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Effects of speed limit reduction on safety, job accessibility and equity

CASE STUDY: AMSTERDAM, SPEED LIMIT REDUCTION OF 50KM/H TO 30KM/H

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Abstract

Safety-improving countermeasures, such as speed limit reduction policies, often result in higher travel times, but the true effect of these policies on accessibility has remained unknown. Usually, the external costs of transport, like traffic crashes, are neglected in the accessibility analyses in both research and practice. Decreasing the maximum speed is not an unknown measure to improve traffic safety. This research examined how reducing the speed limit, from 50 to 30 km/h, effects job accessibility by car and bicycle in different postcode areas, in the municipality of Amsterdam. This is done by integrating traffic crash risks as a cost component in an accessibility model. Additionally, this research investigated how the impacts of speed limit reductions will be distributed over different areas that differ in terms of the total population aged between 15 and 65, income levels, household sizes, gender and immigration background. The new accessibility model was applied in a scenario analysis based on which the equity impacts of the proposed policy were examined by comparing the impacts of the new policies on changes in the potential job accessibility for car and bike users. For predicting the number of car-to-car and car-to-bicycle crashes with property damage only (PDO) and killed or severely injured (KSI) crash results, a negative binomial model and an empirical Bayes method were used. A power model is used to determine the effects of speed limit reduction on the number of crashes during the morning and evening peak hours. Based on the crash risks and the traffic volume a monetary value is determined for each road segment. The total costs for a road segment are based on this monetary value for crash risk and the travel costs, which are determined based on the travel costs and value of travel time. Then an accessibility model using the contour measure determined the number of jobs that could be reached within a threshold. With the help of a spatial analysis method, Local Moran's I analysis, is determined whether the potential job accessibility is clustered or randomly scattered over the study area. Moreover, to recognize the effects of speed limit reduction on certain population groups in Amsterdam the bivariate Moran's I analysis was performed. With the visualization of this analysis, the equity of accessibility change in Amsterdam for the different population groups could be determined. This research concludes that speed limit reduction reduces the accessibility of most car users while most bicyclists will experience an increase in accessibility. From an equity point of view, with the current accessibility there are clear clusters visible with high accessibility as well as clusters with low accessibility. The policy measure to reduce speed limit is most disadvantaged for car users living in regions with a high percentage of males. For other variables such as the number of active population, median income, average household size and percentage of non-western immigrants, no clear group is benefiting more than other groups. The same five variables were tested on equity for changes in bicycle accessibility and showed that the regions with a high percentage of male inhabitants are negatively affected when it comes to cycling accessibility. Again no indication for the other variables showed that one group is more beneficial than another group.

Source illustration front page:

(Ismail, 2018)

Summary

In an attempt to reduce traffic crashes the municipality of Amsterdam has proposed to reduce the speed limit on most of the roads in the city from 50 km/h to 30 km/h. Reducing speed limit is a common method to improve the safety of road users, however, it can also have negative effects on for example accessibility. Accessibility is the number of opportunities that can be reached. Decreasing the speed will increase the travel time thus decreasing the number of opportunities that can be reached. But from a cost point of view, it might be that reducing crashes lead to an overall increase in accessibility. This research, therefore, focuses on the cost benefits when reducing traffic crashes and if they lead to an increase in accessibility. This is important since the reduction of speed limits is not well received by everyone.

This research focuses on the impacts of speed limit reduction on job accessibility in urban areas. The case of Amsterdam is used to analyze the impacts of the reduction from 50 km/h to 30km/h for two modes of transport, car and bicycle. Also, the effects of job accessibility changes on equity are determined. The main research question is: What are the effects of speed limit reduction on urban roads on job accessibility and equity in urban areas of Amsterdam? To answer this question first is determined how traffic safety indicators can be integrated into an accessibility model, then the effects of speed limit reduction on job accessibility are determined and lastly, the effects of equity on different population groups are determined.

Literature

A safety measure such as speed limit reduction is used to change individual choices to optimize the overall outcome from a societal perspective. The majority of trips will not lead to traffic crashes and thus it seems that from an individual perspective reducing the speed limit is disadvantageous. But the costs that are involved in traffic crashes are very high and are mostly carried by the whole society, thus from a societal point of view, it is better to improve safety to reduce crashes. Based on the literature a conceptual model is developed to determine what effects can be expected when transport policies are implemented. A reduction in speed limit will lead to changes in traffic safety, traffic volume and travel impedances.

Lowering speed limits improves safety. This is already proven a long time ago when implementation of lower speed limits led to reductions in traffic crashes and injuries. This can be seen in various researches in the Netherlands, Europe and the rest of the world. Not only car crashes are reduced, but also the safety of bicyclists improves. Most bicycle-related crashes occur on roads with high speed limits, while high speeds also lead to severe injuries or fatalities. Speed limits of 30 km/h reduce injury risks of cyclists by 21%.

The effects on traffic volume after reducing the speed limits are a reduction in the traffic volume. Citywide small reductions can be expected while specific roads can have a reduction of up to 30% in traffic volume. This is caused by changes in decisions of car users, such as changes in routes, mode of transport or trip frequency. Reduction in traffic volume is positive for bicyclists since their exposure to cars becomes less. As can be expected reductions in speed limits led to reductions in average speeds on the roads, which will lead to an increase in travel time. However, this does not always have to be the case. Speed reduction will also decrease congestion. With smart management of traffic signals travel time loss can be reduced to a minimum, which is, for example, the case in Brussels.

Accessibility can be defined as the potential for opportunities for interaction. And often high travel speeds are correlated with high accessibility. The assumption that high accessibility leads to low traffic safety is not correct since proximity is also an important part of accessibility. On the other hand, when accessibility increases it often leads to more trips and therefore congestion, which reduces the overall speed, this effects traffic safety in two ways, more congestion leads to more exposure and therefore crashes, but a lower severity in the crashes since speeds are in general lower.

Study Area

For this research, the municipality of Amsterdam will be used. This municipality consists of the city of Amsterdam and the district Amsterdam-Zuidoost. A majority of 50 km/h roads will face a reduction to 30 km/h roads that are not reduced in speed are mostly located around the edge of the city. The research will focus on PC5 areas as analysis units.

Data

For this research three types of data are collected and used. Firstly, crash data from BRON is used. The period in which the crashes are recorded is from 2015 to 2019. The second data set is provided by the municipality of Amsterdam and consists of information about the road sections, such as current and proposed speed limits and current and predicted traffic volumes. The municipality of Amsterdam did not make any predictions on the actual speeds after speed limit reductions, therefore the speed limits are used. Lastly with the help of CBS and RUDIFUN the data for the zones are collected.

Methodology

This research uses several methods to answer the research questions. Firstly, an accessibility model is created using the contour measure. Crash numbers were determined with a created traffic safety model using a negative binomial regression. The power model in combination with the traffic safety model was used to adjust crash numbers after speed limit reduction. The expected outcomes on accessibility were determined with scenario analysis and the effects on equity were determined using local and bivariate Moran's I.

The first step of the research was to integrate traffic safety into an accessibility model. This research uses a contour measure for the accessibility model. The contour measure counts the number of jobs that can be reached within the threshold. The contour measure was chosen since it is easy to implement and interpret. The chosen thresholds are determined based on the value of travel time and the average travel time. The chosen timeframe is during peak hours. To calculate potential crash costs, the risks of being involved in a crash are first determined. This is done by using the crash data and negative binomial regression. This resulted in a simple traffic safety model. To adjust the data based on the perceived number of crashes, the Empirical Bayes method is used. Then the travel costs were determined based on the value of travel time and the crash risks multiplied by the value of a statistical injury. Then with the help of the network analyst in ArcGIS the accessibility analysis was done.

To show the effects of speed limit reduction on accessibility a scenario analysis was performed, where the different expectations of reductions in crashes are used for the different scenarios. The expectations for the crash reductions were based on the power model. The power model predicts the number of crashes and crash victims based on speed limit reductions. These new predictions were used for the empirical Bayes method as the perceived crashes in the situation with speed limit reduction.

The last step of the research was to use the changes in accessibility to show how it effects equity in Amsterdam. This is done using local Moran's I and the bivariate Moran's I. The bivariate Moran's I compares two variables and shows where there are different types of clusters. The difference in accessibility was compared with five variables to show spatial patterns. Those variables were the number of active population, the median income, the average household size, the percentage of male inhabitants and the percentage of non-western immigrants. These variables were chosen based on literature that showed that there are differences within those population groups when it comes to accessibility.

Results

Including crash risks in the accessibility analysis reduced average accessibility by 34% for car users and 12% for bicyclists. The highest accessibility could be found in the center of Amsterdam for bicyclists, in both the analysis without and with crashes included. For car users the highest accessibility moves from the center of Amsterdam towards the West of Amsterdam after including the crashes in the accessibility model.

The scenario analysis included the crash risk in the model but each of the scenarios changed one variable from the current situation (base scenario) to the predicted situation. In the final scenario all variables were changed according to the proposed situation. Including all variables led to a decrease in traffic victims, thus an improvement in traffic safety. The outcomes showed for car users that accessibility reduces apart from when only the new crash risks were used, which led to an increase in accessibility. Bicyclists showed an increase in accessibility apart from when only the speed limit changes which does not affect bicycle accessibility. The overall effects of implementing the speed limit reductions, from 50km/h to 30km/h were on average a reduction in accessibility by car of 0.7% and an improvement in accessibility by bike of 0.9%. Some regions showed opposite results for both car and bike. To determine the significance of the changes a t-test was performed. It showed that the changes are insignificant and therefore merely an indication of possible outcomes.

The equity analysis showed that currently the clusters of high accessibility are located in the Southwest for car users and in the center for bicyclists. Clusters of low accessibility are located in the East for car users and around the border of Amsterdam for bicyclists. Equity analyses were also performed comparing the difference in accessibility between the current situation including crash risks and the situation after speed limit reduction including crash risks. The result of the difference between those two situations showed that car users located in the center experience the highest reductions in accessibility while car users located more towards the edge of Amsterdam experience the least negative effects. Bicyclists located in the West experience the highest improvement while bicyclists in the East see the least improvement in accessibility. The bivariate Moran's I showed no real relationships between population groups and the change in accessibility after speed limit reduction. Only regions with a higher percentage of male inhabitants seem to have positive effects in changes in car accessibility while those regions showed negative effects when it comes to changes in cycling accessibility.

Discussion

In general, the speed limit reduction leads to a reduction in job accessibility by car and improves the accessibility by bike. It can be expected that this causes a mode shift from car to bike. As was already shown by the scenario analysis this leads to improvements in bicycle accessibility due to reduced exposure to cars. However, the overall accessibility of car users remains larger. From an equity point of view, there are some areas visible that are benefiting or are disadvantaged by the speed limit reduction, when you look into the population groups it seems that males are more advantaged when it comes to changes in car accessibility while they are disadvantaged when it comes to cycling accessibility.

The limitations of this research were, mostly the absence of actual speeds. Based on the literature it is unlikely that car speeds will drop from 50km/h to 30km/h but this research showed still an indication of what can happen with the accessibility. Secondly, the traffic safety model uses a limited number of variables to predict crash risks, while a more advanced version, using more variables, might be able to predict crashes more accurately. Also, the used crash data is possibly for bicycle-related crashes not accurate enough. The chosen study area is sufficient for the research, but the chosen boundary is possibly too small given that average distances are used. In further research, it is also possible to use a different type of accessibility measure to estimate job accessibility. And for the equity analysis additional variables could be chosen to detect the effects on equity. Lastly, the findings of this study cannot be used one on one for other cities since the outcomes are specifically related to the configuration of the city and the effected roads as well as other factors such as the location of the crash and the composition of the different population groups. But the general findings can be expected to be found in different cities in the Netherlands.

