpreted intuitively. The visual aspect of the analysis helps with distinguishing areas that have low or high travel times.

Together with the coverage table, the service areas give a complete picture of accessibility for the whole the RGA and for different modes of transport.

Some limitations have been identified in this first prototype. Firstly, the method does not consider where people actually depart when going to a destination. For instance, it could be the case that the least accessible areas of the RGA are uninhabited, e.g. nature reserves. In terms of network analysis, origins are not considered in these service areas. Secondly, although the travel times have been calculated for different modes of transport, they are not directly compared with each other in this method. Finally, the degree of urbanisation and taxes are not quantitatively assessed in this method, meaning that this approach is not able to show potential financial effects of the future PPU policy.

4.2 Cycle 2: Origin-Destination-based matrix

a) Problem/opportunity framing

To improve the first prototype created in Cycle 1, origins have been considered in the method to measure accessibility for the locations where people actually live. In addition, an opportunity to quantitatively compare travel times for the different degrees of urbanisation has been included in this improved accessibility method.

b) Solution development part 1: origins

Since accessibility of key destinations is often strongly shaped by a person's residential location (Di Ciommo & Shiftan, 2017), places of residency could be included as origins in the accessibility method in this thesis. In this manner, accessibility can be measured for where people live and thus show differences in accessibility for people living in areas with a different degree of urbanisation. Approximately 450 000 people are living in the RGA. However, the exact place of residence of these people is not publicly available due to privacy reasons. Therefore, an origin data set needs to be established with the estimated locations of residency. Statistics Netherlands (CBS) provides independent statistics on the population in the Netherlands on various scale levels, which could serve as input data. Table 5 shows an overview of the considered sources.

Table 5 *Comparison origins (CBS)*

Scale	RGA
All residents (estimated location in BAG buildings per neighbourhood)	477 022
BAG buildings residential function	154 278
CBS Vierkantstatistieken 100m x 100m (inhabited cells)	11 354
CBS Vierkantstatistieken 500m x 500m (inhabited cells)	2061
CBS Neighbourhoods (*buurten*)	471
CBS Districts (*wijken*)	82

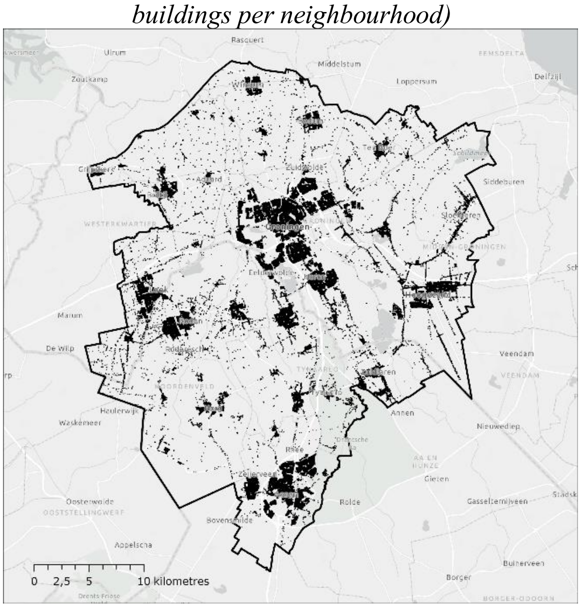
Firstly, a detailed origin data set has been created by estimating the place of residency of all 477 022 people living in the RGA. Based on the amount of residents per neighbourhood (CBS, 2022a), random points have been allocated to all 154 278 buildings with a residential function in the corresponding neighbourhood (Kadaster, 2023) (see Figure 19). Such a detailed data set would provide the most detailed possible results, but could demand high computation times.

A related option is to use the 154 278 buildings with a residential function as input origin data set (see Figure 20). This smaller data set – which could still demand high but overall less computation time – gives detailed locations of the place of residency within the RGA, but does not take into account how many people are living in a building. For instance, no differentiation is made between a high-rise apartment building with 150 people or a single house with two people living in it.

Figure 21 and 22 show inhabited cells per square of respectively 500m x 500m and 100m x 100m. The former also includes data on the degree of urbanisation (*omgevingsadressendichtheid* and the resulting *stedelijkheid*). Within the 100m x 100m squares, the statistics are rounded to fives. The data set consists of squares which contain at least five residents or five houses. Therefore, this data set gives a suitable estimation of where people live. The demographic statistics could be coupled to the results of the accessibility measure to provide additional insights.

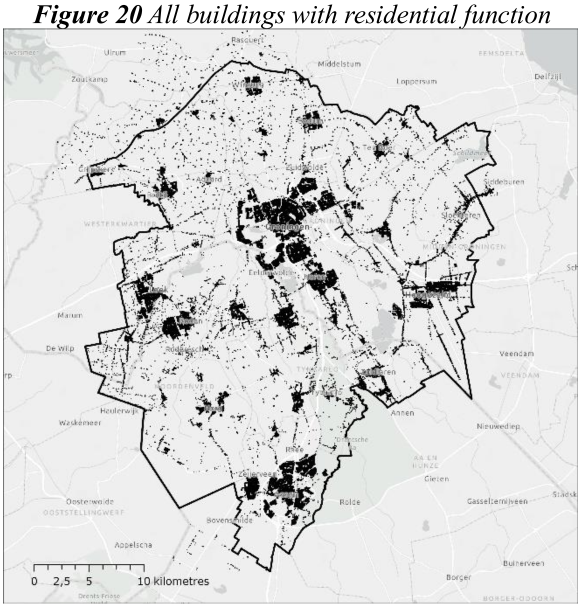
Options for aggregated origin data sets – which would have the advantage of requiring little computation time – would for instance be the centre points of the 82 districts or the 468 neighbourhoods within the RGA (see Figure 23 and 24). These data sets contain statistics about the number of residents, which could be coupled to the results of the accessibility measure. However, a disadvantage is that travel times are only measured from one point within the areas and thus no differentiation within the districts or neighbourhoods could be made. Another limitation is that the areas do not exactly cover the RGA borders.

Figure 19 *All residents (estimated location in BAG buildings per neighbourhood)*



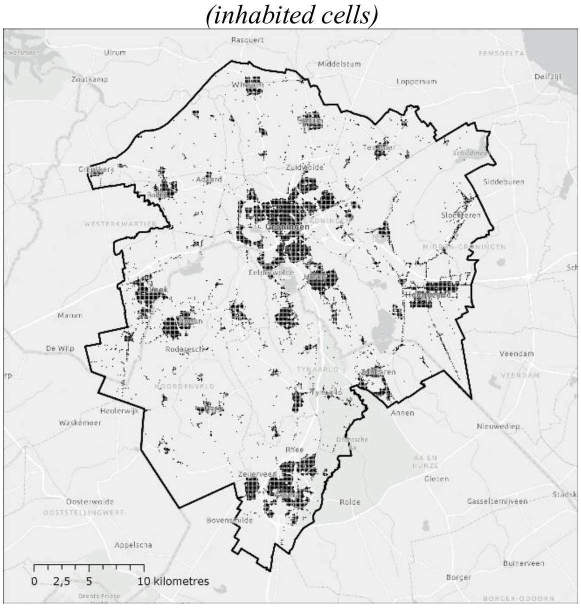
Source: Kadaster (2023); Esri (2022c)

Figure 20 *All buildings with residential function*



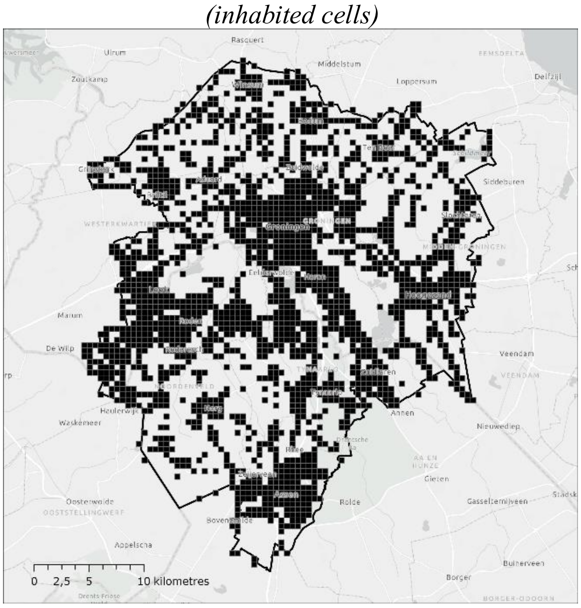
Source: Kadaster (2023)

Figure 21 *CBS vierkantstatistieken 100m x 100m (inhabited cells)*



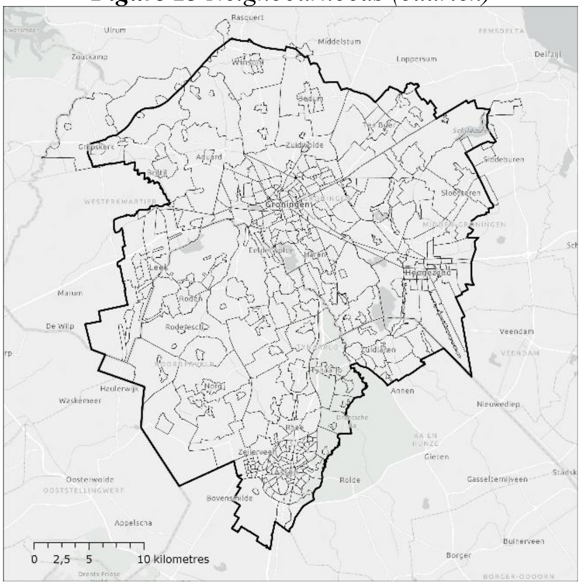
Source: CBS (2022a)

Figure 22 *CBS vierkantstatistieken 500m x 500m (inhabited cells)*



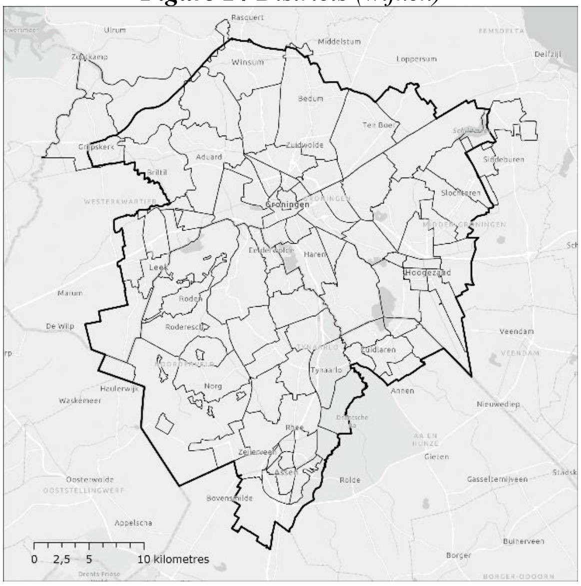
Source: CBS (2022b)

Figure 23 *Neighbourhoods (buurten)*



Source: Esri (2022c)

Figure 24 *Districts (wijken)*



Source: Esri (2022b)

During some simple testing with the origin data sets, it appeared that the building-based data sets require too much computation time. On the other hand, analyses with the districts and neighbourhood data sets lose much detail due to aggregation. It has been chosen to use the CBS 100m x 100m as input data, due to its reasonable computation time and the included demographic and environmental statistics. Origin cells with a population value of -99997 are excluded from the calculations. The number of residents living in these cells is less than five: therefore, the cells should be handled equally to the cells that are not included at all in the 100m x 100 m data set (CBS, 2022a).

Solution development part 2: analysis

In this second accessibility method cycle, Origin-Destination (OD) Cost Matrices have been calculated using the ArcGIS Pro Network Analyst. This type of network analysis finds and measures the least-cost paths along the network from multiple origins to multiple destinations. For each mode of transport (car, public transit, and bike), separate OD Cost Matrix layers have been created per destination type. Table 6 shows an overview of the settings that have been implemented in these layers. Since the service areas in Prototype 1 did not show much difference in public transit travel times between 8:00 and 14:00, only 8:00 is used in this developing phase.

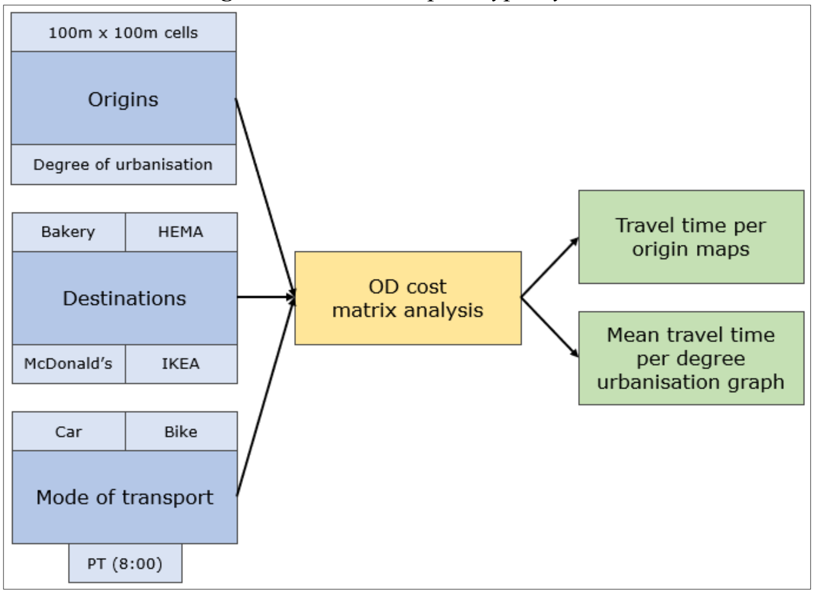
Similar to the first prototype in Cycle 1, travel time has been considered as impedance. Although many accessibility measures take into account the number of destinations that can be reached within a specified period of time (Geurs & Ritsema van Eck, 2001), this thesis solely focuses on the fastest reachable facility. This focus is because the central question of this research about the upcoming PPU policy is about whether people have access in general to alternative mobility options. No differentiation has been made between the number of destinations and their characteristics such as size. In other words, without a maximum travel time (cutoff), the travel times to the fastest reachable (least-cost) destination have been calculated.

The resulting OD matrices – originally represented as line feature classes – for all travel modes have been combined into one data set per destination to compare travel times with each other. Since the degree of urbanisation is not available in the CBS 100m x 100m data set, this has been spatially joined from the CBS 500m x 500m data set. To compare travel times among the different modes of transport and to compare these with the degree of urbanisation, statistics of mean travel times per mode of transport for each degree of urbanisation have been visualised in a bar chart.