Conclusion

The conclusions of this research are that exclusion of unavoidable costs, such as traffic safety costs, in an accessibility model results in significant overestimations of accessibility. Secondly, a reduction in speed limit will lead to an average decrease in accessibility for car users and an average increase in accessibility for bicyclists. As the accessibility by car is much higher the overall accessibility, combining the transport modes, will probably be decreasing. The next conclusion is that changes in accessibility due to speed limit reduction will be unequally distributed over Amsterdam for both modes of transport. However, most differences in the accessibility will not affect the equity of the variables active population, median income, average household size and the percentage of non-western immigrants. Only the regions with a higher percentage of male inhabitants are affected by speed limit reduction. They seem to have positive effects on car accessibility, but negative effects on cycling accessibility.

Thus, the overall effects of speed limit reduction on job accessibility and equity in the urban areas of Amsterdam are that cyclists experience insignificant improvement in job accessibility while car users, especially those located in old neighborhoods will see their accessibility insignificantly decrease. Which could conclude that the minimal effects on accessibility should not stop the municipality from improving traffic safety.

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1. Introduction

Traffic safety measures are used to prevent road users from being killed or injured. To improve traffic safety, several countries in the world commit to a road safety pledge (Brake, 2017). Also, EU countries such as Sweden and several American countries introduced Vision Zero (Vision Zero Network, 2021). In the Netherlands, the sustainable safety policy is implemented since the 1990s (SWOV, 2018). Based on the Dutch Road Safety Strategic Plan 2030 (RSSP 2030, 2019), reaching zero traffic fatalities by 2030 is the aim in the Netherlands. However, in recent years there were still around 600 traffic-related fatalities (SWOV, 2020) and around 20,000 severe injuries due to traffic crashes (Rijkswaterstaat, 2021). To reach the zero-traffic fatality target by 2030 actions should be taken at both local and national levels. More than a quarter of the fatal crashes in the Netherlands have happened on roads with a speed limit of 50 km/h in the past seven years (Rijkswaterstaat, 2021). Moreover, around 70% of fatal crashes occur among vulnerable road users (e.g., pedestrians and cyclists) and most often they crash with a heavier mode of transport on roads with a 50km/h or 70km/h speed limit. Near and around city centers this percentage is between 80% and 90% (Schepers, 2021). In this regard, lowering speed limits is one of the most effective measures that improve traffic safety (Svensson, Summerton, & Hrelja, 2014). This is already proven in practice, for example in Helsinki and Oslo speed limit reductions combined with other measures resulted in zero pedestrian deaths in Helsinki (Teivainen, 2020) and only one traffic fatality in Oslo (Coulon, 2020). Recently, municipalities in four major cities in the Netherlands, including Amsterdam, Rotterdam, The Hague, and Utrecht have decided to reduce speed limits from 50 to 30 km/h on roads in built-up areas. The municipalities state that the car has been centralized far too long with the consequences of a large number of traffic victims. Therefore, they ask the government to change legislation that allows cities to reduce the speed limits easier (NOS, 2021).

This research particularly focuses on a new traffic safety measure introduced by the municipality of Amsterdam (Netherlands News Live, 2021). This policy will most likely lead to higher travel times which decreases the accessibility if only the travel time is taken into account. This policy, also, should reduce the number and severity of traffic crashes, injuries, and deaths. The aggregate impacts of these two changes on general travel costs may increase or decrease accessibility when both travel time and traffic safety costs are taken into account. This research examines the effects of this new measure on accessibility within different areas in the city of Amsterdam. Moreover, it is important to examine the impacts of new public policies such as road safety policies on different population groups (e.g., income level groups) since public policies are expected to enhance well-being in society. Thus, the results of this research also contribute to gaining some ideas about the impacts of reducing speed limits on accessibility equity between different groups of people with different socioeconomic backgrounds and/or residents of different areas.

1.1. Problem Statement and Research Scope

Various traffic safety measures such as reduction in speed limits are common solutions for improving the safety of road users. However, it may be the case that implementation of these safety measures can increase travel times and consequently decline accessibility levels. Accessibility can be described as the extent that (groups of) individuals can attend different activities in different locations using different transport modes (Geurs & van Wee, 2004). The introduction of a traffic safety measure most likely focuses on decreasing the number and severity of crashes and does not necessarily take other transport-related factors into account. However, implementation of these measures might still have positive effects on accessibility by accounting for a reduction in monetary costs and the congestion caused by traffic accidents. It is important to consider traffic safety (e.g., as a cost) to give a good understanding of its impacts on accessibility in an area. That is because only focusing on travel time costs and ignoring traffic safety costs in the accessibility analysis could result in over or underestimation of the accessibility levels. For instance, proposing speed limit reduction in Amsterdam has caused reactions from taxi drivers who state that they will no longer be on time for their customers. This would result in no benefit in taking a taxi to travel. Because in this case cycling would become faster considering the introduced speed limits on all road types in the urban areas (NOS, 2021).

Accessibility measures are fundamental in assessing the functionality of new transport and land use policies. Different factors including traffic intensities and congestions, travel speeds, travel costs, and job availability are considered in accessibility analysis in different researches and transportation plans (Boisjoly & El-Geneidy, 2017). This means that the current applied accessibility analysis methods have not directly considered the impacts of traffic safety and changes in traffic safety in the accessibility analyses. The purpose of this research is to explore the impacts of traffic safety on job accessibility by integrating traffic safety indicators into an accessibility model. This is interesting since everyone prefers higher road safety, but the traffic crash risk is not explicitly concerned in accessibility analyses in both research and practice.

This research specifically investigates the impacts of speed limit reduction (known as a beneficial traffic safety measure) on job accessibility levels in urban areas. This investigation takes the form of a case study of the analyzing impacts of speed limit reductions from 50 to 30 km/h, on the urban roads in the municipality of Amsterdam, on job accessibility by two modes of passenger car and bicycle. This research constitutes of four main steps. Firstly, the impacts of speed limit reduction (from 50km/h to 30km/h) on changes in traffic crash frequency/severity and traffic volumes are estimated. Then an accessibility model with the integration of a monetary value of road safety indicators is developed. This model is used to estimate the job accessibility levels before and after reducing the speed limits in Amsterdam. Using this model, different scenarios are designed to investigate and compare the accessibility levels by considering variations in indicators. The scenarios are constructed based on changes in the speed limit, traffic volume, and traffic crash frequency. Lastly, the outcomes of the new accessibility model are used to determine the effects on equity in changes in job accessibility among different population groups in the city of Amsterdam.

1.2. Research questions

This research aims to investigate the effects of speed limit reduction on the job accessibility of individuals as well as the distribution of job accessibility changes over different population groups, such as different income groups. This research specifically focuses on road users by two common modes of transport: car and bicycle. The overarching research question in this research is:

What are the effects of speed limit reduction on urban roads on job accessibility and equity in the urban areas in Amsterdam?

In this research, the main research question will be answered with the help of analyzing the following sub-questions.

1 **How can traffic safety indicators be integrated into accessibility models?**

- This research question will focus on creating an accessibility model including safety as a variable and estimating job accessibility levels by considering the posted current speed limits in the urban areas.

2 **How can changes in speed limits (and consequently traffic safety) influence job accessibility in urban areas in Amsterdam?**

- For this research question, different situations will be considered in the form of three different scenarios to determine the effects of speed limit reduction. The scenarios will be implemented in the model to examine the changes in accessibility levels after speed limit reduction.

3 **How can reducing the speed limits affect equity in accessibility between different population groups and regions?**

- This research question uses the outcome of the previous question to determine what are the effects of reducing the speed limit on the equity in job accessibility in Amsterdam

1.3. Reading guide

The overall structure of this report takes the form of 12 chapters, starting with the abstract, summary, table of contents, and introduction where the research questions and research scope will be explained. The next chapter will show the theoretical framework of this research. After that, a description of the study area will be given. Followed by a description of the data used for this research and an explanation of the used methods. Then the results of the analyses are given. After the results a discussion of the research can be found, followed by the conclusions of the research. The report is finalized with a list of the used sources and in the appendices several additional figures from the results can be found.

2. Literature Review

This chapter provides an overview of the theoretical aspects of this research. First, the general public impacts of transport policies are shortly described. Then, a short review of the literature about the effects of speed limit reduction on traffic indicators, including traffic safety, traffic volume, and travel impedance factors, is given. Thereafter, an explanation of accessibility models and how accessibility can be used as a measure of transport policy assessments are provided. To conclude this chapter, a conceptual framework and hypotheses are presented based on the literature study.

2.1. Transport policies and their public impacts

People base their decisions for travel on personal benefits. Likewise, governments determine policies based on costs and benefits, however, a government approaches the costs and benefits from a societal perspective (Annema, 2013). To achieve the optimum benefits for society, governments introduce new policies. There are three main reasons for a government to introduce new policies. The first reason is market failure, where individual choices do not lead to optimal outcomes from a societal perspective. Secondly, there are equity reasons, where policies try to divide costs and benefits fairer among the users. The last reason is generating revenues, such as a levy on fuel prices (Annema, 2013).

The reduction of the speed limit to improve safety is mainly a policy against market failure since road safety casualties and injuries are an important external cost that individuals do not consider (Annema, 2013). However, the impacts of speed limit reductions can differ for different origins and destinations and could have both negative and positive equity effects on different population groups. To set or change a speed limit that satisfies all factors (safety, accessibility and equity) at an acceptable level is challenging for policymakers (Lanzaro & Andrade, 2022). Especially since the relationship between equity and speed limits is complex (Wang, 2013). To create a safe and equitable network, first should be determined what a safe speed limit is for each road. Then should be determined which speed limit below the safe speed limit is the best from an equity standpoint (Wang, 2013). Setting a speed limit that

2.2. Effects of speed limit reduction on traffic indicators

Lower speed limits will most likely lead to a reduction in speeds on the roads, however, the amount of speed reduction depends on the type of speed reduction measures (Janssen & Verhoef, 1989). Speed limit reduction could have more effects on traffic characteristics than only changes in travel time and traffic safety. For instance, if the speed limit is reduced on specific roads, drivers may change their routes or even their modes of transport to avoid slow traffic and increasing travel times or costs (Brown, 1972). In this way, reduced speed limits can result in a reduction in traffic volumes on the specified roads, along with a reduction in the number and severity of traffic crashes (Svensson, Summerton, & Hrelja, 2014). Hence, traffic safety will improve. This can also affect the accessibility of road users, as improved safety will decrease crash risks and corresponding crash risk costs. Therefore, it can be hypothesized that speed limit reductions may influence accessibility levels for different road users. This section provides some information about the history of limiting traffic speeds in the Netherlands (or similar regions) and how it has affected traffic safety, volume, and/or travel time.