***Table 6** Settings OD matrix*

	Car	Public transit	Bike
Origins	CBS 100x100		
Destinations	Bakery, HEMA, McDonald's, and IKEA		
Mode	Car driving time	Public transit time	Bike driving time
Cutoff	-		
Destinations	1		
Date and time	-	2-2-2024 08:00	-

***Figure 25** Flowchart prototype Cycle 2*



c) Testing

Figure 26, 27, and 28 show the travels times per origin to the closest bakery for each mode of transport. Although travel times to bakeries differ between the modes of transport, a similar spatial pattern can be observed: the lowest travel times are in the cities and villages, while the highest travel times occur in the remote areas.

Figure 26 Travel time to closest bakery (car)

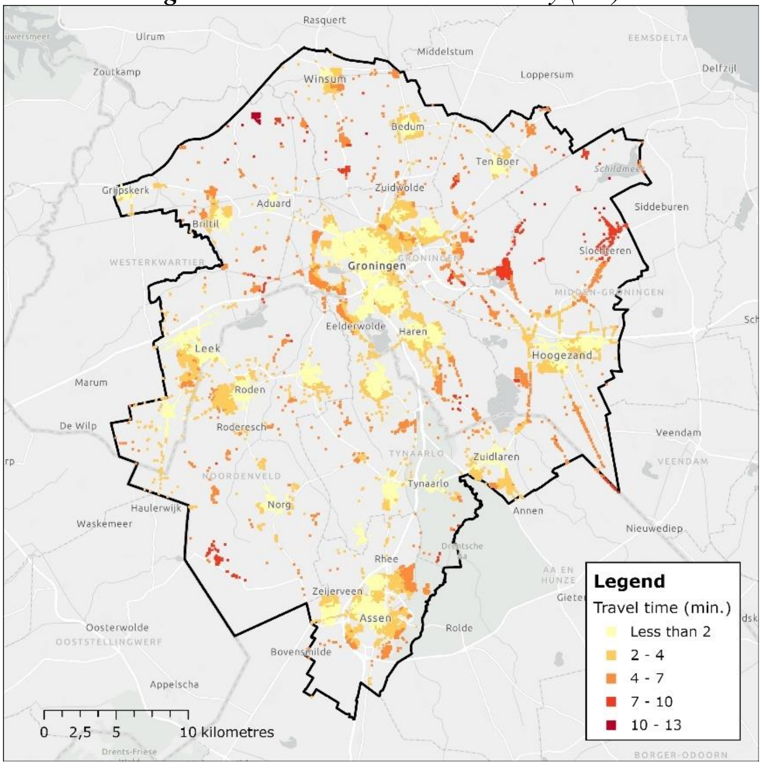


Figure 27 Travel times to closest bakery (bike)

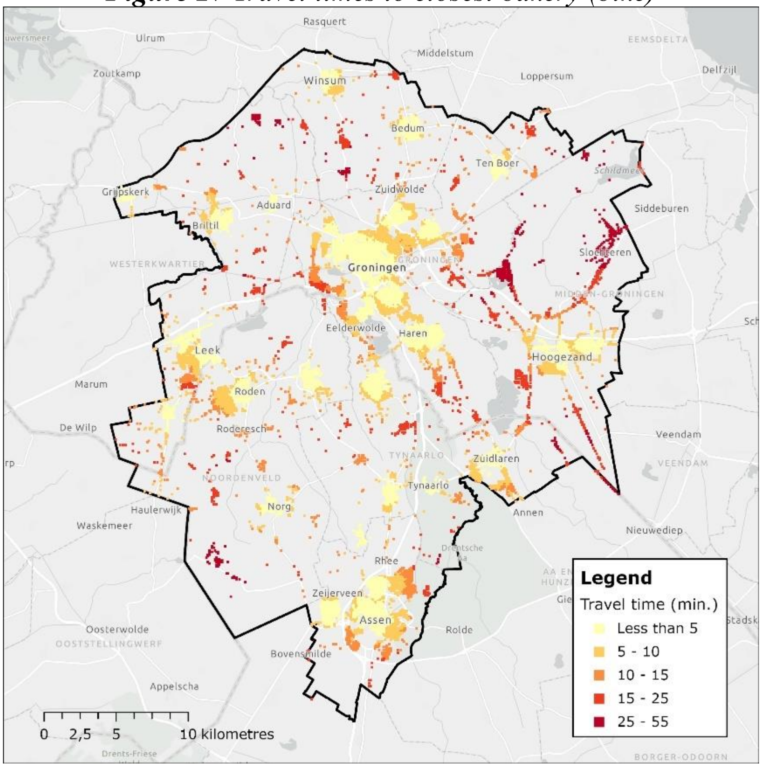


Figure 28 *Travel times to closest bakery (public transit 2-2-2024 8:00)*

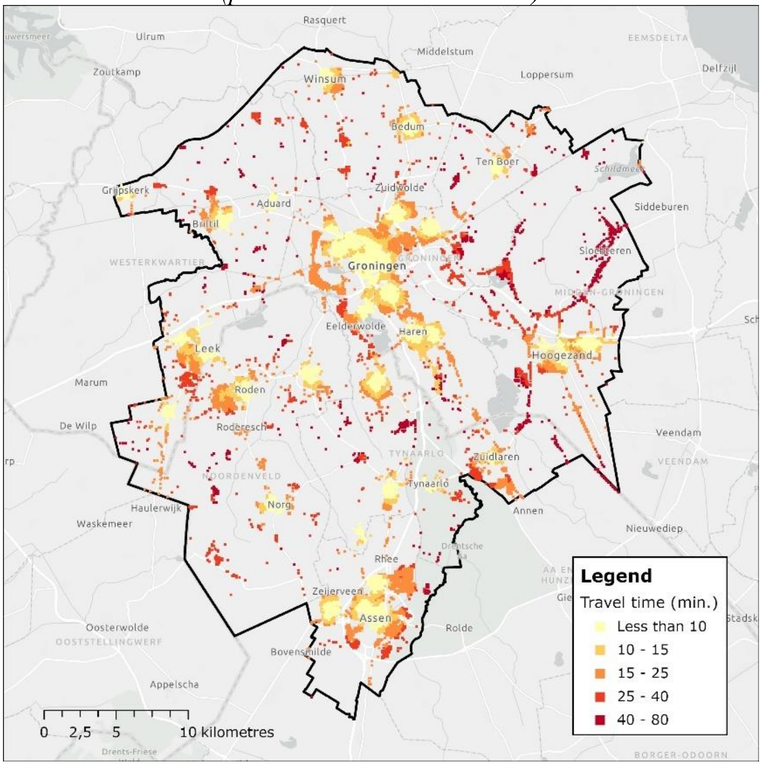
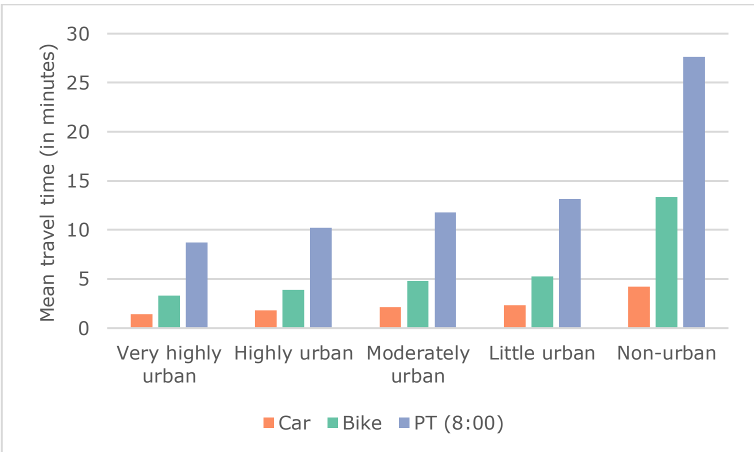


Figure 29 shows the mean travel time for each mode of transport per degree of urbanisation. It appears that in each degree of urbanisation the car is the fastest travel mode, following by the bike, and finally public transit. Especially in non-urban areas in the RGA the differences between the car and public transit are high.

Figure 29 *Mean travel time to bakery per degree of urbanisation per mode of transport*



d) Critical reflection

The OD matrix results show more detailed outcomes compared with the service areas since they consider the location of the place of residency. A clear spatial pattern can be observed in the results. The comparison of both modes of transport as degrees of urbanisation quantitatively shows differences in the distribution of travel times in different types of areas. The OD Matrix therefore appears to give more insight in accessibility inequalities among regions, especially by comparing the mean travel times per degree of urbanisation.

However, some limitations still arise in this method. The decision of only taking one departure time for public transit into account in this cycle is considered too simplistic in retrospect. It has been realised that the results of a public transit travel time analysis can be very dependent on the specified departure date and time, since the transit schedule varies throughout the day. For instance, if a bus departs at 7:59, a departure time of 8:00 provides weak accessibility values, although the connection could in reality be very good if one would depart one minute earlier.

Although the prototype that is created in this cycle considers the place of residency, the isochrones in Cycle 1 might be more intuitively interpretable compared to the 100m x 100m origin cells in the OD matrix. Additionally, the travel times are not yet linked to the amount of people living in an origin cell and direct comparisons between travel times of different modes of transport are lacking. Finally, financial costs of the current MVT and the future PPU are not considered in this prototype, which makes it impossible to evaluate possible inequalities in changing costs due to the upcoming PPU policy.

4.3 Cycle 3: Enhanced Origin-Destination-based Matrix

a) Problem/opportunity framing

In the third prototype the improvements obtained by using the OD-matrix are extended. To improve the prototype in Cycle 2, a solution has been found for the public transit dependency on date and time. Other improvements of the model are creating accessibility scores (e.g. from 0-1) and integrating the amount of people living in a 100m x100m cell to account for the population living in an origin.

Although an accessibility score could already provide insight in possible inequalities as a result of the upcoming PPU policy, the change in tax costs is an interesting addition to evaluate the financial aspect. However, this change in financial costs is hard to determine on an aggregated level: the current MVT is calculated based on – among others – the type of fuel, the emissions, and the weight of a vehicle, while the future PPU is based on the number of kilometres someone drives. Neighbours living in the same 100m x 100 m cell could have very different type of cars as well as very different annual mileage, which makes the calculation of the change of tax costs hard on an aggregated level. Therefore, the improved accessibility method highlights specific people rather than drawing conclusions for entire regions.

b) Solution development

In this final prototype, the calculation of car and bicycle travel times stay the same as in the prototype in Cycle 2. However, for public transit, an alternative tool has been used to calculate travel times to correct for the dependency on date and time. This tool, named Calculate Travel Time Statistics (OD Cost Matrix), is part of the additional ArcGIS Transit Network Analysis Toolbox. For each origin-destination pair, the tool calculates the minimum, maximum, and mean travel time over a specified time window. Firstly, the number of destinations has been changed from 'None' to '1' in the Python configuration file to find a route between the origin and the least-cost destination. The departure date has been specified again at 2 February 2024. To account for the dependency on the transit schedule, a time window between 7:00 and 19:16 has been set, in which the travel times are measured every 23 minutes. This time window has been chosen since the destinations (bakeries, HEMAs, McDonald's, and IKEAs) are generally opened. The 23 minutes time interval makes sure that each iteration starts at a different minute of the hour over the course of the service day. In this way, processing time and temporal coverage have been balanced.

Accessibility inequalities

With the recalculated travel times for public transit, an overview for travel times for all modes of transport and each destination type has been created. To account for the population, the amount of origin cells and the accompanied amount of people living in those cells are presented for each travel time class (see Table 7 in Chapter 5). This overview gives insight in absolute travel times to all four destinations for traveling with car, bike, and public transit. This overview has been created by reclassifying the absolute travel time fields into the travel time classes. For each class, the amount of origin cells has been counted and the accompanying population has been summarised.

To spatially illustrate the inequalities of alternative mobilities besides the car on maps by means of accessibility scores, the travel times of the different modes of transport have been compared with each other. Comparable with Benenson et al. (2011), the ratios of the public transit and bike travel time (i.e. the alternatives) compared to the car travel time have been calculated by dividing the amount of minutes with each other. However, it soon became apparent that this could give undesirable results: for instance, ratios for origins with low travel times for all modes of transport could still be high, due to the relative nature of this method. Although reaching a destination from a certain origin cell would e.g. only take 0,1 minutes by car and 0,9 minutes by public transit, this origin cell would have a relatively high ratio, while the origin cell in reality has a good accessibility for both car and public transit.

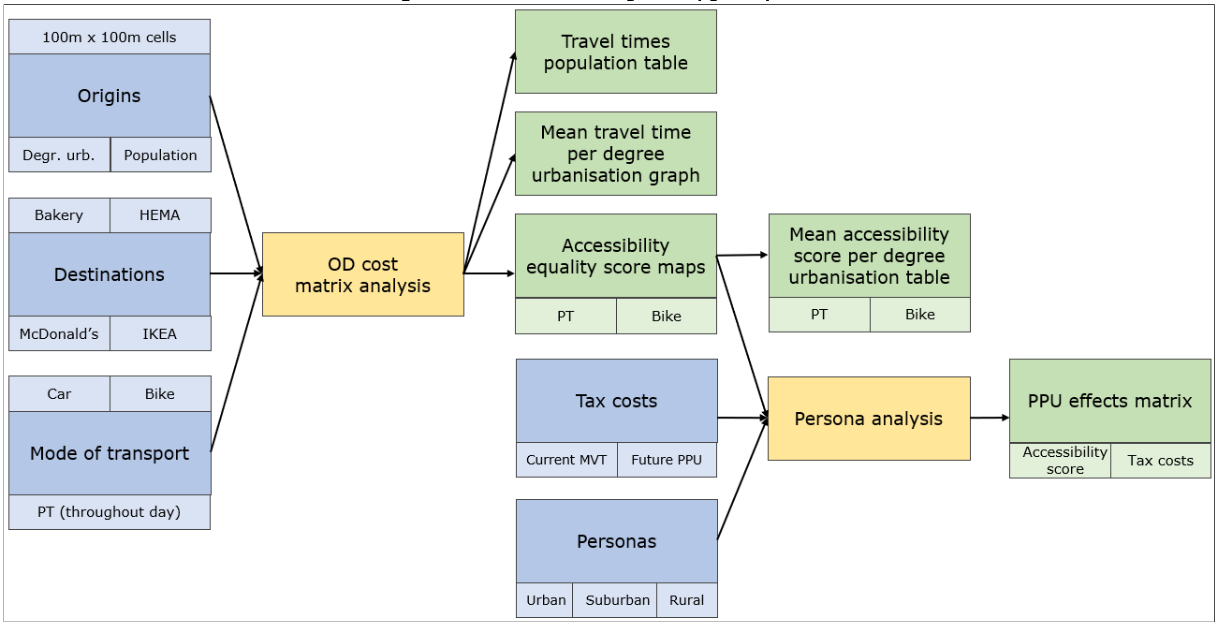
Therefore, it has been chosen to focus on the absolute differences of travel time of the different modes of transport as a means of showing inequalities between regions. For each destination, the absolute differences have been calculated separately between respectively (1) travel times of the car against public transit and (2) travel times of the car against the bike. The absolute values have subsequently been transformed into scores from 1 to 10 using the decile technique proposed by Joubert (2022) (see Figure 35 until 42 in Chapter 5). Such scores might be more intuitive and easier to understand than absolute numbers. With this technique, the origin cells with a score of 10 belong to the 'most equal' 10%, in which travel times of the alternative mobility differ the least from the car. On the other hand, the origin cells with a score of 1 belong to the 'least equal' 10%: travel times of the alternative mobility differs the most compared to the car travel time. Therefore, the higher the score, the higher the equality in accessibility alternatives. Some experiments have been conducted to also include population per cell into the accessibility scores, which is also conducted by Joubert (2022). However, it appeared quickly that these results give uninterpretable results as they are calculated based on absolute travel time differences. Therefore, the actual meaning of a certain accessibility equality score becomes rather unclear which could result in drawing wrong conclusions. Finally, for each degree of urbanisation and for each type of destination, the mean accessibility equality score for both public transit and cycling has been calculated (see Table X in Chapter 5).

Financial effects PPU for personas

Since drawing conclusions on the change of financial costs on an aggregated level appears to be difficult due to varying types of cars and annual mileage, it is chosen to focus on specific people in terms of personas. Three fictional personas have been set up that represent three types of inhabitants of the RGA (see Figure 43 in Chapter 5). It is important to mention that these personas are created arbitrarily: the purpose of setting up personas is to illustrate examples of changing costs, rather than drawing conclusions for certain types of regions within the RGA.

To compare the possible financial effects of the upcoming PPU among the three personas, a matrix has been created combining the different destinations in terms of accessibility and changing tax costs (see Table 9 in Chapter 5). For each destination and each persona, the table shows (1) the accessibility equality scores for public transit and bike against the car, and (2) the changing car tax costs for a trip to the nearest facility. The calculation of the current MVT tax costs is based on a comparison made by the Ministry of I&W and the Ministry of Finance (2023), who calculated costs for different types of cars and type of fuels. For each persona, a car and annual mileage have been chosen from this comparison. By dividing the yearly MVT costs by the annual mileage, tax costs per kilometre have been calculated. Although a fixed price per kilometre in the potential future PPU policy has not been confirmed yet, the estimation of 6,82 cents per kilometre by the Ministry of Finance (2022) has been assumed in this thesis. The taxes per kilometre have been multiplied with the actual driven distance by car to the fastest reachable destination. In this way, the costs per trip to each destination could be calculated for the current and potential future situation.

__Figure 30__ Flowchart prototype Cycle 3



c) Testing and d) Critical reflection

The results of this final accessibility method can be found in Chapter 5. The critical reflection of the method in this cycle as well as of the complete thesis can be found in Chapter 6.

5 Results

This chapter show the results of the final multi-part accessibility method – which has been created in Cycle 3 (Section 4.3) – for all four destination types. Section 5.1 presents the results on accessibility inequalities for the entire RGA region, whereas Section 5.2 zooms in on three personas to display changes in financial costs as a result of the future PPU policy as opposed to the current MVT.

5.1 Accessibility inequalities

5.1.1 Travel time comparison table

Table 7 shows the share of origin cells (n=11 354) and the share of the population living in those origin cells (n = 455 530) that have to travel a certain amount of minutes to visit the fastest reachable destination, calculated separately for each mode of transportation. The results reveal variations in travel times, highlighting large differences in travel times for different modes of transport across the population of the RGA. From this table it appears that – for each type of destination – car travel times are generally the lowest, followed by respectively cycling and public transit. Overall, bakeries request the lowest travel times, while the IKEA in Groningen requires the highest travel times.

Approximately all residents living in the RGA (99,7%) could reach a bakery within 10 minutes by car, juxtaposed against 86,5% by bike and 44,2% by public transit. Although cycling and using public transit takes more travel time, most people living in the RGA can reach a bakery within 20 minutes of traveling with these alternative mobility options. The distinction between the amount of origin cells and the population within those cells shows the effect of considering population density: for instance, 73,9% of the origin cells have a cycle travel time to a bakery between 0 and 10 minutes, whereas 86,5% of the population is living in these cells. Conversely, although from roughly 28% of the cells the travel time to a bakery by public transit is higher than 20 minutes, this only accounts for 14,3% of the population. Overall, the share of both origins and population decreases as travel time increases.

A similar pattern of travel times can be observed for the department store HEMA in terms of car travel time: almost all residents (96,3%) can reach a HEMA in 10 minutes of driving. However, especially for public transit, higher shares of the population are now observed in classes with higher travel times than 10 minutes. 38,7% of the population has to travel 10-20 minutes by public transit, whereas only 22,5% of the population has access to a HEMA in under 10 minutes with this mode of transportation. Apart from this observation, the share of both origins and population generally decreases as travel time to a HEMA increases.

Although everybody in the RGA can still reach a McDonald’s within 20 minutes of driving by car, travel times of the alternative mobilities are getting larger for higher shares of the population. More than half of the residents of the RGA (60,5%) could reach a McDonald’s within 20 minutes of cycling, as opposed to 28,8% by travelling 20 minutes with public transit. Overall, the share of both origins and population generally still decreases as travel time to a McDonald’s increases.

Larger variations in travel time throughout the RGA can be observed for the IKEA in Groningen. Although still roughly half of the population (47,4%) can reach the IKEA in 10 minutes of driving, the other half of the population has to drive up to 40 minutes. Conversely, the distribution of population shares among the travel time classes for the other modes of transportation differ substantially. Only small shares of the population – 9,0% for cycling and 0,2% for public transit – can reach an IKEA in 10 minutes of travelling with alternative mobilities. Around a quarter of the population (28,0%) has to travel more than an hour to visit the IKEA with public transit. Whereas for all other destinations the share of both origins and population decreases as travel time increases, another pattern is visible for cycling to IKEA: 16,1% of the people living in the RGA have to cycle more than 100 minutes to go to the IKEA in Groningen.

***Table** 7 Share of origin cells (ori.)(n= 11 354) and population in origin cells (pop.)(* n = 455 530) *(in %) per travel time class (in minutes) per mode of transport per destination*[5]

Travel time	**Bakery**						**HEMA**						**McDonald's**						**IKEA**					
	Car		*Bike*		*PT*		*Car*		*Bike*		*PT*		*Car*		*Bike*		*PT*		*Car*		*Bike*		*PT*	
	ori.	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*	*ori.*	*pop.*
0-10	99,3	99,7	73,9	86,5	32,6	44,2	93,4	96,3	49,5	65,9	14,6	22,5	69,1	79,4	16,1	30,8	2,8	7,6	29,1	47,4	3,9	9,0	0,1	0,2
10-20	0,3	0,2	18,2	10,2	38,5	41,2	6,2	3,5	27,9	22,9	29,6	38,7	30,5	20,4	24,9	29,7	11,4	21,2	50,9	35,7	12,7	25,3	2,0	4,9
20-30			5,3	2,0	15,4	9,5			9,7	4,4	26,1	24,7			17,2	13,3	22,8	28,6	19,3	16,5	11,6	13,0	5,4	12,3
30-40			1,9	1,0	6,7	2,6			8,8	4,6	14,2	8,1			10,7	6,0	28,2	23,7	0,4	0,2	5,6	3,5	11,9	19,9
40-50			0,2	0,1	5,1	1,9			2,4	1,2	8,8	3,4			12,2	7,9	18,6	12,1			8,5	5,5	17,4	16,7
50-60			0,1		0,9	0,2			1,3	0,7	4,4	1,9			9,0	6,1	8,6	4,3			8,3	5,7	20,3	17,7
60-70					0,3	0,1					1,4	0,3			6,8	4,7	4,2	1,4			12,8	9,6	26,2	21,6
70-80											0,5	0,1			1,8	0,7	2,0	0,6			9,9	6,3	7,6	3,5
80-90															0,8	0,4	0,6	0,1			6,1	3,8	2,7	0,7
90-100																	0,4	0,1			3,5	1,9	3,5	1,3
>100																					16,7	16,1	2,5	0,9
No data	0,4	0,2	0,4	0,3	0,4	0,3	0,4	0,2	0,4	0,3	0,4	0,3	0,4	0,2	0,4	0,3	0,4	0,3	0,4	0,2	0,4	0,3	0,4	0,3

[5] Cells with value 0,0% have been left blank for readibility purposes. Each column sums up to 100% (rounding may cause minor deviation)

5.1.2 Degree of urbanisation comparison graph

Figure 31, 32, 33, and 34 show comparisons of mean travel times for each mode of transportation among regions with different degrees of urbanisation for respectively bakeries, HEMAs, McDonald's, and IKEA. The mean travel times are calculated from all inhabited 100m x 100m cells in the RGA in which at least five people live. For each destination, it appears that the car is evidently the fastest travel mode for all degrees of urbanisation. Large differences in travel times for each mode of transport can be observed especially in the non-urban – i.e. rural – areas in the RGA. For destinations on a local and sub regional scale (respectively bakeries and HEMAs), mean travel times for cycling and public transit differ substantially: on an average level, cycling appears to be roughly twice as fast as using public transit (see Figure 32 and 33). Although this pattern is also visible in (very) highly urban areas for McDonald's as a destination, mean travel times of cycling appear to approach travel times of public transport in the other degrees of urbanisation (see Figure 34). The mean travel time of cycling to IKEA is – except for very highly urban areas – larger than the mean travel time of public transport (see Figure 35).

Figure 31 *Mean travel time to bakery per degree of urbanisation per mode of transport*

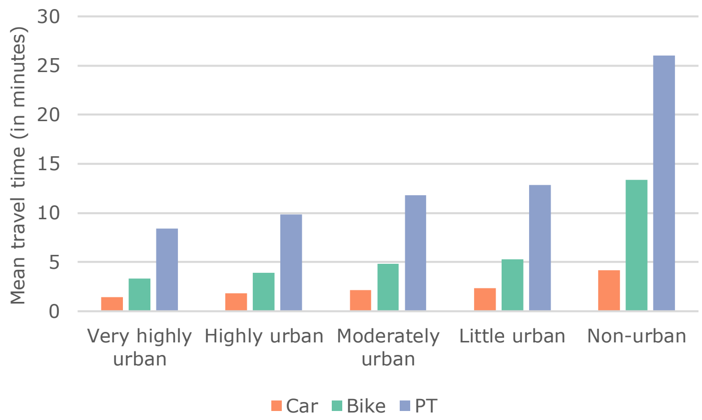


Figure 32 *Mean travel time to HEMA per degree of urbanisation per mode of transport*

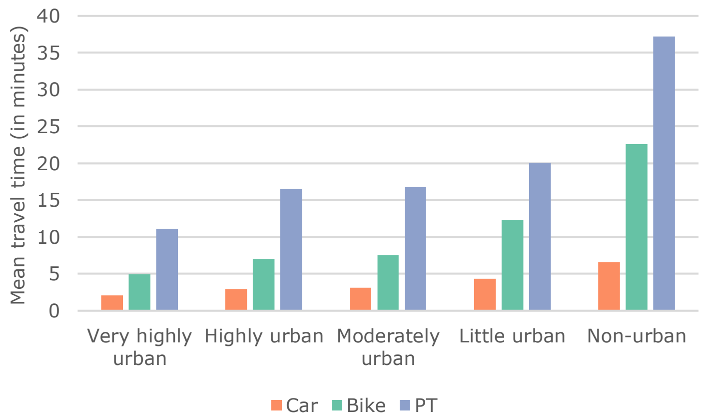


Figure 33 *Mean travel time to McDonald's per degree of urbanisation per mode of transport*

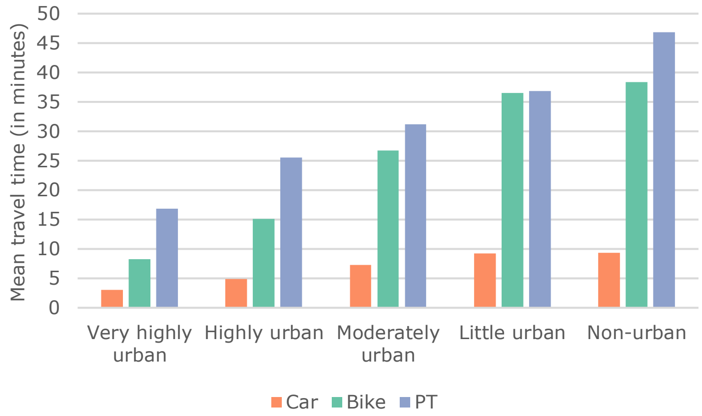
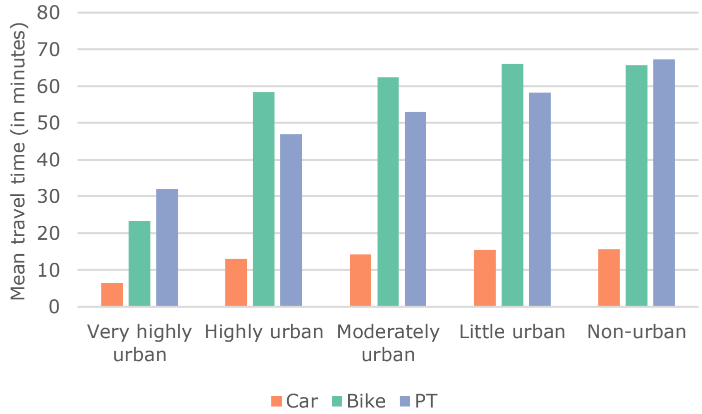


Figure 34 *Mean travel time to IKEA per degree of urbanisation per mode of transport*



5.1.3 Accessibility inequality maps

Figure 35 until 42 show the resulting accessibility inequality scores for all origin cells in the RGA where five or more people live. For each destination, the score is based on travel time differences between car and either public transit or the bike. The higher the score, the more equal the travel time in a cell is in terms of accessibility. For instance, a score of 1 represents the 10% highest travel differences in the RGA with either bike or public transit, as opposed to the car. Conversely, a score of 10 represents the 10% lowest travel differences in the RGA compared with the car.