2.2.1. Effects on traffic safety

Since 1983, in the Netherlands, municipalities have had the authority to implement a speed limit of 30km/h in residential areas (Vis, Dijkstra, & Slop, 1992) (Denmark was five years earlier with a similar ruling (Engel & Thomsen, 1992)). 30km/h speed limit in residential areas is considered acceptable since the likelihood of a crash is small due to the limited braking distance and when a crash occurs the speed of the car is below 30km/h (Vis, Dijkstra, & Slop, 1992). A 30km/h speed limit results in a minimization of the probability of serious injury (Vis, Dijkstra, & Slop, 1992). After the initial implementation of a speed limit of 30km/h in the Netherlands, several experimental areas were chosen to determine the effects of enforcing 30km/h. This resulted in a reduction of 25% of crashes with injuries and a reduction of 5% in the total number of crashes (Vis, Dijkstra, &

Slop, 1992). From 1979 to 1981, an experiment was performed in two cities of Rijswijk and Eindhoven, in the Netherlands, in which different combinations of measures were implemented to enforce a speed limit of 30km/h. This experiment resulted in a decrease in the number of injury crashes by 70% (Janssen & Verhoef, 1989).

Similarly, studies in Denmark showed that the number of crashes per kilometer of the road was reduced by 24% and the number of fatal crashes was reduced by 45% (Engel & Thomsen, 1992). It was also found that implementation of this measure resulted in a reduction of 72% in fatal crashes and 78% in the total number of serious injuries in Denmark (Engel & Thomsen, 1992).

In Brussels also speed limit reduction policy was implemented in early 2021. Similar to Amsterdam, in Brussels, all roads are limited to 30km/h except for several major access and ring roads. Although the implemented speed limit policy is new in Brussels, improvement in traffic safety is observed. Comparisons between the number of crashes in the first quarter of 2020 and the same period in 2021 reveal a reduction of crashes from 814 to 635 (The Brussels Times, 2021) and a reduction in serious injuries from 46 to 30 (Moore, 2021). Over an entire year, there was a reduction of 20% in serious injuries and the fatalities reduced from 13 (2018) and 11 (2020) to 5 in 2021 (Leclercq, 2021). The main reductions can be found in crashes with vulnerable road users (pedestrians, cyclists) (Moore, 2021).

Along with increased safety for car drivers, bicyclists benefit a lot from a decrease in the speed limit. Most fatal and severe bicycle-involved crashes occur on roads with high speed limits (Kim, Kim, Ulfarsson, & Porrello, 2007). In the Netherlands, the probability to be involved in a crash resulting in a serious injury or fatality is higher on roads with a speed limit of 50km/h than on roads with a 30km/h speed limit. Additionally, it is reported that about 80% of road deaths in cities are on roads with a 50km/h speed limit (Asadi, Ulak, Geurs, Weijermans, & Schepers, 2022). The increase at higher speeds is caused by an increase in kinetic energy that will be exchanged in a car-to-bicycle crash. A speed limit of 30km/h reduces the injury risk of bicyclists by 21% (Uijtdewilligen, et al., 2022). Likewise for car crashes a majority (75%) of car-to-bicycle crashes occur on roads with a speed limit between 50 and 70 km/h (Uijtdewilligen, et al., 2022). Thus, the safety of cyclists will be improved by reducing the speed of vehicles. Speed reductions do not have the same effect on all roads and road users, since the effects of other factors also influence perceived safety such as the road environment (Elvik, 2013).

2.2.2. Effects on Traffic volume

Reducing speed limits has not only effects on road safety. As mentioned before a speed limit reduction may cause road users to take a different route or transport mode, which effects the traffic volumes. Nightingale et al. (2021) studied the effects of speed reduction on traffic volume in the city of Edinburgh. To do this research a phased citywide speed limit of 20 miles/h (roughly 30km/h) from 2016 to 2018 was implemented. The results showed a reduction of 2.4% in traffic volume on the main and residential streets. It is also revealed that the reduction in average speeds was almost the same during different days in the week and times of the day. Only during the night (01:00 – 06:00), the traffic volume was relatively low which resulted in relatively higher average speeds (Nightingale, et al., 2021). Whilst implementation of a 30 km/h speed limit in the Netherlands also contributed to a 5 to 30% decline in traffic volume (Vis, Dijkstra, & Slop, 1992). The big difference between the two studies is because of the scale of the research on the impacts of implementation of the speed limit reduction on traffic volumes. In the case of the Netherlands, specific streets were chosen for a speed limit reduction and the case of Edinburgh had a citywide speed limit reduction, which is more comparable with the case in Amsterdam.

Furthermore, there have been many model studies performed to estimate the possible impacts of an increase in travel time on car usage. This is comparable to the effects of a decrease in speed limit (increase in travel time) on traffic volumes (car usage). In a study by de Jong and Gunn a time elasticity of -0.39 was found for commuting in the Netherlands (de Jong & Gunn, 2001). In a more recent meta-study, performed in Britain, time elasticities of -0.47 for car users and -0.54 for all transport users in urban areas were found (Wardman, Meta-analysis of British time-related demand elasticity evidence: An update, 2022). This means that significant changes in traffic volumes can be expected when the speed limit is reduced.

Moreover, reduced travel speeds can affect the travelers' decisions such as their trip frequency, their destinations, and mode (Toivanen & Kallberg, 1998). For example, traveling by car can be discouraged due to the increase in travel time as a result of lower speed limits. Also, traveling by bicycle and foot is more attractive due to the declined crash risks (Elvik, 2018) which were also detected in Brussels after the speed limit reduction. (Moore, 2021).

2.2.3. Effects on Travel impedances

As mentioned before, the impacts of the reduction in speed limits are not solely on traffic safety and traffic volume. The change in speeds may also influence travel impedances, such as travel time and travel costs which influence accessibility. The travel time depends on two factors, travel speed and travel distance. Travel time increases when the average speed on roads reduces or when the travel distance becomes larger (Toivanen & Kallberg, 1998). A reduction in speed limit will likely reduce the speeds on the roads. This is shown in research in Sweden, where research showed that for every 10km/h speed limit reduction the mean speed on a road was reduced by 2-3 km/h. This research was performed on rural roads and motorways with speed limits above 80km/h (Vadeby & Forsman, 2018).

After the speed limit reduction in Brussels, researchers measured a decrease of 15% in the speeds on the roads that reduced the speed limit to 30km/h. However, the responsible minister of mobility who implemented the speed limit reduction stated that using smarter programming in the traffic signals and the speed limit remaining 50km/h on the major roads does not increase the travel time of road users (Leclercq, 2021).

The previous paragraph explained that a reduction in the speed limit does not mean that the average speed will drop with the same speed difference as the speed limit difference. This is revealed in research in the Netherlands. Where after implementing a lower speed limit of 30km/h the average speed of only 22% of road users was below 30km/h (Janssen & Verhoef, 1989). Another research state that the road design must justify 30km/h (Vis, Dijkstra, & Slop, 1992), since only informative measures of a 30km/h speed limit, without the roads nature to reduce the speed, does not decrease the speed of the road user enough. Their research showed a decrease in average speed that differs based on the road design. Streets with solely informative measures did show an average speed reduction but this was less than streets with suggestive or persuasive measures (Vis, Dijkstra, & Slop, 1992).

An increase in travel time will influence travel costs. However, the actual effects of an increased travel time on travel costs depend highly on the mode of transport, income level, or the location where someone is living. The value of time differs for each person. Thus, an increase in travel time has a lesser effect on costs for someone with a low value of time in comparison with someone with a high value of time (Niedzielski & Boschmann, 2014). More factors that influence travel costs are for example the reduction in crash risk, which decreases the costs of traveling.

All the effects on travel costs influences accessibility since that depends on the number of opportunities within a certain threshold, such as travel costs. Increasing the travel time to the same opportunities will decrease the number of opportunities that can be reached within the same threshold and thus decreases the accessibility but decreasing the crash risk and costs will increase the accessibility.

2.3. Accessibility: A measure for transport policy evaluation

Accessibility is a key element of integrated sustainable transport and land use planning (Vale, 2020). Accessibility is defined in different ways such as the potential of opportunities for interaction (Hansen, 1959) or the ease with which any land-use activity can be reached from a location using a particular transport system (Dalvi & Martin, 1976). Accessibility also indicates the number of possibilities that can be reached within a certain threshold based on travel time or costs (Cui & Levinson, 2018). In practice, accessibility is a measure to indicate reduced travel time or increased traffic speeds in the areas. However, for instance, the job accessibility levels in the central parts of Amsterdam are relatively high (Cheng & Bertolini, 2013), while the travel speeds are relatively slow in these areas (Figure 1).

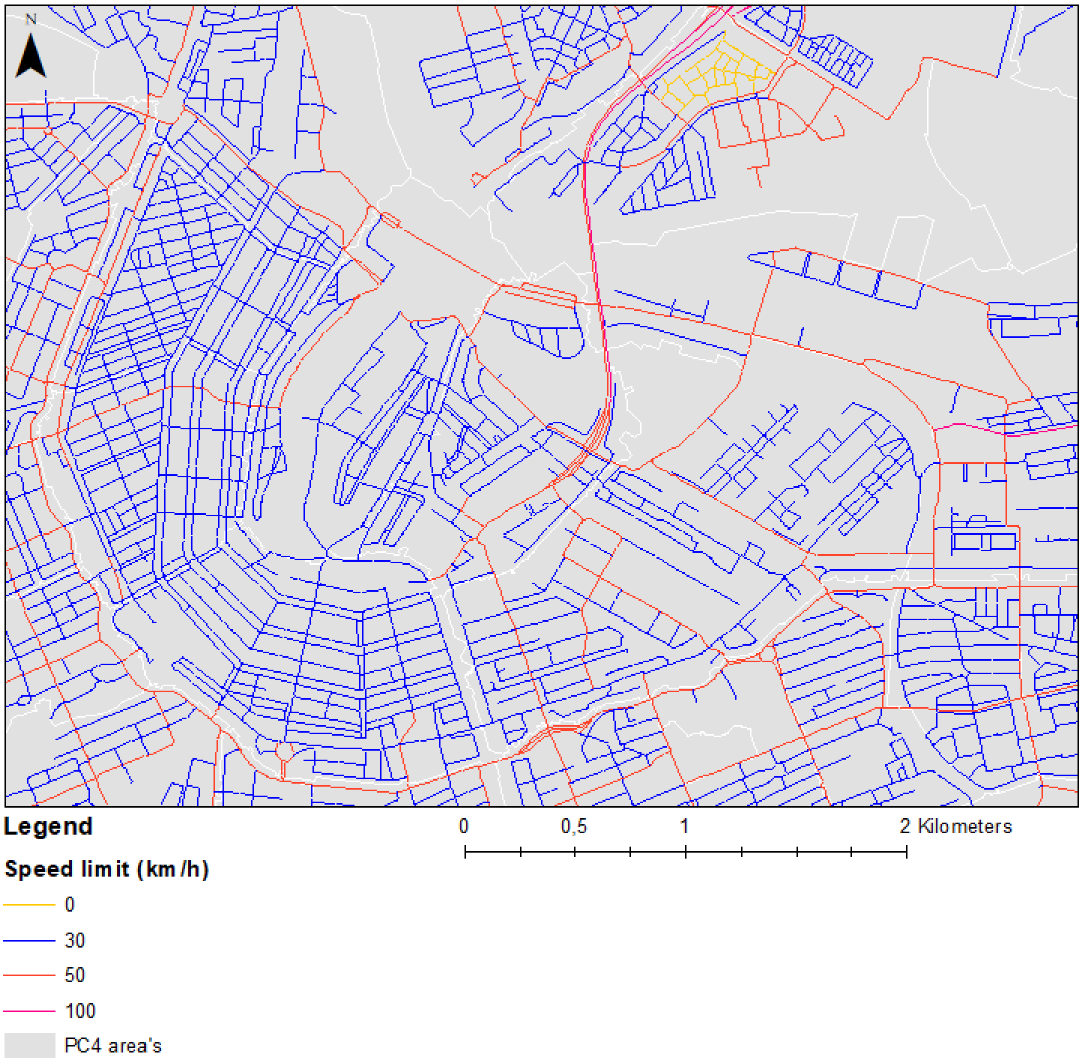


Figure 1: Current speed limits in the center of Amsterdam

Countermeasures for improving accessibility can have unplanned influences on traffic safety (and vice versa). For instance, roads designed with a high number of intersections and driveways of buildings to increase accessibility create safety problems when used at high speeds (Litman, 2003). Similarly, traffic safety measures can have positive or negative effects on accessibility in an area. For example, a reduction in speed limits benefits traffic safety but increases travel time which may lead to declined accessibility (Vadeby & Forsman, 2018). When improved, both accessibility and traffic safety play a significant role in the satisfaction of travelers, it is important to research the effects of safety measures on accessibility and vice versa. Accessibility can be enhanced by improving the proximity of locations or by decreasing travel impedances (i.e., travel time, costs, and efforts) (Silva, Bertolini, te Brömmelstroet, Milakis, & Papa, 2017). To determine the effectiveness of a proposed transport measure (e.g., for improving traffic safety), such as the reduction of speed limits, accessibility analysis is a very reliable tool.