For both public transit and cycling, the accessibility in equality scores for bakeries have a similar spatial pattern (see Figure 35 and 36). Overall, high accessibility equality scores are observed in centres of cities and villages, whereas low scores are mainly scattered throughout the rural areas within the RGA. Areas with high concentrations of low scores are mainly located east of the city of Groningen and north of Hoogezand.

The concentration of high scores in the city centres is also visible for HEMA as a destination (see Figure 37 and 38). However, the spatial distribution has changed slightly in a sense that smaller villages overall have lower accessibility equality scores compared with bakeries as destination. Although the spatial pattern between public transit and bike is relatively equal, some notable differences arise: the villages Winsum and Ten Boer have relatively high scores in the public transit comparison, while they have low scores in the bike comparison. This means that differences in travel time with the car in these villages are relatively smaller compared with public transit, than compared with bike.

Figure 35 *Bakery public transit score*

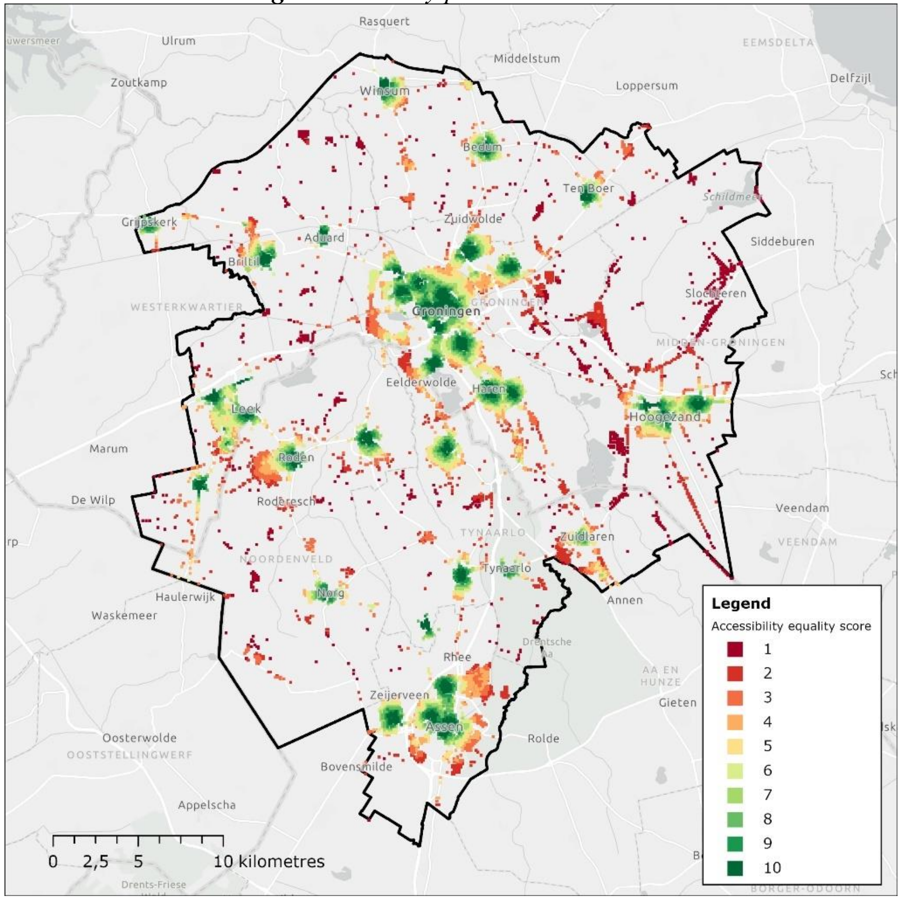


Figure 36 *Bakery bike score*

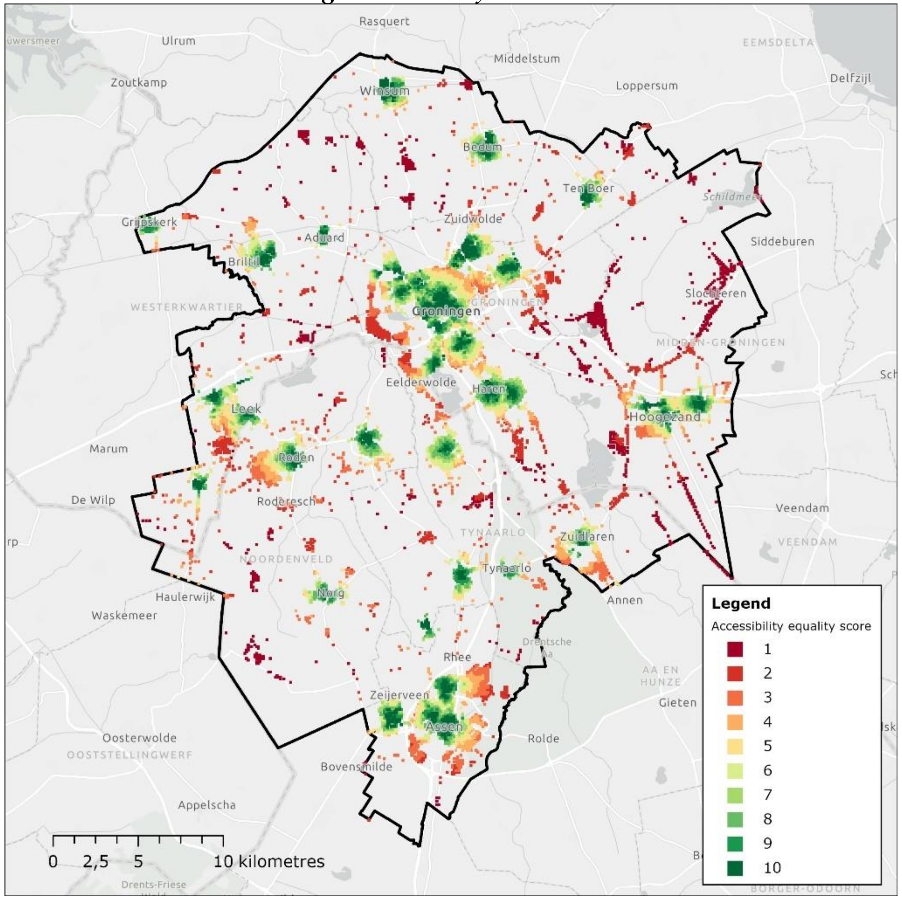


Figure 37 *HEMA public transit score*

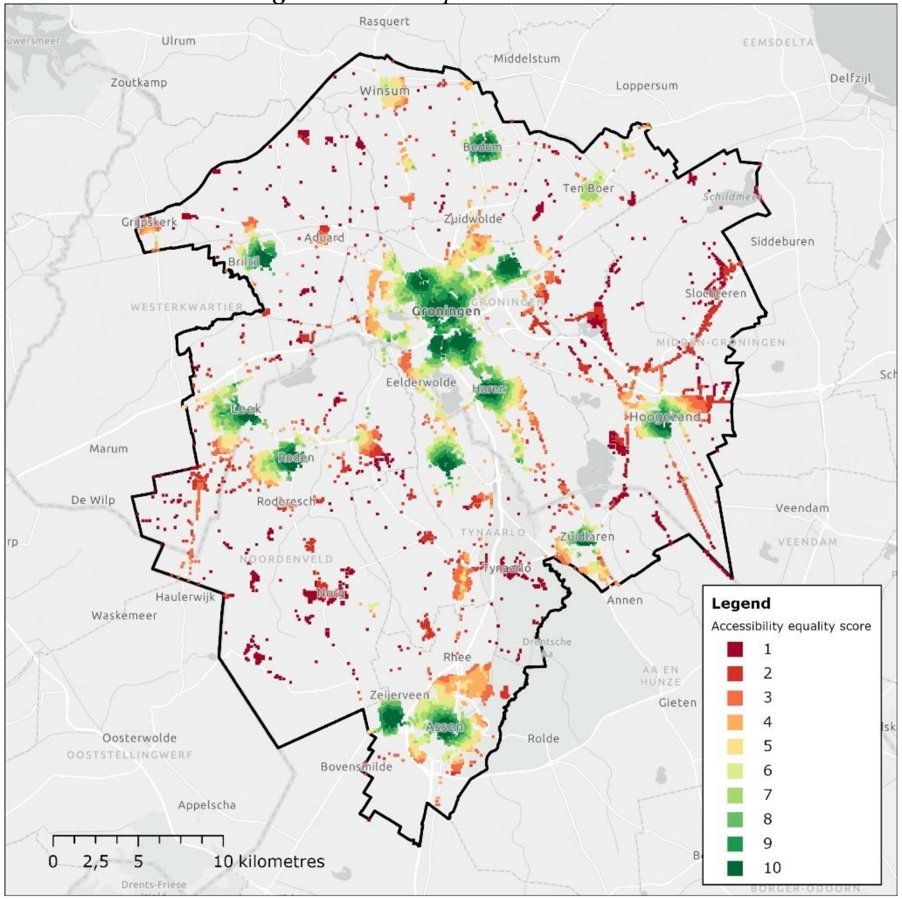


Figure 38 *HEMA bike score*

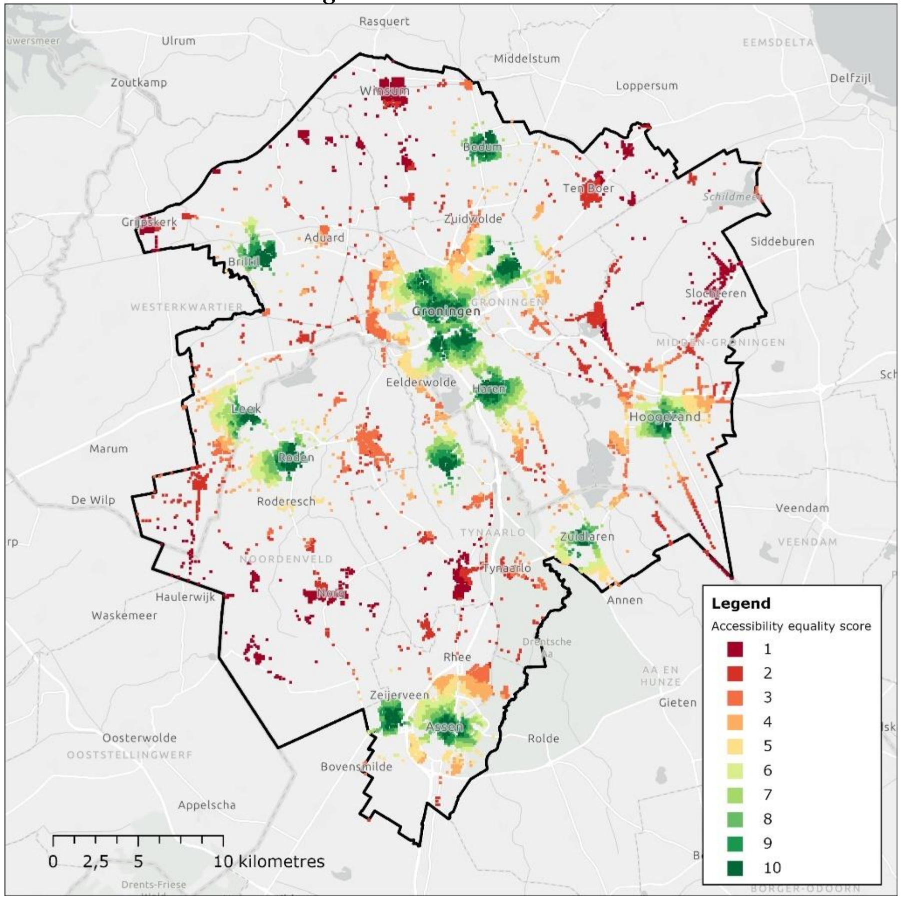


__Figure 39__ McDonald's public transit score

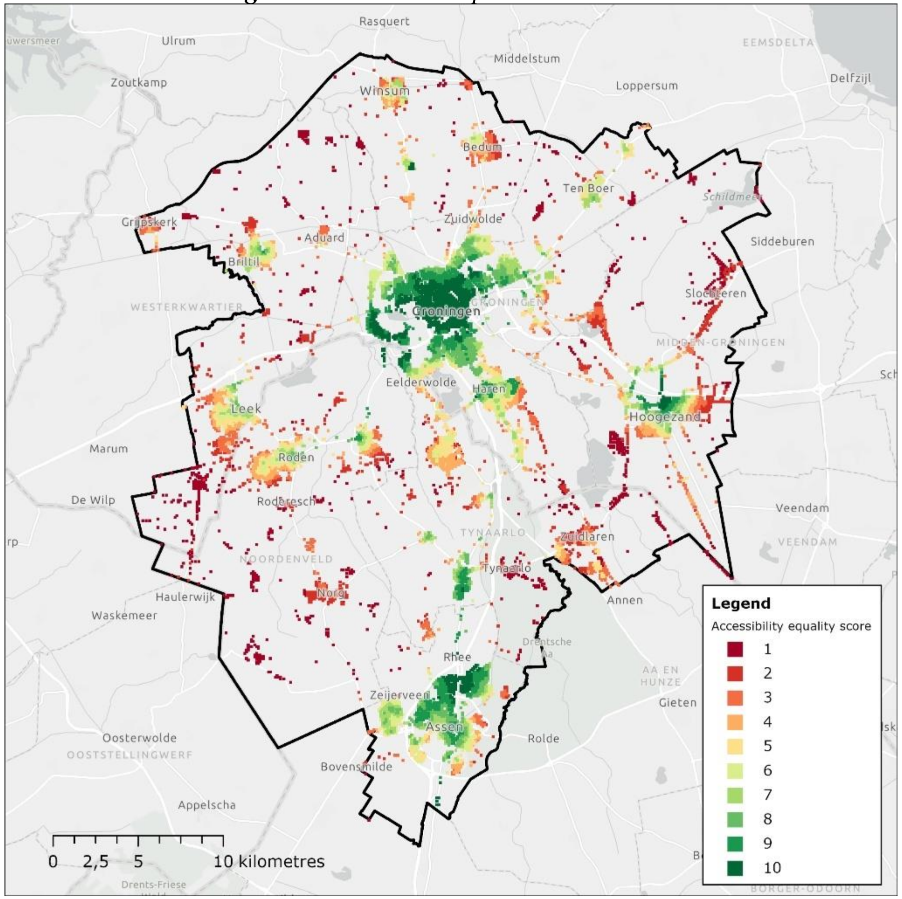


__Figure 40__ McDonald's bike score

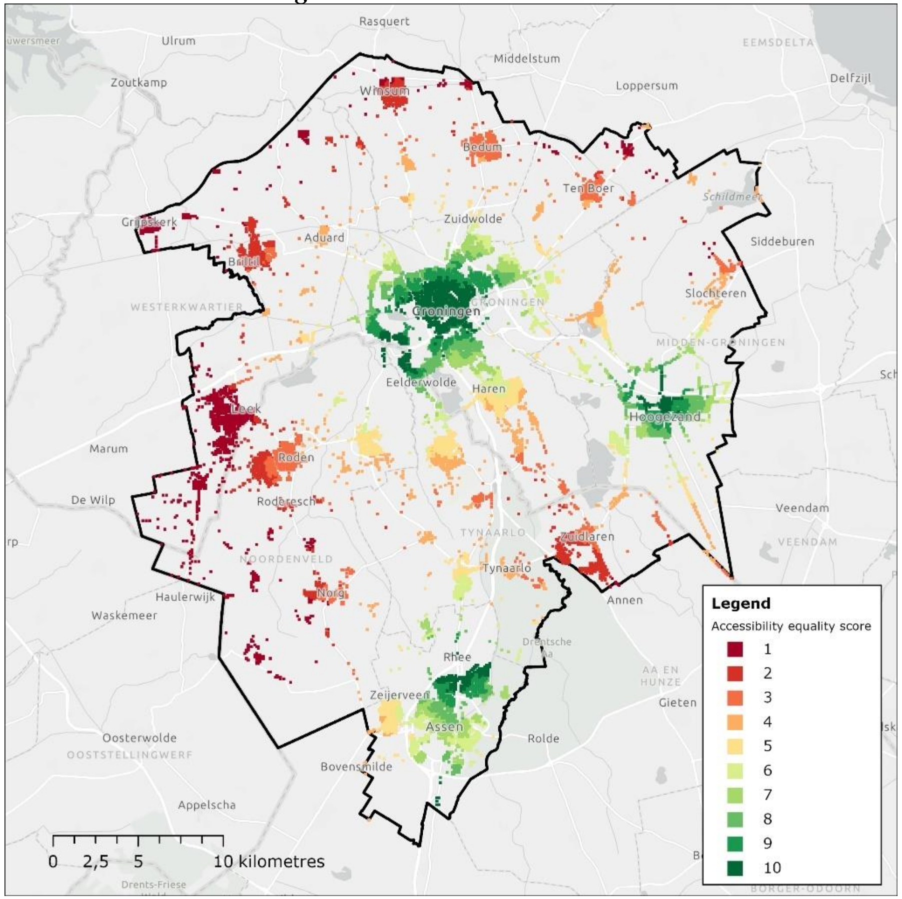


Figure 41 *IKEA public transit score*

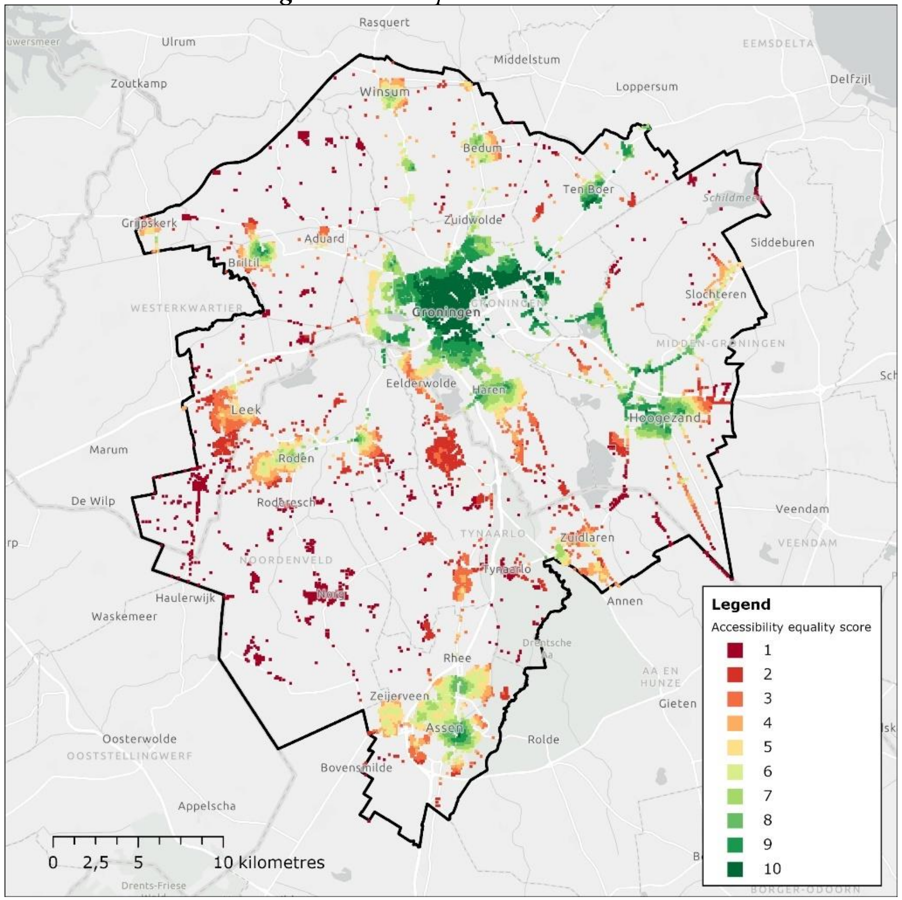
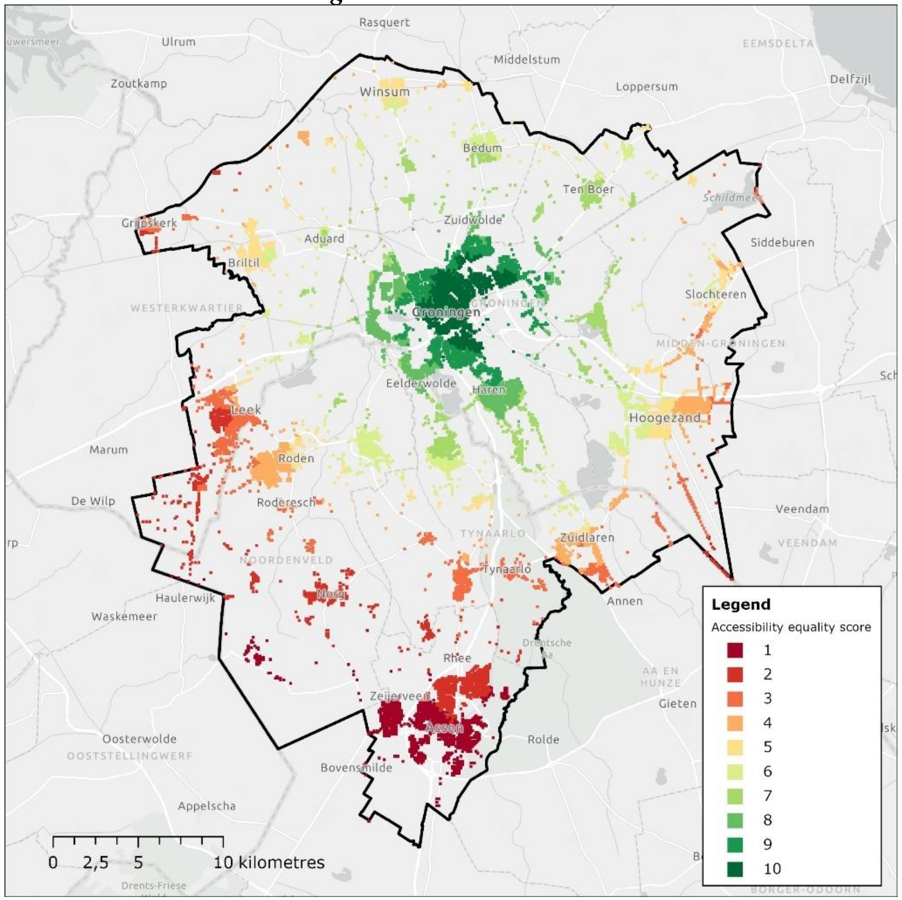


Figure 42 *IKEA bike score*



Differences between public transit and bike accessibility equality scores are more apparent for McDonald's as a destination (see Figure 39 and 40). Whereas the distribution of public transit scores is quite scattered throughout the RGA, the bike scores follow a more concentrated and smooth pattern. High equality scores for cycling are mainly observed in and around the towns where one or more McDonald'ses are located (Groningen, Assen, and Hoogezand), while high scores for public transit also appear in towns which do not house a McDonald's in the north and eastern part of the RGA (e.g. Winsum, Bedum, Zuidhorn, Leek, and Roden). Conversely, higher bike scores are observed in the eastern part of the RGA (e.g. around Hoogezand) compared to public transit scores in this region.

For IKEA as a destination, prominent differences in accessibility equality scores of cycling and public transit appear, especially in Assen. While differences in travel time between the car and bike to the IKEA in Groningen appear to be large in Assen, the differences in travel time between the car and public transit seem relatively small. This indicates a good public transit connection between Assen and Groningen. In opposition, Paterswolde and Eelde (south of the city of Groningen) have low equality scores for public transit compared with bike.