Accessibility is also a good indicator to analyze the effect of transport policies on spatial equity in Amsterdam. Changes in accessibility can easily be visualized in the format of a map to show which regions are (dis-)advantaged by the introduced policies. For example, in research from Kelobonye, et al. (2019) the spatial equity of five key urban land uses in Perth was examined and visualized with the help of spatial accessibility.

2.4. Accessibility and traffic safety

Research by Kim, Pant & Yamashita (2010) states that there is a complex relationship between accessibility and traffic safety. This research was done in Honolulu, Hawaii, where they focused on the relationship between crashes, severity, fatalities for different road users and types of collisions with accessibility measures such as road length, the number of intersections, bus stops and bus route lengths. In general, they found that with an increase in mobility the accessibility increases, but also the exposure of road users and therefore the risk of a crash also increases. While the increase in safety is also often linked to congestion as a consequence of reduced speeds. An increase in traffic flow, which should improve accessibility, is associated with an increase in crashes (Kim, Pant, & Yamashita, 2010). This would imply that higher accessibility is negative for traffic safety. However, another study by Kim, Pant, & Yamashita (2011), tried to find the relationship between accessibility and crash severity. Accessibility is described as the proximity of people to the transportation system. In this research, they found an interesting relationship between accessibility and traffic safety when it comes to the severity of crashes. It is often the case that when fewer vehicles are involved more severe crashes occur. Higher accessibility relates to lower severity of crashes. This can be explained since increased accessibility means more roads and vehicular movements and this causes congestion and lower speeds leading to less opportunity for high speed and therefore less severe crashes (Kim, Pant, & Yamashita, 2011).

In more recent research was found that higher proximity to grocery stores increases the probability of KSI crashes. On the other hand, shorter distances to 50km/h municipal roads decrease the probability of KSI crashes (Asadi, Ulak, Geurs, Weijermans, & Schepers, 2022). The paper describes that the short distances to main roads may indicate that traffic safety is considered in a better designed infrastructure. In areas with high proximity to main roads the distance to the city center is often longer which creates a less dense road network that might lower traffic conflict and crashes (Asadi, Ulak, Geurs, Weijermans, & Schepers, 2022). For cyclists an interesting relationship was found between traffic crashes and travel speed. On roads with higher bicycle speeds a reduction in the car to bicycle crashes is perceived. This is possibly caused by a detached bicycle path without conflicts with cars (Asadi, Ulak, Geurs, Weijermans, & Schepers, 2022). This implies that due to higher travel speed accessibility is higher and also traffic safety is higher. Lastly, they state that in the newer developed areas the safety of cyclists has improved while these areas also increase accessibility by shortening travel distances (Asadi, Ulak, Geurs, Weijermans, & Schepers, 2022).

2.5. Conceptual Model

This section presents a conceptual model which shows how traffic safety policies can affect job accessibility and consequently equity. The model also shows which relations are important for this research. The conceptual model can be found in Figure 2. In this section, the important factors and relationships that are used in the model are described. The conceptual model shows, that changes in road safety policy, such as a reduction in the speed limit, not only affect traffic safety but also influence traffic volume and travel impedances (e.g., travel time, costs, and efforts). Moreover, the literature shows that changes in traffic volume and travel impedances, in addition to the land-use characteristics (indicating the location of activities), affect the accessibility level (Geurs & van Wee, 2004). In this research accessibility is described as the number of opportunities that can be reached within a certain limit of money, therefore all factors that influence the costs of traveling also influence accessibility which consequently can have equity impacts.

Factors that can increase or decrease travel time and costs are speed, traffic safety, and traffic volume. A decrease in traffic speed increases travel time and this will decrease accessibility. An increase in traffic safety decreases travel costs and therefore increases accessibility. Traffic volume does not have direct effects on accessibility but can have an effect on safety and traffic speed and therefore have an indirect effect on job accessibility. As is shown in Figure 2 this research aims to investigate the impact of traffic safety on job accessibility levels (shown by a thick full arrow). Along with the impact on job accessibility, this research looks into the equity effect of the changes in accessibility caused by the introduction of a new road safety policy.

Based on what is found in the literature and the links in the conceptual model it can be assumed that an increase in road safety, due to speed limit reduction, will increase traffic safety, while the travel costs will also increase due to longer travel times. The increased traffic safety will decrease travel costs due to the risk reduction of being involved in a traffic crash. Thus, job accessibility will both positively and negatively be affected by a speed limit reduction, this research aims to find which factor, in the case of Amsterdam, is more important. Lastly, the changes in job accessibility could influence spatial equity, these effects will also be researched.

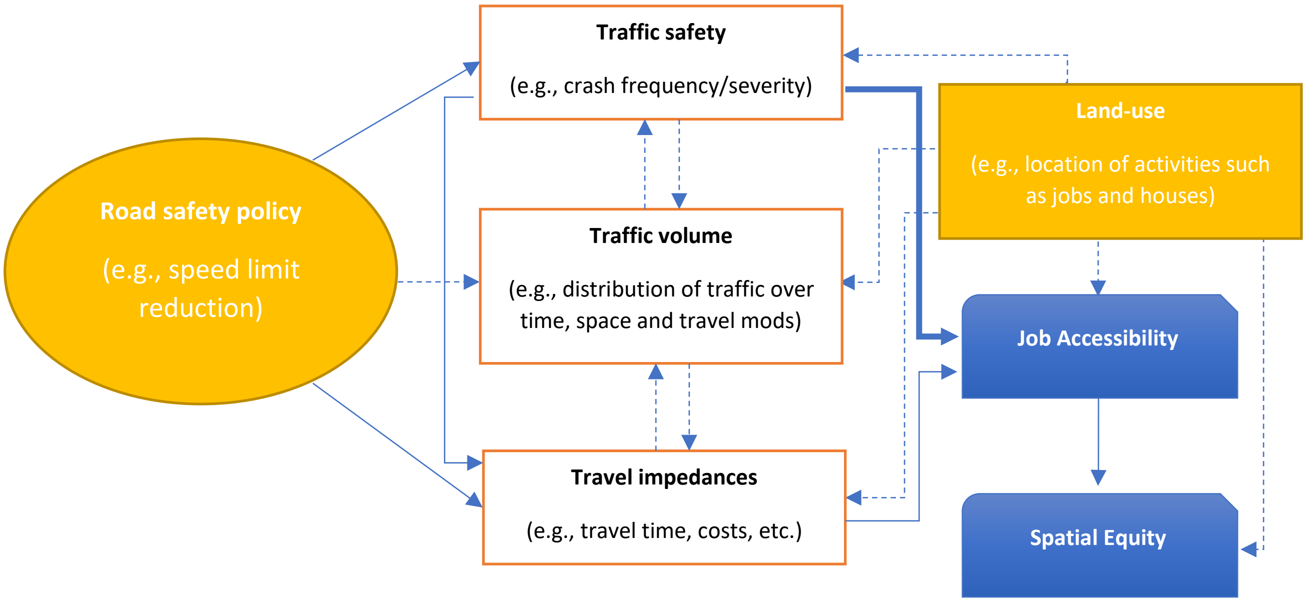


Figure 2: Conceptual Model for this research. (The full thin arrows indicate the relationships used in this research, the full thick arrow indicates the research hypothesis, and the dashed arrows are out of the scope of this research.)

2.6. Research assumptions and hypotheses

Based on the conceptual model and the literature research some assumptions and hypotheses are made. The assumptions are that a reduction in the speed limit leads to a decline in the number of traffic crashes (Elvik, 2013). The second assumption is that speed limit reduction will cause longer travel time for car users which can result in a decline in job accessibility levels (Toivanen & Kallberg, 1998). It is also assumed that the reduction in speed limit will increase the travel time for car users which in turn changes the car traffic volumes (de Jong & Gunn, 2001) (Wardman, 2022). Lastly, for this research there was no data available with the actual speeds before and after speed limit reduction therefore it is assumed the actual speed on the roads is equal to the speed limit.

There are two main hypotheses for this research. The first hypothesis is that speed limit reduction improves accessibility when safety effects are included. Despite the increased travel time it is hypothesized that the reduction in crashes has a larger benefit and in the end the speed limit reduction improves accessibility. The second hypothesis is that the effects of speed limit reduction are not equal in the city. Since a lot of roads that are proposed to reduce their speed limit are located near the center of Amsterdam. Therefore, it is likely that equity is impacted by the speed limit reduction when it comes to job accessibility.

3. Study Area

The research focuses solely on the municipality of Amsterdam and the roads that connect different regions of Amsterdam even if they go through a different municipality or province. The municipality of Amsterdam consists of the city of Amsterdam and the district Amsterdam-Zuidoost, located Southeast of the city. This study area is chosen since the municipality of Amsterdam has proposed a speed limit reduction from 50km/h to 30km/h on specific road sections within the built-up areas. The municipality of Amsterdam has already published some reports about this proposal and provided useful data related to the new speed limits on road segments and the expected traffic flows resulting from the proposed speed limit policy (Gemeente Amsterdam, 2022). Figures 3 and 4 show the study area with the current and proposed speed limits on the main roads. As can be seen in these figures, a speed limit reduction from 50 to 30 km/h is proposed for the majority of the roads mainly located in the center of Amsterdam.