Based on these accessibility equality scores, Table 8 shows the mean score per degree of urbanisation, for each type of destination. The population column presents the number and share of the people living in these regions to provide a picture of the affected population. Population density however is not weighed in the accessibility equality scores (see Section 4.3). From Table 8 it appears that the more urban a region is, the higher the average accessibility equality score is. Mean scores lower than 5 are mainly observed in non-urban – i.e. rural – regions: however, less than 20% of the population of the RGA is living here.

Table 8 *Mean accessibility inequality scores per degree of urbanisation per destination*[6]

	Population		**Bakery**		**HEMA**		**McDonald's**		**IKEA**	
	n	*%*	*PT*	*Bike*	*PT*	*Bike*	*PT*	*Bike*	*PT*	*Bike*
Very highly urban	139680	30,7	8	7	9	8	9	9	9	9
Highly urban	68120	15,0	7	7	7	7	8	8	8	6
Moderately urban	77090	16,9	7	7	7	7	6	6	6	5
Little urban	88820	19,5	6	6	6	6	5	4	5	5
Non-urban	81820	18,0	3	3	3	3	3	4	4	5

[6] Rounded to zero decimals.

5.2 Financial effects PPU for personas

To evaluate the possible financial effects of the upcoming PPU policy on accessibility, three fictive personas have been set up. Figure 43 shows an overview of the three personas, including their location of residency, the degree of urbanisation of the cell they are living in, the car they own, their annual mileage, and their current MVT tax in cents per kilometre. With an assumed price of 6,82 cents per kilometre in the situation of the future PPU policy, Persona 1 and 3 will experience a higher price rate compared with their current situation, respectively 128% and 11% higher. However, the PPU price per kilometre for Persona 2 will be 12% lower than their current MVT tax. Besides the accessibility scores for each persona, Table 9 presents the tax costs of a ride to the fastest reachable destination by car, for both the current MVT tax and the possible future PPU policy.

Figure 43 *Overview personas*

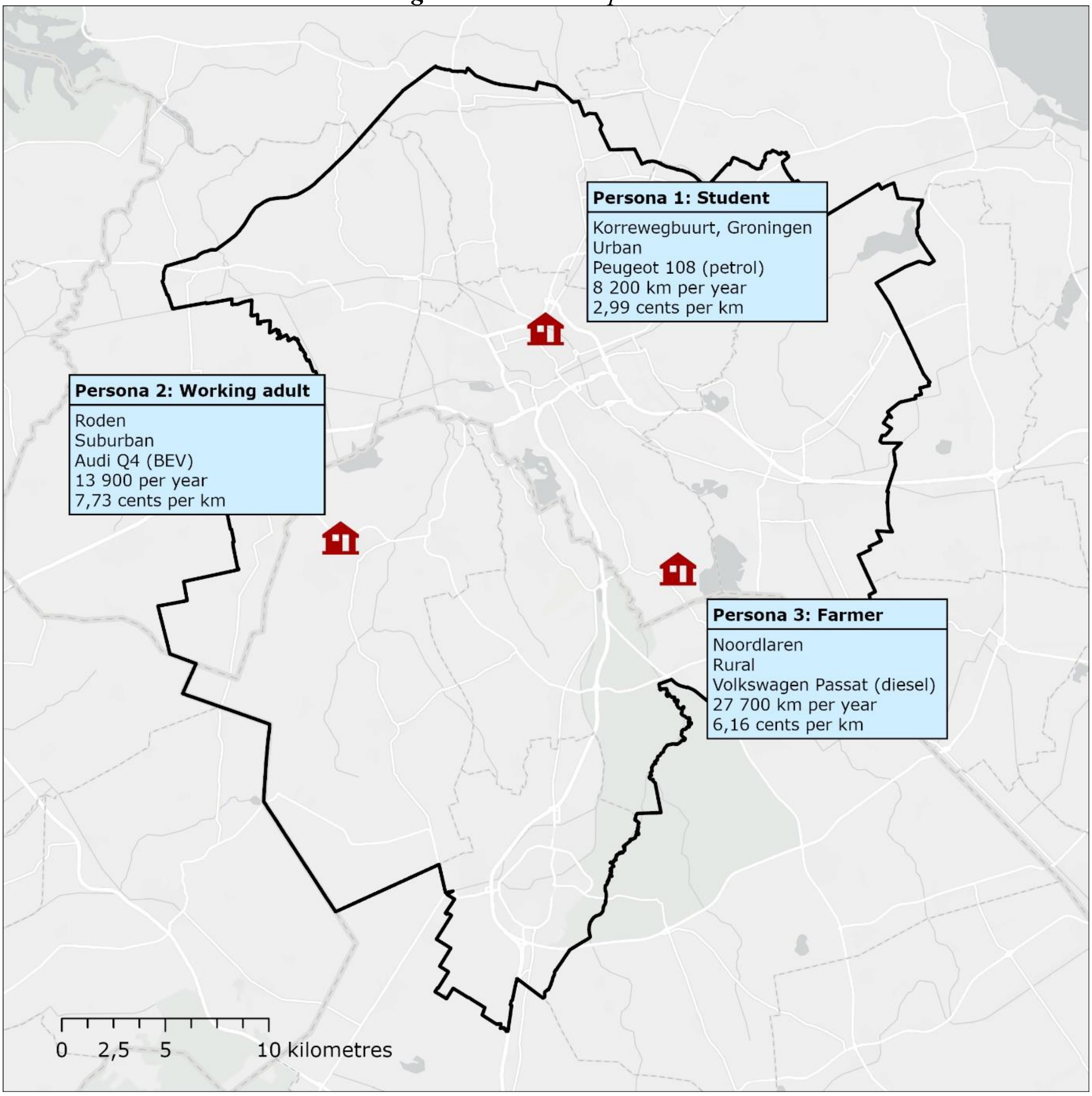


Table 9 *Accessibility scores and tax costs (in cents) of a ride to the fastest reachable destination by car per destination*

		Persona 1 (urban)	Persona 2 (suburban)	Persona 3 (rural)
Bakery (local)	PT score	6	8	2
	Bike score	6	8	2
	Tax MVT	4,32	6,69	28,86
	Tax PPU	9,86	5,90	31,95
	Abs. difference	**+5,54**	**-0,79**	**+3,09**
HEMA (sub regional)	PT score	7	9	2
	Bike score	6	9	3
	Tax MVT	6,62	7,79	28,61
	Tax PPU	15,09	6,88	31,68
	Abs. difference	**+8,48**	**-0,92**	**+3,07**
McDonald's (regional)	PT score	10	6	1
	Bike score	10	3	3
	Tax MVT	8,51	96,91	109,23
	Tax PPU	19,42	85,50	120,94
	Abs. difference	**+10,90**	**-11,41**	**+11,70**
IKEA (national)	PT score	10	6	1
	Bike score	10	4	6
	Tax MVT	9,55	150,72	104,76
	Tax PPU	21,79	132,98	115,99
	Abs. difference	**+12,24**	**-17,74**	**+11,22**

Generally, public transit and bike accessibility equality scores are lower for Persona 3 – living in a rural area – compared to Persona 1 and 2. On a local (bakery) and sub regional (HEMA) scale level, the scores for both public transit and bike are higher for Persona 2 than Persona 1. However, this pattern turns around on the regional (McDonald's) and national (IKEA) scale level. On these scale levels, Persona 1 lives in an area which belongs to the 10% least travel time differences of alternative mobilities compared with the car, while Persona 3 lives in an area belonging to the 10% biggest travel time differences opposed to the car.