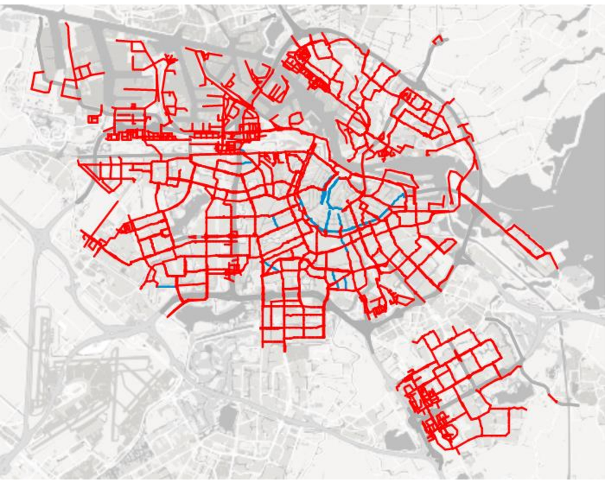


Figure 3: Amsterdam with current speed limits (Red 50km/h, blue 30km/h) (Gemeente Amsterdam, 2022)

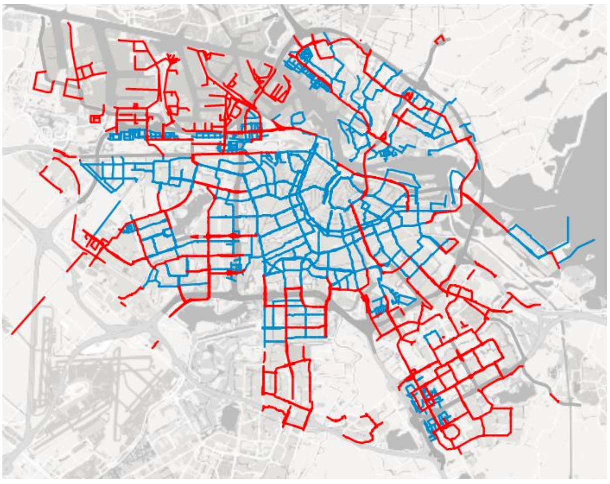


Figure 4: Amsterdam with proposed speed limits (Red 50km/h, blue 30km/h) (Gemeente Amsterdam, 2022)

The research is performed using PC5 areas as analysis units. In Amsterdam, there are a total of 1123 PC5 areas. The reason for choosing PC5 areas is that this is the highest resolution which has significant data available, such as the number of inhabitants (Figure 5). A higher resolution (PC6) did not have all the significant data available since the numbers were often too low. Another problem with a higher resolution is the number of zones in Amsterdam (more than 18,000) which would make an accessibility model computationally challenging. Lower resolutions (PC4) would result in too few units for an accessibility model to give a good insight into the accessibility of Amsterdam. The number of jobs was only available in PC4 but is converted to PC5 (Figure 6). Descriptive statistics about the data of Amsterdam and the data that is used can be found in chapter 4.

4. Data

In this chapter, the data that is used for this research is described. To start a few tables are given with the overview of the used data, followed by an explanation of data collection and data process steps. The general descriptive statistics per analysis unit that are used for this research are given in Table 1. Table 2 gives the descriptive statistics per analysis unit. This table also provides information on the source of data as well as in which research questions the data is used. Figure 5 until Figure 11 display the spatial distribution of the used variables. Larger images can be found in appendix A. Similarly to table 2, in Table 3 the statistics can be found for the road section data.

Table 1: General statistics of Amsterdam

Statistic		**Amount**	**Source**
PC5 regions		1123	(CBS, 2021)
Road sections		22668	(Gemeente Amsterdam, 2022)
Crashes	Total	5827	BRON (Rijkswaterstaat, n.d.)
	Car	4794	
	Bicycle	1033	
Median Income Level	1	31	(CBS, 2021)
	2	49	
	3	341	
	4	120	
	5	305	
	6	58	
	7	128	
	8	15	
	9	39	
	Unclassified	37	

Table 2: Statistics per analysis unit

Statistic	**Minimum**	**Maximum**	**Average**	**Source**	**Used in…**
Total Population	0	2815	757	(CBS, 2021)	
Total Area (m^2)	196.6 m^2	9,825,200 m^2	174,623 m^2	(CBS, 2021)	
Number of Jobs	0	14477	503	(CBS, 2021)	RQ 1-2
Area of accommodation and shop (m^2)	0 m^2	99,398 m^2	2942 m^2	RUDIFUN[1]	RQ 1
Total population aged 15 to 65	0	2530	551	(CBS, 2021)	RQ 3
Average household size	1	3,2	1,8	(CBS, 2021)	RQ 3
Percentage Male	32%	100%	50%	(CBS, 2021)	RQ 3
Percentage non-western immigrants	0%	90%	32%	(CBS, 2021)	RQ 3

[1] (Planbureau voor de Leefomgeving, n.d.)

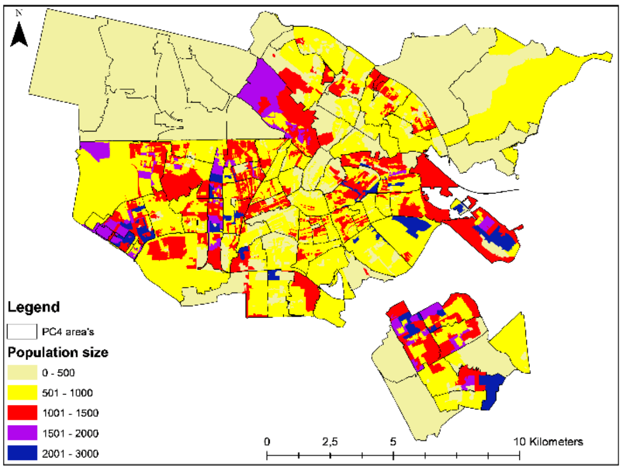


Figure 5: Population size per PC5 area

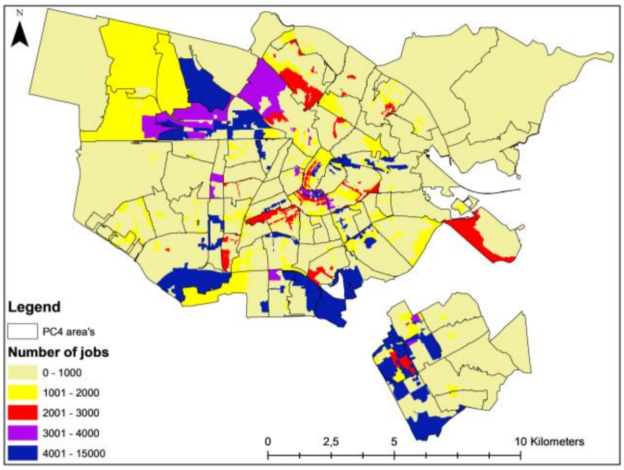


Figure 6: Number of jobs per PC5 area

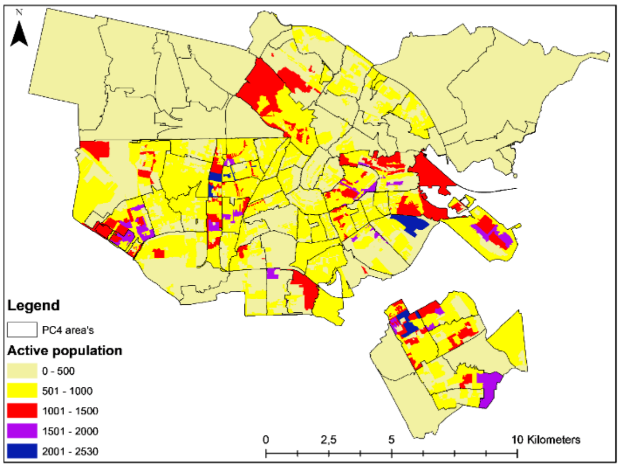


Figure 7: Active population (age 15-65)

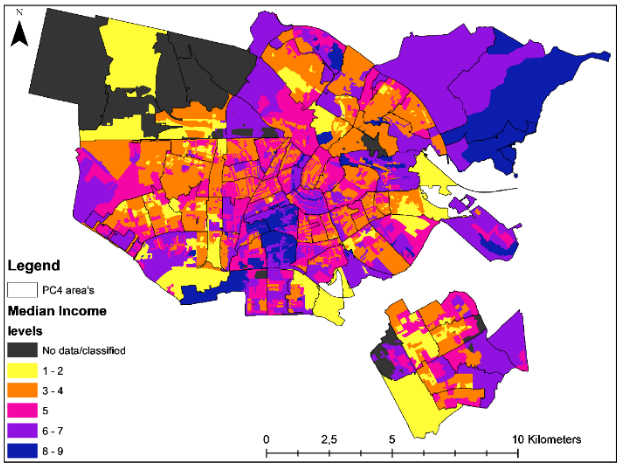


Figure 8: Median Income

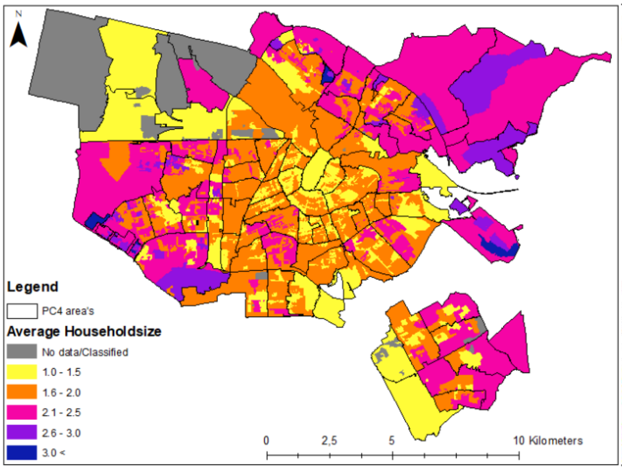


Figure 9: Average household size

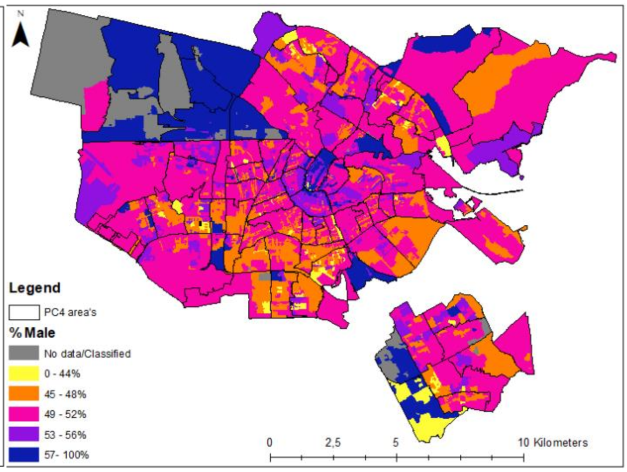


Figure 10: Percentage of male inhabitants

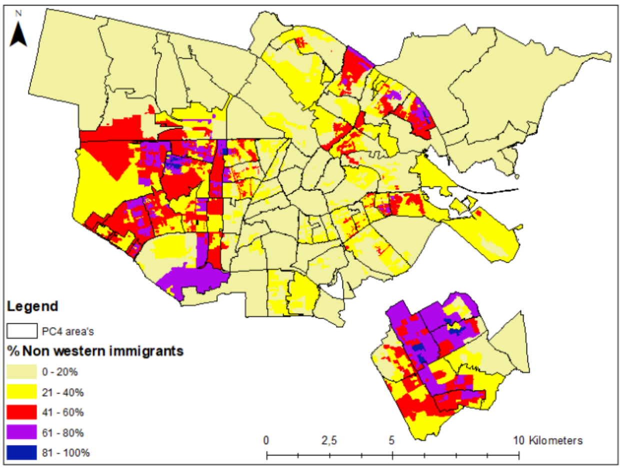


Figure 11: Percentage of non-western immigrants

Table 3: statistics per road section base scenario

Statistic		Minimum	Maximum	Average	Source	Used in…
Length		0.8 m	6,684 m	118 m	(Gemeente Amsterdam, 2022)	RQ 1-2
Traffic volume	car	1	6998	179	(Gemeente Amsterdam, 2022)	RQ 1-2
	bike	0	54648	1301	(Fietstelweek, n.d.)	RQ 1-2

4.1. Crash data

The crash data that has been used is BRON data for the period 2015 – 2019 (Rijkswaterstaat, n.d.). BRON data are the most used source of information for traffic crashes. This information is recorded by the police. BRON should contain all traffic crashes on Dutch roads, but it has been found that this is not the case. In principle, the rule applies: the more serious the crash, the better registered (about 94% of crashes with fatalities and only 10% of crashes with minor injuries) (SWOV, 2010). These crashes are divided into five categories: dead, hospitalized, first aid, lightly wounded and PDO. For this research, the categories hospitalized, first aid and lightly wounded are combined into an injury category. From the BRON data two types of car-to-car and car-to-bike, crashes are used in the analyses of this research. The timeframe is the peak hours (6.30-9.30 & 15.30-19.00) (ANWB, 2022). Since the crashes are allocated to a certain location the crashes could be linked to a road segment in the road network. Crashes that did not have a specific location but instead the municipality as a location were excluded from the research. A visualization of the crashes can be found in Figure 12.

Figure 12: Crash locations in the center of Amsterdam (PC 1011 & 1012)

4.2. Road network and traffic volume data

The road network data was provided by the municipality of Amsterdam (Gemeente Amsterdam, 2022) and includes data such as the current maximum speed and the proposed maximum speed but also the traffic intensities on the road segments. However, some segments, specifically the minor road segments missed some information. To overcome this issue for the speed limits, google Streetview was used in combination with the surrounding streets to get an idea of the speed limit of the segment with missing data. For the intensities again surrounding roads with the same speed limits were used to make a close estimation of the intensities.

Bicycle intensities and speeds are retrieved from the Fietstelweek data (Fietstelweek, n.d.) and linked to the road segment. Fietstelweek is a week in which participants can provide information about cycling trips via an application. In 2016 almost 30.000 participants participated. The Fietstelweek data consists of the bicycle roads including data such as the number of cyclists and average speed on the sections of the cycle roads.

On each road segment, the total number of fatalities, injuries, and PDO crashes in each of the two types of crashes (car-to-car, car-to-bicycle) was determined based on the crash data and used to determine for each type of crash the total crash costs. Lastly, the travel costs for each segment were calculated using the crash costs, intensities, and travel speed.

4.2.1. Traffic model data

The municipality of Amsterdam uses for their traffic related calculations the verkeersmodel Amsterdam (VMA, traffic model Amsterdam). The VMA is an urban traffic model for the city of Amsterdam for all their strategic road and public transport studies. The base of the model is traffic questionnaires, traffic counts, characteristics of the road and public transport network and knowledge of spatial planning in terms of numbers of inhabitants and job opportunities. The original model is created in 2015 and is every two years updated with new data and technical model updates. For this research, the most recent version (version 4.0) is used. New data and factors that each update considered are the future development of infrastructure and projects (including the new 30km/h speed limit), the expected number of households, inhabitants, composition of the population, job locations, and education locations (Gemeente Amsterdam, 2022)

Version 4.0 uses 2019 as the base year (same data as used in this research) and includes the proposed speed limit reduction for 2023. According to the traffic model in the scenario of 2025, the overall peak hour traffic volume is reduced by 3% in comparison with the current situation. Figure 13 shows the road network and the difference between the predicted 2025 scenario and the current situation. Not all roads of Amsterdam were present in this dataset, missing roads were given the same traffic flow as in the current situation. The traffic volume for scenario 2025 was used in the scenario analysis to predict the effects of the speed limit reduction. For the flow of bicyclists no predictions for the future were made by Amsterdam and the same data as in the base scenario is used.

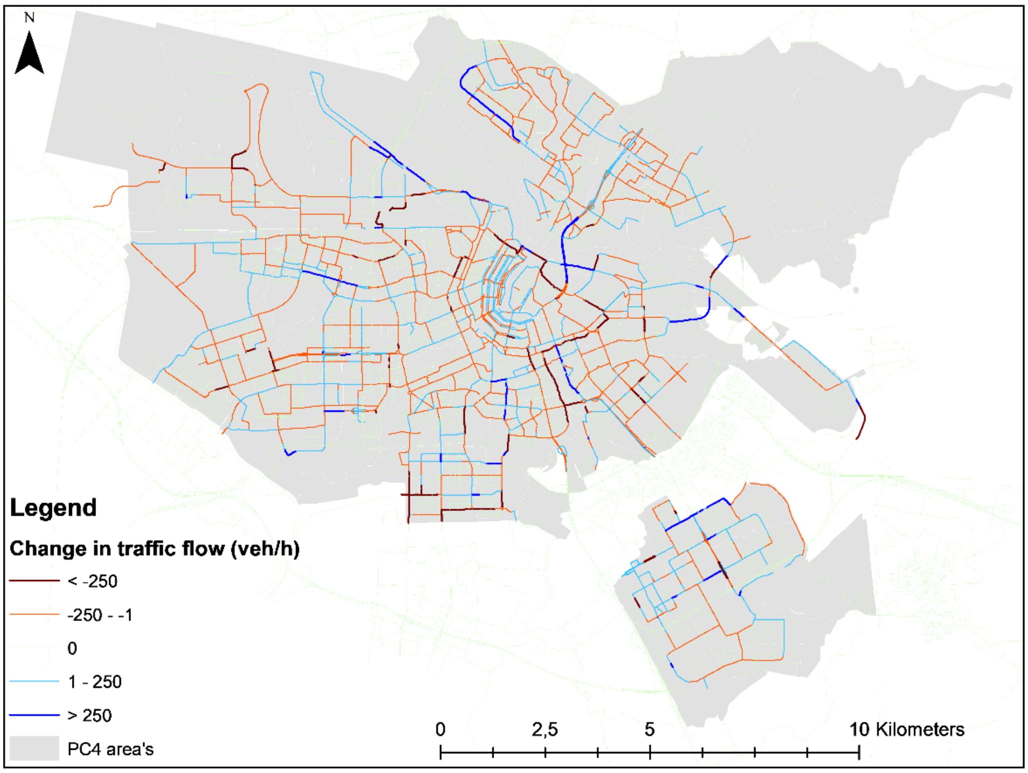


Figure 13: Difference between current and predicted car traffic flow

4.3. PC5 data

The PC5 data was mainly retrieved from CBS and consisted among others of the number of inhabitants aged between 15 and 65 years old (workers) in the PC5 (CBS, 2021). The total number of available jobs is only available in the PC4 areas. Since this research uses PC5 areas the data had to be converted to PC5 level. To achieve this several types of data retrieved from the CBS dataset as well as RUDIFUN data (Planbureau voor de Leefomgeving, n.d.) that is available on PC5 and PC4 level had been used to find a correlation with the number of jobs. The correlation was determined using an Excel file with the data for each of the PC4 areas in Amsterdam and the correlation function of Excel. In the end, the best correlation was found between the number of jobs and the sum of the area of shops and logistics from the RUDIFUN dataset. The correlation was 0.72 and deemed sufficient.

For research question 3 only data on PC5 level is used. The data that is used for this research question is either from the last previous research questions or retrieved from an external source such as CBS. In Table 4 the variables and sources that are used in this section are listed. Like the rest of this research, PC5 areas are used as analyzing units.

Table 4: Variables used for research question 3

Variable	Figure	Source
Accessibility Base scenario		Research question 1
Accessibility scenario 1		Research question 2
People between 15-65	Figure 7	(CBS, 2021)
Median Income	Figure 8	(CBS, 2021)
Average Household Size	Figure 9	(CBS, 2021)
% Male	Figure 10	(CBS, 2021)
% Non-western immigrants	Figure 11	(CBS, 2021)

5. Methodology

In this chapter, for each of the research questions is explained which methods are used and what steps are taken to answer the research questions.

5.1. Accessibility model & scenario analysis

In this section, the methods that were used to create the accessibility model and perform the accessibility and scenario analysis are explained.

5.1.1. Accessibility analysis

To perform the accessibility analysis first the accessibility model was created. The crash risks of each road section were determined by a created traffic safety model in combination with the empirical Bayes. To determine the effects of speed limit reduction a scenario analysis is performed. The scenarios were based on different expectations in the reduction of crashes determined by the power model.

This research focuses on passenger cars and bicyclists as the main transportation mode since car users are mostly affected by reducing the maximum speeds. The safety of bicyclists should be influenced by speed reductions in urban areas since research generally finds that at higher speed limits the fatal and serious injury car-bicycle crash rates rise (Kim, Kim, Ulfarsson, & Porrello, 2007). To integrate traffic safety in the accessibility analysis, both travel time and traffic crashes are monetized to determine the accessibility levels using both travel time and traffic safety. Another option is using the time in combination with loss of life years on the life expectancy due to fatal crashes (Li, Ma, Bishai, & Hyder, 2017). Another possibility is the combination of the two methods which would make the accessibility model quite complex. Therefore, the sole use of a monetary value is used in this research. This allows the inclusion of less severe crashes, such as property damage only crashes, in the accessibility model.

The accessibility of jobs in Amsterdam is determined using a contour measure. The contour measure counts the number of opportunities available within a threshold. There are some benefits and downsides to contour measures. The benefits are that they are easy to interpret, however, they do not take competition into account (Geurs & van Wee, 2004). The accessibility of jobs can be expressed as Equation 1. In which A_i is the job accessibility of origin *i* and O_j is the number of opportunities in zone *j*. The cost for traveling between origin *i* and destination *j* is given by C_{ij}. If C_{ij} is larger than the determined threshold the value of $f(C_{ij})$ will be 0, if this is not the case $f(C_{ij})$ will be 1 (Cui & Levinson, 2018). The origins are the PC5 zones of Amsterdam, while the destinations are again the PC5 zones of Amsterdam and PC4 zones outside of Amsterdam within 16 km.

$$A_i = \sum_{j=1}^{n} O_j f(C_{ij})$$

Equation 1: Accessibility of jobs (Cui & Levinson, 2018)

In this research, there will be no variation in the time since this is outside the scope of the research. Although it would give a much more complete result when it comes to the difference in accessibility for the different scenarios. No or limited time variation can still give a good indication of the effects of the measures implemented, as long as the chosen timeframe is a good indication of the accessibility (Kwan, Murray, O'Kelly, & Tiefelsdorf, 2003). Since the focus is on job accessibility the timeframe chosen for this research is during the office peak hours, when most workers are on the road to/from their jobs. Another reason that temporal variation is not very important for this research is that job opportunities do not change during the day.

This research focuses on the accessibility of working people to job opportunities in Amsterdam. As stated before, the monetary value of travel time and crash consequences are used in the analysis. To determine the monetary value of travel time the estimated value of (travel) time for commuting is used. In the Netherlands, this is approximately €9.25 per hour by car (Kouwenhoven, et al., 2014) and €13.43 by bike (van Ginkel, 2014). The value of time differs between the two modes for two main reasons. The first being the type of people that use a certain transport mode can be influenced by their income and secondly the comfort and conditions for a transport mode are different (Wardman, 2004). This will lead to a difference in what the users estimate 1 hour of traveling is worth. The crash costs in case of injury or fatality are based on the value of statistical life or serious injury. The cost of a fatality and serious injury are estimated at €6.3 million and €1.0 million respectively (Wijnen, Schoeters, Bijleveld, Daniels, & Van der Horst, 2022). Since this research uses only a KSI type of victims the value costs for a severe injury is chosen for these types of crashes. However, in the traffic safety model fatal crashes were weighted 6.3 to account for the higher costs. The average cost of property damage only crash is €2,000 (ANWB, 2022). Crash risks are based on the possibility of being involved in a crash when using a certain road segment.