From a financial perspective, Persona 1 (urban) and Persona 3 (rural) experience higher costs to reach their destinations as a result of the upcoming PPU compared to the current MVT situation. For instance, a trip to the bakery by car would cost Persona 3 around 30 cents, while Persona 1 and 2 could reach a bakery by paying less than 10 cents. A ride to the fastest reachable HEMA will cost 15 cents for Persona 1 with the future PPU, while this would currently be around 7 cents. Where a trip to the IKEA would cost Persona 1 currently almost 10 cents, this would be more than 21 cents with the future policy. Thus, although taxes per trip are still lower for Persona 1 compared to Persona 2 and 3, the relative increase in costs is visible in these results. Conversely, although the tax costs of Persona 3 are generally higher than Persona 1 and 2, the relative increase is lower. For instance, a current trip to McDonald's by car would cost €1,09 for Persona 3, whereas with the future PPU policy this would cost €1,20. Due to the decreasing tax price per kilometre, Persona 2 will benefit from the PPU policy, which could reach up to almost 18 saved cents for a trip to IKEA by car compared with the current situation. However, on a local (bakery) and sub regional (HEMA) scale, the decrease of costs is only under 1 cent.

Due to high accessibility scores for Persona 1 on regional and national scale level, cycling and public transit could be considered appropriate alternative mobility options in the future PPU situation. These modes of transport could save up to paying 20 cents for PPU tax for making that trip by car. Although the price per kilometre decreases for Persona 2 in the future PPU situation, high accessibility scores provide options for choosing public transit or the bike on a local and sub regional scale level instead of the car. Overall, despite a relative small increase in tax costs, Persona 3 experiences low accessibility equality scores and high financial costs to reach the fastest reachable destination in both the current MVT and the future PPU situation.

6 Discussion

This chapter presents the interpretation of the results (Section 6.1), followed by the strengths (Section 6.2) and limitations of the research (Section 6.3).

6.1 Interpretation results

While assessing the spatial equity aspect of accessibility for public transit and cycling, the objective of this thesis is to identify whether people living in either urban, suburban, or rural areas will be most financially affected by the potential new PPU policy. The results indicate that people living in rural areas of the Groningen-Assen region deal with high travel times for public transit and bike to reach all destinations, especially compared to car travel times. Following Benenson et al. (2011), these areas in the RGA in which car accessibility is considerably higher than public transit accessibility can be considered car dependent. Regions with the lowest accessibility equality scores, which are mostly distributed throughout the rural areas of the RGA, experience inadequate accessibility of destinations and inadequate alternative travel options: in combination with limited personal capabilities or skills, the chance increases that some groups of people living in these areas suffer from transport poverty (Jorritsma et al., 2018). Based on the type of car and the annual mileage, the PPU tax would be disadvantageous as opposed to the current MVT for two out of three personas. Although the rural persona experiences a slight increase in tax per kilometre as a result of the future PPU, the overall tax expenses are much higher compared to the other two personas due to higher driving distances: at the same time, accessibility equality scores are low, indicating that public transit and bike are no suitable alternatives.

Accessibility equality scores and financial effects cannot be viewed in isolation. Although accessibility inequalities mainly arise in rural areas, the results also show that population density in areas with high public transit and cycling travel times is low. Cities and villages with higher population density such as Groningen, Assen, and Hoogezand accommodate the highest accessibility equality scores for all studied destinations, indicating small differences in travel time between the different modes of transport in urban and suburban areas within the RGA. Considering a temporal aspect, a trip to the bakery or HEMA would probably be desired more often compared to a trip to McDonald's or IKEA. The accessibility results for these local scale level destinations generally show lower travel times and more distributed accessibility scores throughout small villages within the RGA. From a financial perspective, the persona analysis results show lower trip costs for these local destinations compared to the higher scale destinations. Although the rural persona experiences considerably the highest trip costs to almost each destination, it should be accounted that some people living in rural areas are willing to accept less mobility as a trade-off for a rural lifestyle (Cooper & Vanoutrive, 2022). Finally, although favourable travel times for public transit and cycling to IKEA exist for the residents of the city of Groningen, the mode preference aspect should also be considered: public transit would be a suitable alternative when buying new kitchenware, whereas a car is actually needed for buying new furniture.

While there are numerous approaches to quantify accessibility, both the transport and land use components described by Geurs & Ritsema van Eck (2001) are integrated in the final multi-part method of this research, by combining the disutility that people encounter when attempting to travel from their origin to their destination with how these activities are distributed throughout space. By considering people's residential location (Di Ciommo & Shiftan, 2017) and travel times (Higgins et al., 2022), the method in this thesis – which is able to show potential car dependency and geographical exclusion (Church et al., 2000) – builds upon other accessibility studies that compare different modes of transport from an equity perspective (e.g. Benenson et al., 2011).

6.2 Strengths

This thesis presents an innovative accessibility methodology, highlighting inequalities in both travel time and financial costs. By analysing bike and public transit travel times as opposed to car travel times for various destination types within the Groningen-Assen region, this research offers a comprehensive understanding of mobility options, surpassing traditional analyses that often focus solely on one mode of transport. By considering the demographic characteristics of each origin, the research provides insights into accessibility disparities that exist across urban, suburban, and rural areas. The accessibility equality scores in combination with the changing costs for the personas – illustrated by tables, graphs, and maps – facilitate easy interpretation and communication of the results. This makes the research accessible to a broad audience, including policymakers, urban planners, and the general public. Moreover, the RtD approach employed in this study allows for flexibility and adaptability, enabling the research process to evolve iteratively. This approach encourages innovation and responsiveness to unforeseen challenges, ultimately enhancing the relevance of the research outcomes.

6.3 Limitations

Although the RtD approach allowed for improvement of the prototypes during the research, the final accessibility method is still subject to several limitations. Firstly, multi modal trips are not being considered in the accessibility inequality method, which entails trips in which different modes of transportation are being combined to reach a destination. Additionally, e-bikes are excluded as an alternative mode of transportation in this research. Given their increasing popularity and extended travel range compared to traditional bicycles (De Haas et al., 2022), e-bikes could function as a significant alternative to cars. The absence of e-bikes from the analysis overlooks a potentially valuable alternative mobility option. Furthermore, although the central question of this thesis is focused on the financial aspect of the PPU policy, the calculation of the possible changes in car taxes is relatively simplistic. Relying on basic cost calculations, a few fictional personas have been featured in this study. This approach lacks the depth needed to comprehensively evaluate the financial implications of the proposed policy change for all people living in the RGA.

Additionally, it's essential to recognise that the methodology primarily relies on assessing the closest destination for each origin cell within the study area. This approach overlooks the amount and diversity of facilities reachable within a certain timeframe and does not incorporate the attractiveness (e.g. size) of destinations. Accessibility equality scores are calculated based on travel times for each destination separately, which makes it hard to observe differences in accessibility between various destinations. Consequently, this final method may not fully capture all aspects of accessibility. Moreover, the concept of inequality in the final method in this thesis is based solely on absolute differences in travel times: more nuanced (statistical) measures of inequality – such as the Gini coefficient – could potentially offer a more nuanced understanding of inequalities within the region. Although the final accessibility inequality method includes insightful evaluations for car accessibility against separately cycling and public transit, the methodology falls short in integrating both alternative modalities into one unified inequality accessibility score. This lacking holistic assessment encompassing all modes may limit the ability to draw comprehensive conclusions regarding accessibility disparities.

A technical performance issue that should be addressed is that the computation times for generating enhanced public transit OD matrices are notably lengthy, requiring multiple hours for completion. In addition, no travel times results have been calculated for a small subset of origin locations due to connectivity errors in the networks. Although only a small portion is affected by this, this could introduce potential inaccuracies into the analysis. Furthermore, while direct comparisons of travel times for different modes of transport are being made in the inequality accessibility method, these travel times could be subject to under- or overestimation. Systematic checks for potential biases in estimation accuracy are not conducted, posing a potential limitation to the validity of the results. Finally, the accessibility methodology created in this thesis is not automated, which lacks efficiency for repeating the analysis with possible other origins, destinations, and parameters in the future.

7 Conclusion

7.1 Overall summary and conclusion

Although the Ministry of I&W and the Ministry of Finance (2023) expect that the cost increase of the potential upcoming PPU tax will be greatest in urban areas, people's access to alternative mobility options - such as public transit and cycling - is not being considered. To account for the spatial equity aspect of accessibility, this thesis aimed to answer the following central question: "*To what extent will people living in urban, suburban and rural areas be financially affected by the upcoming 'Pay-Per-Use' motor vehicle tax policy, taking into account alternative mobility options?*"

Residents of rural areas are having concerns about rising costs as a result of the new PPU policy, caused by car dependency and lacking mobility alternatives. By combining people's place of residency, four destinations on different scale levels, actual network data sets for different modes of transport, population density, changing tax costs, and travel times resulting from network analysis, a multi-part method has been created in this research focusing on the equity aspect of accessibility. Inequalities of accessibility have been studied for the RGA, with a focus on three fictional personas.

The results show that rural residents in the RGA face high travel times for public transit and cycling to reach destinations on different scale levels, particularly compared to car travel times. Changes in PPU tax costs compared to the current MVT rely heavily on the type of car and the annual mileage: the PPU policy could actually be beneficial when the car is left parked a little more often, depending on the destination that needs to be reached, how often, and for what purpose. High accessibility equality scores within the RGA, mainly occurring in the cities Groningen and Assen, impose possibilities for leaving the car at home, since public transit and cycling are valid alternatives to reach destinations. Due to high driving distances and low accessibility equality scores in rural areas, car tax costs can be high as a result of the PPU policy while traveling with alternative modalities is no suitable option. However, the amount of affected people living in such regions is relatively low compared to urban and suburban areas.

While the Ministry of I&W and the Ministry of Finances (2023) expects the highest tax increases as a result of the PPU policy in urban regions, this thesis underlines the importance of addressing the sufficing or lacking presence of alternative modalities among regions to account for spatial equity. Car dependency therefore is probably overlooked by current research commissioned by the government.

7.2 Future research

Future research holds several opportunities for advancing the accessibility inequality method created in this research. Automation of the methodology using tools like ArcPy or PostgreSQl (PostGIS) could enhance efficiency and reproducibility. Streamlining the analysis process enables researchers to conduct larger-scale studies with greater ease, facilitating more effectively assessing accessibility inequalities. In such an automation process, open-source network options could also be explored to enhance transparency and flexibility of the method. Furthermore, integrating all considered modes of transport into one unified network model could enrich the accessibility analysis, by allowing multi modal trips within the calculation of travel times. In this extent, the method could be improved in terms of modelling more realistic situations of travel behaviour across diverse urban, suburban, and rural contexts. Employing statistical measures such as Spearman correlation and Moran's I could also facilitate a more nuanced understanding of accessibility inequalities across regions. Whereas this study focused on the RGA as a case study in the Netherlands, it would be interesting to apply the method in a new context, location, and/or culture. For instance, the water taxi could be an interesting alternative mode of transport in the region of Rotterdam.

Additionally, deeper insights into the possible financial effects of the upcoming PPU could be obtained by expanding the considered prices of for instance purchase prices, fuel, and tickets. For instance, although public transit might be considered a suitable alternative for certain destinations, high ticket prices as a opposed to low fuel prices of the car could trigger a preference for using the car. It is important to consider scale levels in such calculations: although cycling might appear to be a cheaper alternative to the car, the range that people are willing to cycle should also be accounted for. By examining the full spectrum of costs associated with different modes of transportation, researchers could deeper comprehend the potential effects of a change tax system on the occurrence of transport poverty and geographical exclusion throughout regions with varying degrees of urbanisation. Actually studying the tipping point of when the future PPU would be more economic beneficial than the current MVT would be interesting for future research.

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Appendix A Selection case study area

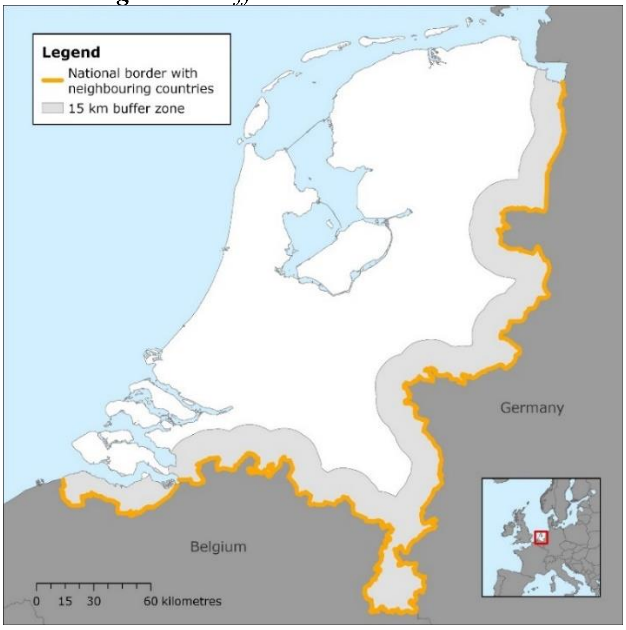
1: The Netherlands

To meet the first requirement, the case study area should be completely within the boundaries of the Netherlands (see Figure 44).