The transport model from Amsterdam only determines the traffic volumes and does not use travel speeds or travel times. Therefore, in both the current and predicted situation the effects on the traffic speeds are outside the scope of this research and the assumption is made that traffic obeys the speed limit during this research and travel costs for the road segments are calculated based on the length of a road segment and the uncongested speeds, which is equal to the maximum speed of the road.

The cost of traveling along a road section (C_{travel}) is determined using Equation 2. The total crash costs (C_{total}) of a road segment are divided by the total estimated traffic volume (V_{total}) during the same timeframe of the crashes. The total traffic volume is determined by multiplying the peak hour traffic flow with the number of peak hours in a day (6.5) and the number of weekdays in the years 2015 – 2019 (1304). The cost for the travel time (travel time in hours) is the length (l) of the road section (in km) divided by the speed limit (S) of the vehicles (in km/h), VoT=Value of time, or the cost for traveling 1 hour) will be added to give the total cost of traveling on a road section.

$$C_{travel} = \frac{C_{total}}{V_{total}} + (l/S * VoT)$$

Equation 2: Travel cost (in €) of a road segment

The accessibility analysis is done with the network analyst within ArcGIS. The opportunities are represented by available jobs in the PC5 areas. Different thresholds for travel costs (€4,39 for car users and €4,87 for bicyclists) are used to show the difference in accessibility on shorter and longer trips. These values are chosen since these are the average travel times per trip (28.46 minutes by car and 21.77 minutes by bike) (CBS, 2022) when converted to monetized value. If job accessibility analysis is performed for a large number of regions with a large number of individuals it will give a good indication of the overall accessibility of an area. To ensure the large number of regions the PC5 areas of Amsterdam are chosen as the zones (1,123 zones). To slightly simplify the analysis the accessibility of only people living in Amsterdam is determined and the assumption is made that they either work in Amsterdam or in the region within 16 km of Amsterdam. Since the average commuting distance of a car user in Amsterdam is 16 km (CBS, 2018). Another assumption is that all workers take the cheapest route to their job in terms of travel costs (Equation 2). An excluded factor is the temporal factor, the accessibility will be determined during the peak hours when is assumed that the workers are traveling to and from their job. Fuel costs are also excluded in this research since it is out of the scope of the research to determine the effects of speed limit reduction on fuel consumption and costs. Another excluded factor is the delay caused by crashes. A crash likely causes congestion on roads which will increase travel time. But it will be near impossible to accurately determine these delays and the assumption is that the average speed on roads with a high probability of crashes is already decreased and shows an average travel time on those streets with additional time for the crashes.

5.1.2. Traffic safety model

To determine the number of crashes for each road segment a traffic safety model is created. Since traffic crashes happen randomly (i.e., they are probabilistic phenomena) it is possible that the estimated crash risks on roads are over or underestimated when using solely observed crashes. To improve this limitation a traffic safety model is created. A traffic safety model is a simple equation that predicts based on certain variables what the expected crashes on a road section are. The type of model that is used is a negative binomial regression model, which is most common when modeling crashes (Lord, 2006). This is an extension of the Poisson model to overcome possible overdispersion in the data. This type of model is used when the data follows a gamma probability (Lord & Mannering, 2010). Equation 3 is the general form of what a negative binomial model looks like. In this equation a is the intercept, b_i is the estimated coefficient of a variable and x_i is the measured value of that variable. For this research, the crashes were separated into four types of crashes, based on the modes, car-to-car and car-to-bicycle, and results of the crashes, property damage only (PDO crashes) and killed or severely injured (KSI crashes). The reason that the killed and severe injuries are grouped is that the very limited data on fatal crashes made it impossible to create a significant relationship between fatal crashes and the used variables. The variables used to determine the number of crashes are the length of the road segment, car traffic volume, speed limit, type of road, bicycle traffic volume and bicycle speed.

$$y = e^{a+b_i*x_i}$$

Equation 3: Negative binomial function (Lord & Mannering, 2010)

Ideally, the crash risks are determined based on observations and expectations, since the traffic safety model ignores the observed crashes completely the empirical Bayes method is applied. The empirical Bayes method adjusts the predicted crashes from the traffic safety model according to the perceived crashes. The benefit of the empirical Bayes method is that it increases the precision of estimates of a short period of crash data, in this case 5 years. While on the other hand, it prevents the regression to mean bias by using the perceived crashes (Hauer, Harwood, & Griffith, 2002). The number of expected crashes on a road section based on the traffic safety model in combination with the observed crashes can be calculated by Equation 4. To calculate the weight Equation 5 can be used. In these equations mu (μ) is the predicted number of crashes according to the traffic safety model, Y is the number of years of which data is used (5 years in this research) and phi (Φ) is the overdispersion parameter.

$$Expected\ crashes = weight * \mu + (1 - weight) * observed\ crashes$$

Equation 4: Expected crashes (Hauer, Harwood, & Griffith, 2002)

$$Weight = 1/(1 + \frac{\mu * Y}{\Phi})$$

Equation 5: Weight (Hauer, Harwood, & Griffith, 2002)

5.1.3. Power model

Various attempts by researchers to find a mathematical relationship between speed and road safety resulted in different outcomes. One of those outcomes is the power model. The exponents of the model vary by different types of crashes and different traffic environments. With the help of the power model the expected number and severity of crashes can be determined after the speed limit reduction. The crashes can be calculated with Equation 6. The exponents of the equations that will be used in this research can be found in Table 5 (Elvik, 2013).

$$Crashses_{after} = Crashes_{Befor} * (\frac{Speed_{after}}{Speed_{befor}})^{exponent}$$

Equation 6: Power model (Elvik, 2013)

Table 5: Exponent for the power model for urban and residential roads (Elvik, 2013)

Crash severity	Best Fit	Lower Limit	Upper Limit
Killed or seriously injured	2.0	0.8	3.2
Property damage only (PDO) crashes	0.8	0.1	1.5

Another way to describe the relation between speed and road safety can be done by using an exponential function (Equation 7). The main difference between the developed exponential functions and the power model is that the reduction in crashes is not only based on the percentage of speed reduction but also the initial speed (Elvik, 2013).

$$AMF\ (For\ speed\ change\ from\ v\ to\ v^{*}) = e^{\alpha\left[v-v^{*}+\left(\frac{\beta}{2}\right)*\left(v^{2}-v^{*2}\right)\right]}$$

Equation 7: Exponential function (Elvik, 2013)

Elvik (2013) improved the exponential function and compared it with the power model to determine which method is better. The conclusion is that both methods are very similar and fit the data well. For fatal crashes, the power model was slightly better. For injuries and PDO crashes the exponential model was slightly better than the power model. The difference between the methods is especially visible at higher speeds which is less important for this research. Given the small difference at the speed of 50km/h between the models and the high complexity of the exponential method, it is decided to use the power model to determine the expected changes in crashes for this research (Elvik, 2013).

To predict the number of crashes in the scenarios again the traffic safety model in combination with the empirical Bayes method was used. For the roads with speed limit reduction the power model was used to determine the new number of perceived victims and crashes, the outcome of the model was not rounded, and decimal numbers were used to calculate the crash costs for the different road segments.

5.1.4. Scenario analysis

Assessing the impacts of speed limit reduction on accessibility levels is done by comparative research combined with scenario analysis. In comparative research two or more objects, ideas, or results are qualitatively analyzed and compared, to show how similar or different they are. This is done by focusing on the common points in both systems (in this research job and household locations), along with areas where they significantly differ (in this research traffic safety and accessibility) (Bukhari, 2011). Scenario analysis is an aid focusing on alternative visions of the future. It is a powerful tool to answer the what-if questions that arise when exploring uncertainty. By working with different scenarios, the focus is shifting away from what is most likely to happen toward what could happen under different circumstances (Duiker & Greig, 2007)

To perform the scenario analysis an accessibility analysis similar to section 5.1 will be performed, but with certain inputs adjusted. The inputs that will be changed in the scenario analysis in this research are the following: speed limits, traffic flow, and the number of traffic crashes. In Table 6 the different scenarios are given, the colors indicate the variables that have been adjusted in that scenario in comparison with the base scenario. For each of the first three scenarios one of the variables will be changed. For speed limits, there will be two inputs used. The current speed limit and the proposed speed limit (scenario 1, green), where the speed limit will be decreased from 50km/h to 30km/h on lots of roads in Amsterdam. Similarly, the traffic flow will differ based on the data provided by the municipality of Amsterdam. The current measured car traffic flow is from 2019 and the predicted car traffic flow is for the year 2025 (scenario 2, yellow) which includes the proposed speed limit and predictions of new routes that might be taken by road users. The last input that will change during the scenario analysis is traffic safety. In the base scenario, the current number of crash victims based on the traffic safety model will be used. For the scenarios, the Power model will be used to determine new input numbers of traffic victims for the traffic safety model. The best fit value of the power model from Table 5 will be used (Scenario 3, turquoise) A more in-depth explanation of the data that is used can be found in the data chapter (chapter 4). It is important to note that, the number of households and job possibilities remains the same in all situations.

Table 6: Different scenarios for the scenario analysis

	Speed limit	Car flow	Crashes
Scenario 0	Current	2019	None
Base Scenario	Current	2019	Original
Scenario 1	Proposed	2019	Original
Scenario 2	Current	2025	Original
Scenario 3	Current	2019	Best fit
Scenario 4	Proposed	2025	Best fit

5.2. Equity analysis

This part of the research aims to find if the transport policy has an effect on the equity of Amsterdam and which regions and population groups benefit or suffer from the reduction in speed limit. This will be done with Moran's I. Other possible methods that could have been used are the Theil index or the Gini index (Sharma & Patil, 2021). However, these indexes only give a single value to determine equity. And one value could be caused by different distributions (Sharma & Patil, 2021). Moran's I makes it possible to visualize the cluster location and to compare it with other land use and socio-demographic variables.

Moran's I is a coefficient to determine the overall spatial correlation of a data set. It determines how similar or different an object is in comparison with its surrounding (Glen, 2016). When objects are attracted or repelled by each other indicates that the observations are not independent. This method is selected for this research since it can be visualized and used to show the possible equity differences in accessibility with the local Moran's I. The Anselin Local Moran's I is performed to show the location of the clusters and spatial outliers in the base scenario. A second analysis was done with the difference in accessibility to show how the changes in accessibility affect equity in Amsterdam. For this step, the difference between the base scenario and scenario 1 (best fit) is used. This is all performed with ArcGIS.

Bivariate local Moran's I is an adjusted version of the local Moran's I which measures the spatial association between two observations and their clustering spatial patterns (Lee, 2001). This method has already been used to analyze the correlation between the walkability of neighborhoods and the population size of specific population groups (Weng, et al., 2019). In this research the correlation between the change in accessibility and different population groups will be determined.