2: 15 kilometres from national border Germany and Belgium

To meet the second requirement, the case study area cannot be located within fifteen kilometres from the national border with Germany and Belgium. Therefore, a 15-kilometre land inwards buffer has been created from the Dutch border with Germany and Belgium (see Figure 44).

Figure 44 *Buffer zone in the Netherlands*



Source: Esri (2023)

3: Contiguous area with urban, suburban, and rural area(s)

To meet the third requirement, the case study area should be a contiguous area which contains urban, suburban, and rural area(s). CBS measures the degree of urbanisation of an area by calculating the average surrounding address density (*omgevingsadressendichtheid*) for that area. This average surrounding address density is defined as the number of addresses within a circle with a radius of one kilometre around an address, divided by the area of the circle (CBS, n.d.). The average surrounding address density of an area is the average of the surrounding address densities of all addresses in that area. This measure therefore shows the concentration of human activities (CBS, n.d.). CBS distinguishes five classes:

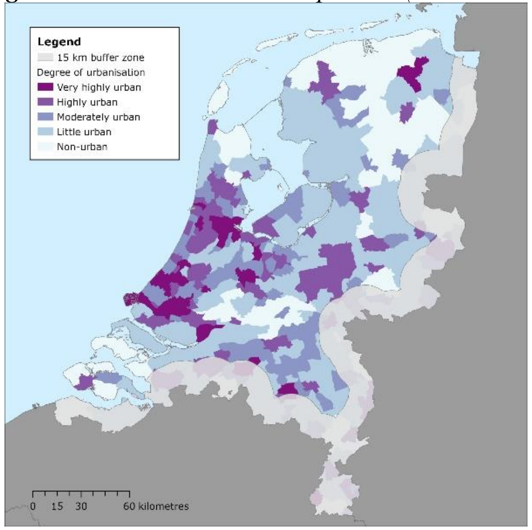
1. *Very highly urban*: average of 2500 or more addresses per km2;
2. *Highly urban*: average of 1500 to 2500 addresses per km2;
3. *Moderately urban*: average of 1000 to 1500 addresses per km2;
4. *Little urban*: average of 500 to 1000 addresses per km2;
5. *Non-urban*: average of less than 500 addresses per km2.

Figures 45, 46, and 47 show the degree of urbanisation for municipalities (*gemeenten*), districts (*wijken*), and neighbourhoods (*buurten*). However, as the aim of this thesis is to compare urban, suburban and rural areas, these five classes have been reduced to three categories:

1. *Urban*: average of 1500 or more addresses per km2 (formerly class 1 and 2);
2. *Suburban*: average of 1000 to 1500 addresses per km2 (formerly class 3);
3. *Rural*: average of less than 1000 addresses per km2 (formerly class 4 and 5).

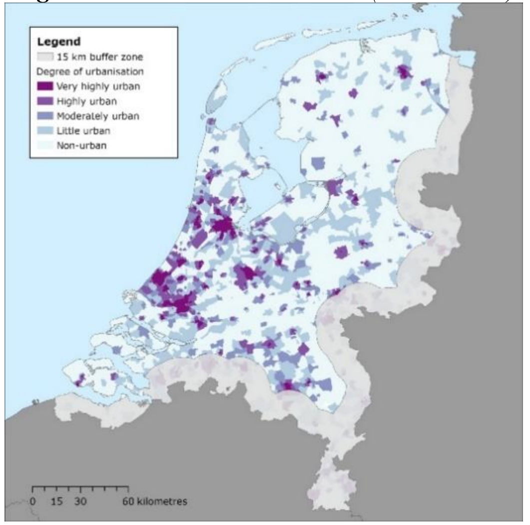
Figures 48, 49, and 50 show this newly created distinction for municipalities, districts and neighbourhoods. Rural municipalities are mainly located in the northern part of the Netherlands, while urban municipalities mainly occur in the Randstad region (the conurbation in the western part of the Netherlands). However, municipalities contain relatively aggregated data. From Figure 48, 49, and 50 it appears that a municipality often consists of a combination of urban, suburban, and rural districts and neighbourhoods. Therefore, many regions in the Netherlands area suitable as case study area, as long as it is a contiguous area which contains urban, suburban, and rural neighbourhoods.

Figure 45 *Urbanisation municipalities (CBS classes)*



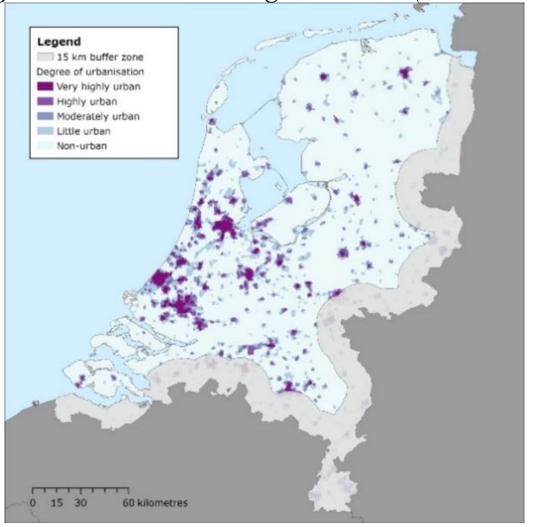
Source: Esri (2022a)

Figure 46 *Urbanisation districts (CBS classes)*



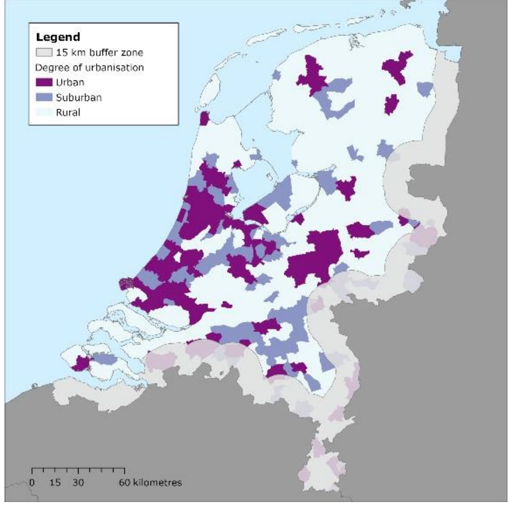
Source: Esri (2022b)

Figure 47 *Urbanisation neighbourhoods (CBS classes)*



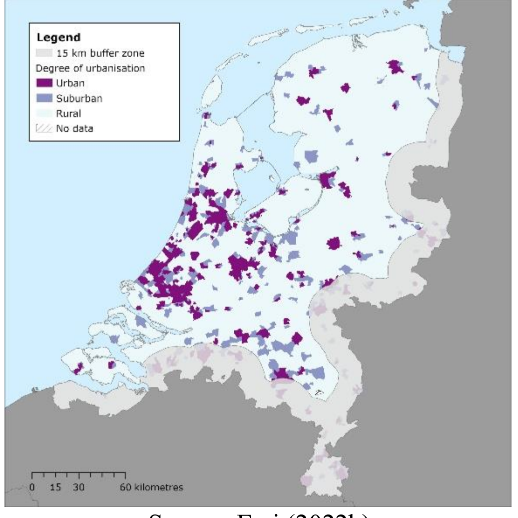
Source: Esri (2022c)

Figure 48 *Urbanisation municipalities*



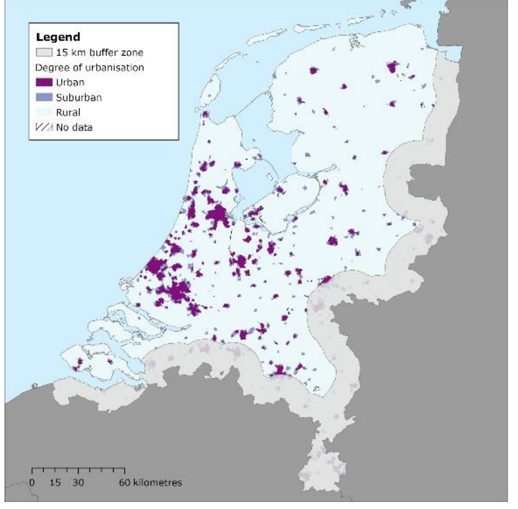
Source: Esri (2022a)

Figure 49 *Urbanisation districts*



Source: Esri (2022b)

Figure 50 *Urbanisation neighbourhoods*

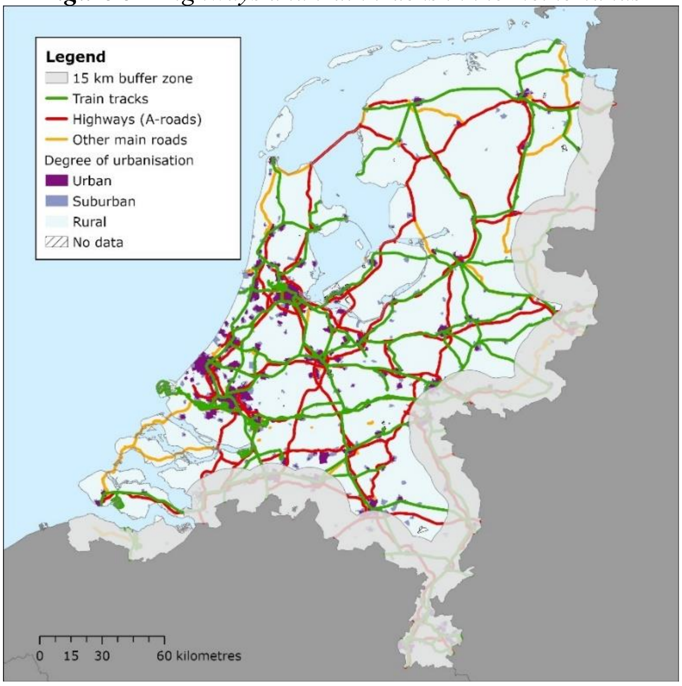


Source: Esri (2022c)

4: Highway

To meet the fourth requirement, the case study area should contain at least one highway. All highways in the Netherlands have been visualised in Figure 51. The road data are retrieved from the Dutch National Road Database (*Nationaal Wegenbestand*), which serves as an open database with all public roads in the Netherlands. All road sections that are managed by the government are included in this map, with a distinction between A-roads (highways) and other roads managed by the government. Although the former are the official highways, the latter serve as main roads as well.

Figure 51 *Highways and train tracks in the Netherlands*



Source: Esri (2022c); Rijkswaterstaat (2023); ProRail (2022)

5: Train tracks

To meet the fifth requirement, the case study area should contain at least one hub of multiple train tracks. All train tracks in the Netherlands have been visualised in Figure 51. The train track centrelines are retrieved from ProRail, the railway manager of the Netherlands. The highway and train track networks logically connect urban areas with each other.

Appendix B Selection and creation road network data set

B1 Esri ArcGIS Online network service

a) Problem/opportunity framing

A road network data set needs to be established as input for performing network analysis for cars. The built-in Esri ArcGIS Online network data set could be an opportunity.

b) Solution development

Within the ArcGIS Pro Network Analyst, a standard ArcGIS Online network is included which is hosted by Esri. This built-in network is ready to use and thus does not need any preparation for performing network analysis. Therefore, the availability of this network service would save time in establishing a network.

c) Testing

Some simple Shortest Route analyses have been performed between random locations.

d) Critical reflection

The source data set - and thus the location of the streets - cannot be visualised, which in turn makes it impossible to assess the accuracy of the network in the case study area. Although the simple Shortest Route analyses show realistic results, various other limitations have been observed for using this network data set in this thesis. Firstly, solving network analysis layers created with this network data source consumes ArcGIS service credits from the organisation (Utrecht University). While estimating the number of credits, it appeared that solving multiple network analyses with many facilities could become expensive for the organisation. Secondly, although many modes of transport are included, it is not possible to choose a bike as a travel mode. Finally, the built-in network source imposes analysis limits, such as the number of inputs that can be used. The dependency on the consumption of credits and the restriction on input data could hinder the experimentation aspect of the RtD methodology. Therefore, it has been decided to not use this network service in the accessibility measure.

B2 Dutch National Road Database (NWB)

a) Problem/opportunity framing: local needed

Based on the this reflection, implementing a local network could be an opportunity for solving network analysis in ArcGIS Pro. Such a local network could be established with the Dutch National Road Database (*Nationaal Wegenbestand*)(NWB).

b) Solution development

The NWB data set has been retrieved from Rijkswaterstaat, who offers the most current version as a shapefile. This shapefile could easily be downloaded and consulted in ArcGIS Pro. The NWB is a file with routable properties and can be combined with a separate file that contains certain road features(*Wegkenmerkendatabases*)(*WKD*), such as maximum speeds. Such relevant attributes make it possible to create a network data set. However, after contacting the NWB organisation, it appeared that no documentation is available on setting the properties in ArcGIS Pro. Some experiments have been conducted with setting the properties, such as restricting one way streets and turns and adjusting bridge and tunnel connectivity.

c) Testing

After implementing these properties, some simple Shortest Route analyses have been performed between random locations.

d) Critical reflection

The results of these analyses show that prohibited routes are taken to get from one location to another. The properties have thus not been set correctly. Therefore, it could be concluded that completely and correctly setting up this network without clear guidance for ArcGIS Pro would take too much additional research and time for this thesis.

B3 OpenStreetMap

a) Problem/opportunity framing

The problem of the lacking guidance could be tackled with implementing a well-known global source instead of a Dutch national source. Therefore, the suitability of street data from OpenStreetMap (OSM) for creating a local network data set has been examined.

b) Solution development

Geofabrik offers shapefiles of all OSM data for all provinces in the Netherlands, but not for the Netherlands as a whole. The OSM shapefile for Drenthe has been downloaded via Geofabrik to test a small area within the case study area. Alternatively, Overpass Turbo offers the possibility to select certain data in a self-determined bounding box by using queries. All streets (highway=*) for the region surrounding the RGA have been downloaded via Overpass Turbo to test these data. OSM street data in Europe have also been retrieved from the ArcGIS Portal and from the Humanitarian OpenStreetMap Team. Due to differences in retrieval methods, the attributes of these OSM sources differ from each other. Many OSM data sources did not include all necessary attributes to successfully prepare a network data set, such as maximum speeds. Comparable with the NWB data set, manuals on how to set the correct network properties in ArcGIS Pro are lacking. Some experiments have been conducted with setting the properties, such as restricting one way streets and assigning which roads are prohibited for certain modes of transport.

c) Testing

After implementing these properties, some simple Shortest Route analyses have been performed between random locations.

d) Critical reflection

Similar to the NWB network, some prohibited routes are taken in the results of these Shortest Route analyses. Due to time constraints, it has been decided not to prepare an OSM street data set as a road network.

B4 Esri Nederland OpenStreetMap Premium Data

a) Problem/opportunity framing

Since creating a local network appears to require more research and time than available in this thesis, a preset local network would be an opportunity. Therefore, access has been requested for the OSM Premium Data network offered by Esri Nederland.

b) Solution development

The properties of this up-to-date Premium Data network data set have already been set by Esri Nederland, which makes this network data set ready to use in ArcGIS Pro. The data set covers the Netherlands and parts of the neighbouring countries. Different modes of transport are included (car, fire truck, bus, bike, pedestrian, and truck). However, the user is also able to adjust all properties and to add transport modes.

c) Testing

Some simple Shortest Route analyses have been performed between random locations.

d) Critical reflection

The Shortest Route analyses show realistic results. Due to its preset properties, up-to-datedness, and coverage within the case study area, it has been chosen to use the OSM Premium Data network data set for solving network analysis.

Appendix C Results Cycle 1 HEMA, McDonald’s, and IKEA

C1 HEMA

Figure 52 *Service areas HEMA (car)*

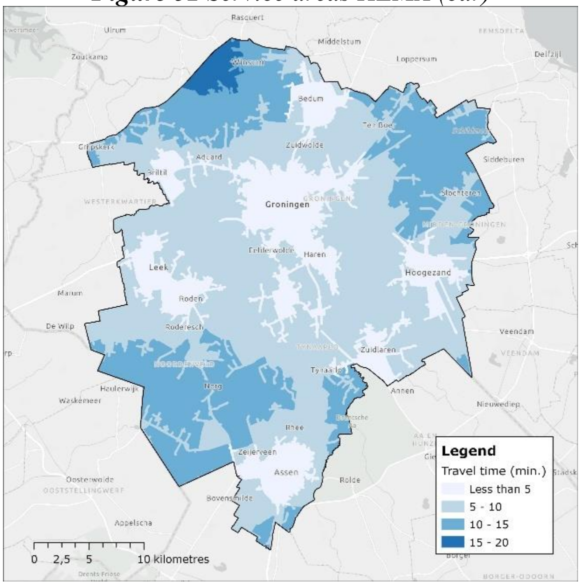


Figure 53 *Service areas HEMA (bike)*

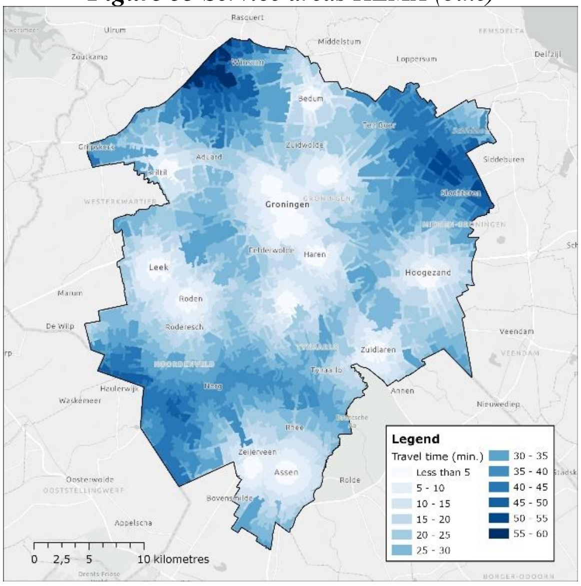


Figure 54 *Service areas HEMA (public transit 2-2-2024 8:00)*

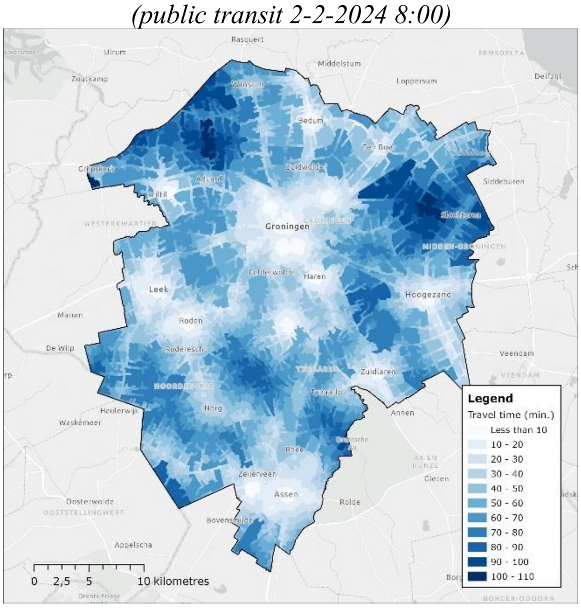
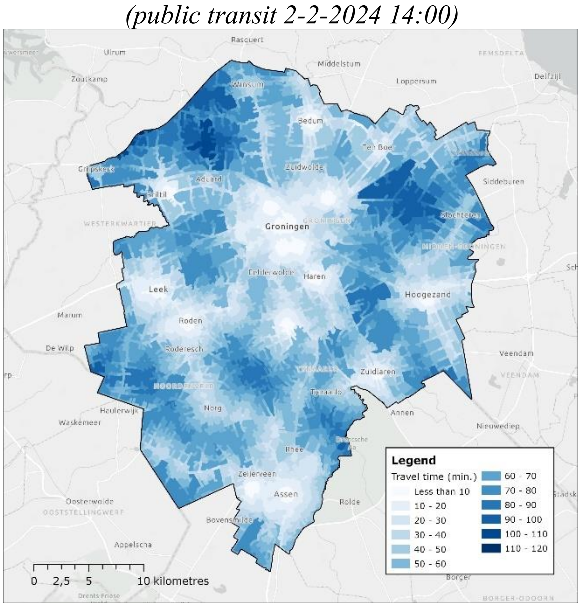


Figure 55 *Service areas HEMA (public transit 2-2-2024 14:00)*



C2 McDonald's

Figure 56 *Service areas McDonald's (car)*

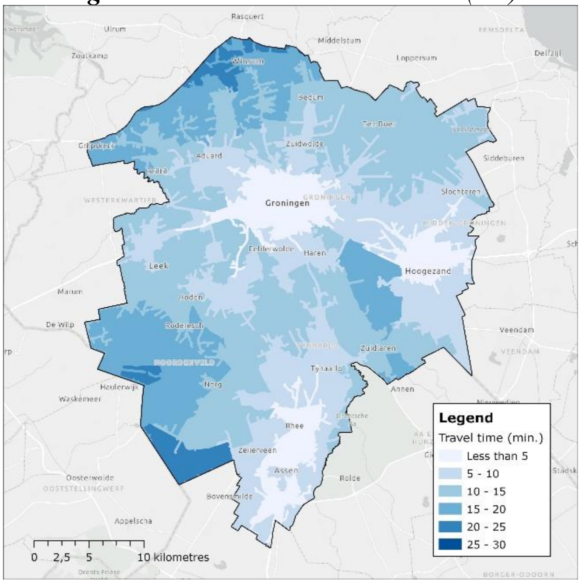


Figure 57 *Service areas McDonald's (bike)*

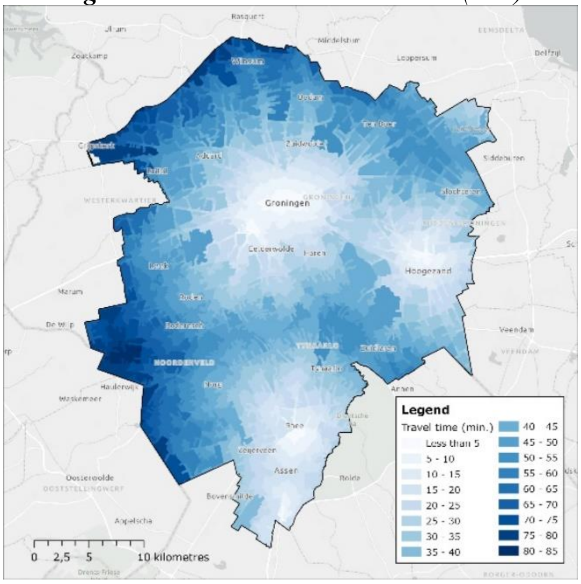


Figure 58 *Service areas McDonald's (public transit 2-2-2024 8:00)*

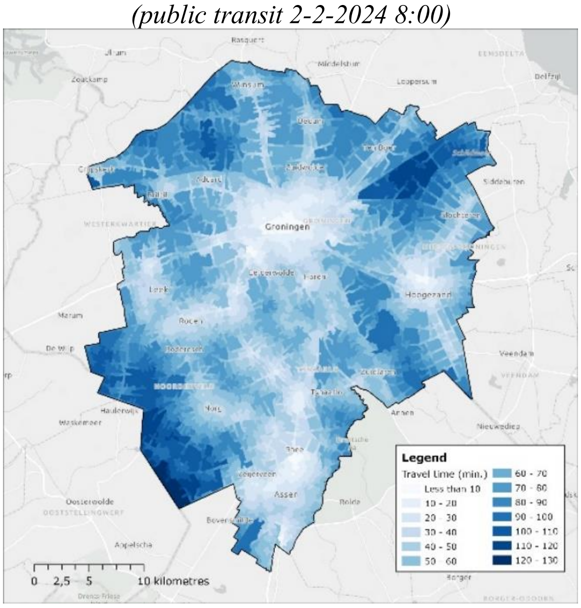
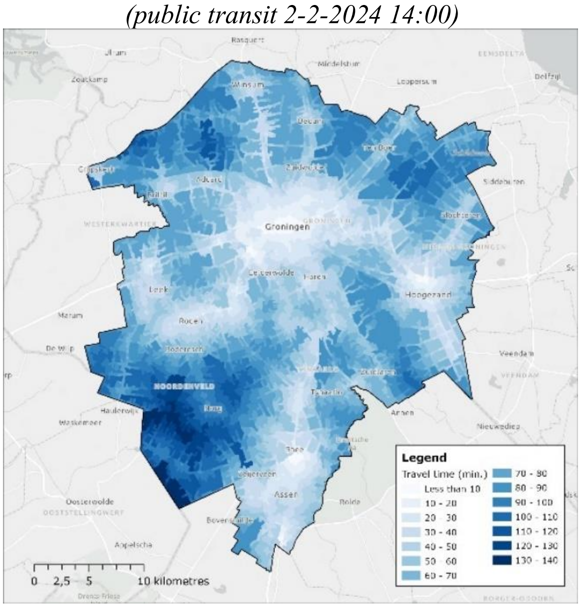


Figure 59 *Service areas McDonald's (public transit 2-2-2024 14:00)*



C3 IKEA

Figure 60 *Service areas IKEA (car)*

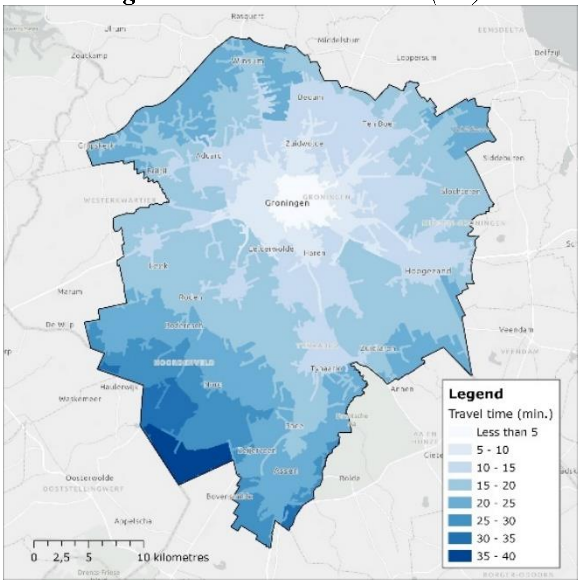


Figure 61 *Service areas IKE (bike)*

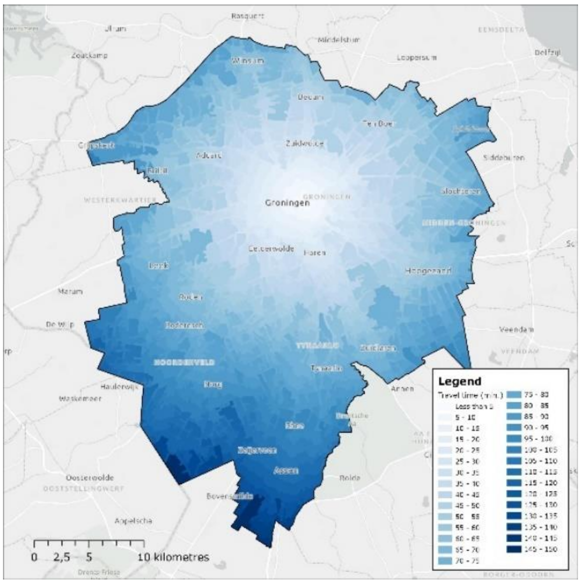


Figure 62 *Service areas IKEA (public transit 2-2-2024 8:00)*

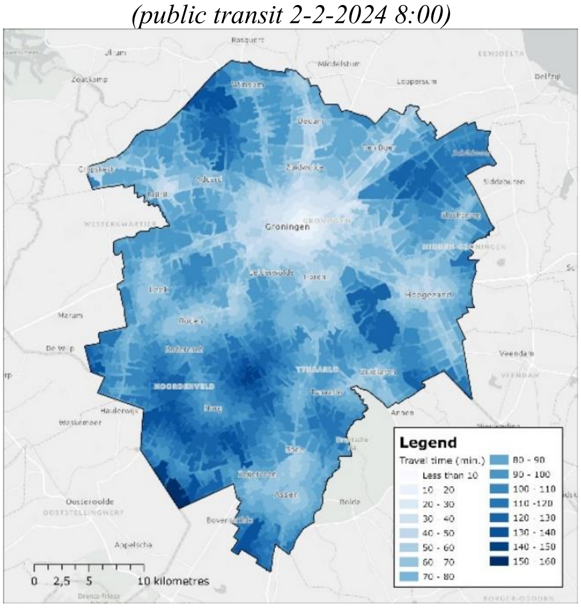


Figure 63 *Service areas IKEA (public transit 2-2-2024 14:00)*