In this research, the spatial pattern of deviation of job accessibility levels in the designed scenarios (see Table 6) from the base scenario is compared with the spatial distribution of five variables. Those variables are active population (age 15-65), income level, household size, percentage of male inhabitants and percentage of non-western immigrants. This research focuses on these variables to investigate the correlation between the changes in accessibility levels and these variables due to the following reasons:

- The active population is chosen since it is expected that regions with a high number of people who can work should also have good access to jobs.
- The literature shows that people with a low income are more exposed to traffic crashes (Asadi, Ulak, Geurs, Weijermans, & Schepers, 2022) therefore it is interesting to know the effects of speed limit reduction specifically on this population group. It can be hypothesized that a reduction in speed limits,

and subsequently traffic crashes, can be more beneficial in low-income areas than in high-income areas. Based on research from Levinson (1998) additional children are associated with longer commutes. Sermons & Koppelman (2001) also show that the presence of children is an important factor for people to base their commuting time on, therefore the household size is chosen as a variable.

- Gender also plays a role in the commuting time. Research shows that women have shorter trips but travel more often (Manaug, Miranda-Moreno, & El-Geneidy, 2010). Also are females more likely to use nonmotorized transport modes (Miralles-Guasch, Melo, & Marquet, 2016). Therefore, it can be expected that a higher percentage of males live in regions with higher accessibility by car. While a low percentage of males can be found in regions with higher accessibility by bike.
- The last variable, the percentage of non-western immigrants, is chosen since research shows that there is a difference in the distance and time of commuting between locals and migrant workers. Migrant workers tend to have shorter commuting trips than locals (Li, Geertman, Hooijmeijer, Lin, & Yang, 2021). Specifically in the Netherlands it is known that non-western (female) immigrants are most likely limited in their cycling accessibility and experience therefore transport exclusion (Van der Kloof, Bastiaanssen, & Martens, 2014).

Since some of the variables had a few regions with missing data those regions were excluded in the bivariate Moran's I. Bivariate Moran's I is performed using QGIS version 3.12 with the 'Hotspot Analysis' plugin.

6. Results

This chapter shows the results for each of the research questions as well as an explanation of the results.

6.1. Integration of traffic safety indicators in accessibility analysis

The first part of the research focuses on the integration of traffic safety indicators in accessibility analysis. This is in line with the first sub-research question: ***"How can traffic safety indicators be integrated into accessibility models?"***. First, the results of the traffic safety model are given in this section, followed by the results of the job accessibility analysis of Amsterdam considering the current speed limits on roads without and with the inclusion of traffic crash costs in the analyses.

The variables included in the traffic safety models are the length of the road segment, car traffic volume, speed limit and bicycle traffic volume. Other tested variables were insignificant according to the analysis. Table 7 to Table 10 represents the most important results of the models for the different types of crashes and severity. All results of the regression analysis can be found in Appendix B.

Table 7: Traffic safety model for PDO car crashes

Significant variables	Estimate	Standard error	P value
(Intercept)	-3.471	6.650e-02	0
Length of road section	1.834e-03	9.635e-05	0
Speed limit	3.976e-02	1.736e-03	0
Car traffic flow	7.405e-04	6.170e-05	0
Theta (overdispersion parameter)	0.12267		
AIC	25079		
2x log-likelihood	-25068.835		

Table 8: Traffic safety model for KSI car crashes

Significant variables	Estimate	Standard error	P value
(Intercept)	-6.786	0.1869	0
Length of road section	1.491e-03	1.500e-04	0
Speed limit	3.854e-02	3.651e-03	0
Car traffic flow	3.900e-04	1.071e-04	2.72e-04
Theta (overdispersion parameter)	0.0691		
AIC	2451.7		
2x log-likelihood	-2441.694		

Table 9: Traffic safety model for PDO bicycle crashes

Significant variables	Estimate	Standard error	P value
(Intercept)	-3.433	4.342e-02	0
Length of road section	5.033e-04	1.046e-04	1.50e-6
Car traffic flow	3.302e-04	6.333e-05	1.85e-7
Bicycle traffic flow	4.254e-03	2.825e-04	0
Theta (overdispersion parameter)	0.1784		
AIC	8126.4		
2x log-likelihood	-8116.422		

Table 10: Traffic safety model for KSI bicycle crashes

Significant variables	Estimate	Standard error	P value
(Intercept)	-4.368	6.828e-02	0
Length of road section	5.515e-04	1.593e-04	5.34e-4
Car traffic flow	4.309e-04	9.39e-05	4.45e-6
Bicycle traffic flow	4.410e-03	4.385e-04	0
Theta (overdispersion parameter)	0.0730		
AIC	3991.9		
2x log-likelihood	-3981.877		

Before the implementation of the traffic crashes the average travel costs of the road segments for car users were €0.026, after the implementation of the traffic crashes this increased to €0.801. Based on a T-test significance value of 0.0004 it can be said that this increase is significant. For cyclists the average travel costs were €0.095 before the implementation of crashes and increased to €0.227 after the implementation of crashes. Based on a T-test significance value of 0 it can be said that this increase is also significant.

Table 11 presents the average job accessibility in the PC5 area for two different mode users. As explained in the methodology the chosen thresholds are €4.39 for car users and €4.87 for cyclists, since this is the converted average travel time for the transport modes. Moreover, Table 11 involves average job accessibility calculated in two situations with and without integration of crash costs in the accessibility model, the last column shows the difference between the two results. The distribution of the number of jobs is also put into histograms (Figure 14 and Figure 15). A visualization of the job accessibility by car and bicycle (excluding the crash costs) can be found in Figure 16a and Figure 18a. The job accessibility with the inclusion of crash risk costs is also calculated for the two different transport modes and is shown in Figure 16b and Figure 18b (for car accessibility also Figure 17 is added with an adjusted legend).

Table 11: Average job accessibility (total number of accessible jobs) with and without crashes

Transport mode	Without crashes	With crashes	Difference	P value
Car	1,112,123	733,733	-378,024 (-34.0%)	0
Bike	241,384	211,677	-29,707(-12.3%)	1.8e-9

As the results show, when the traffic crash costs are considered in the model the accessibility is reduced for each of the transport modes. This indicates that, as can be expected, crash risks are implemented as a limitation for accessibility. The histograms show clear differences for the car users, while the bicyclist seems to have a much more similar pattern in both situations, however, it is clear that the accessibility decreases. The results also show that for car users, most of Amsterdam, apart from some regions in the east, has an accessibility of over 1 million jobs when crash costs are not taken into account. However, when crashes are taken into account job accessibility by car is higher in the Southwest of Amsterdam than in the other regions. For cyclists, the center of Amsterdam has higher job accessibility levels in comparison with the outskirts of the city, in both cases of inclusion or exclusion of traffic crash costs in the accessibility analysis. Also, as expected, job accessibility by car is higher than by bicycle within the thresholds. Figures of the differences between accessibility for the scenarios with and without crashes are provided in Appendix C.

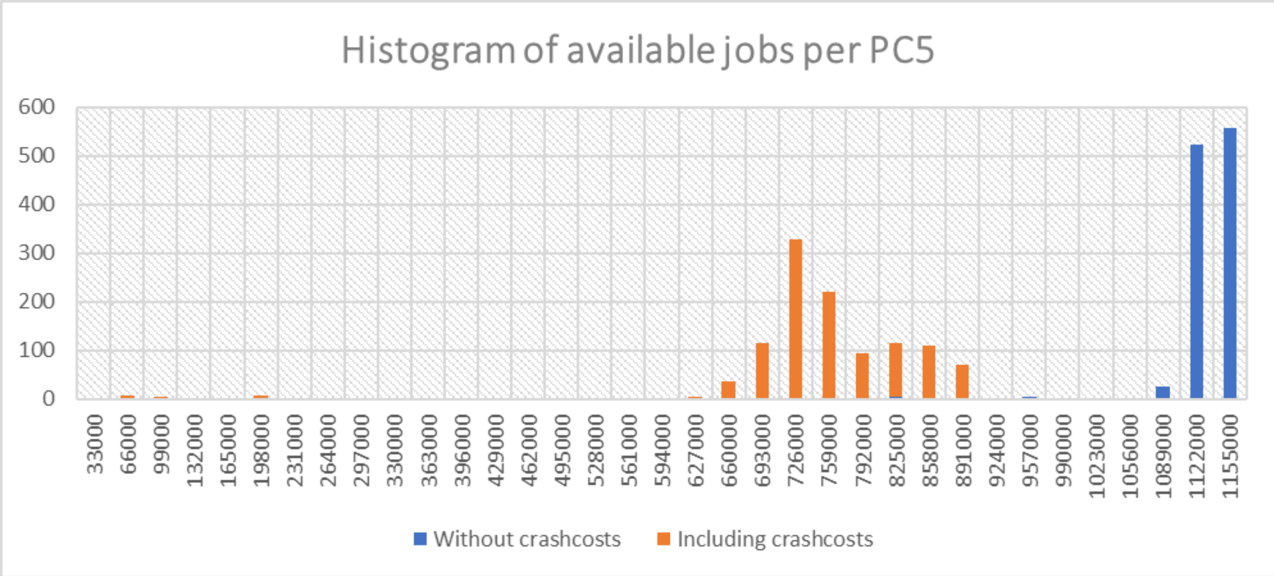


Figure 14: Histogram of available jobs by car with and without crashes included

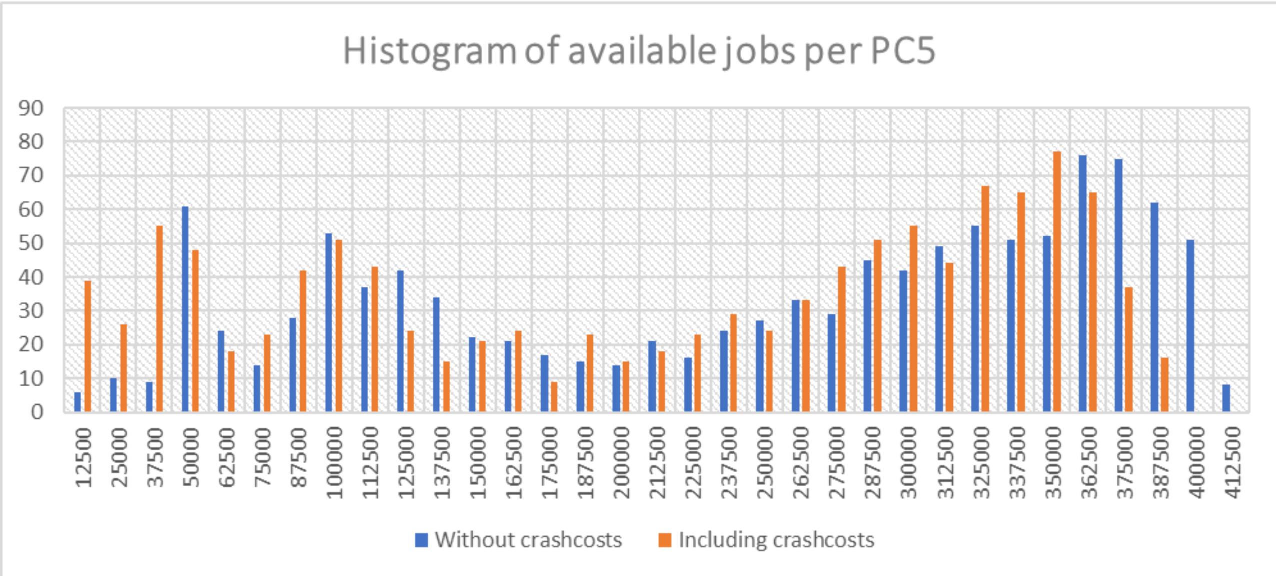
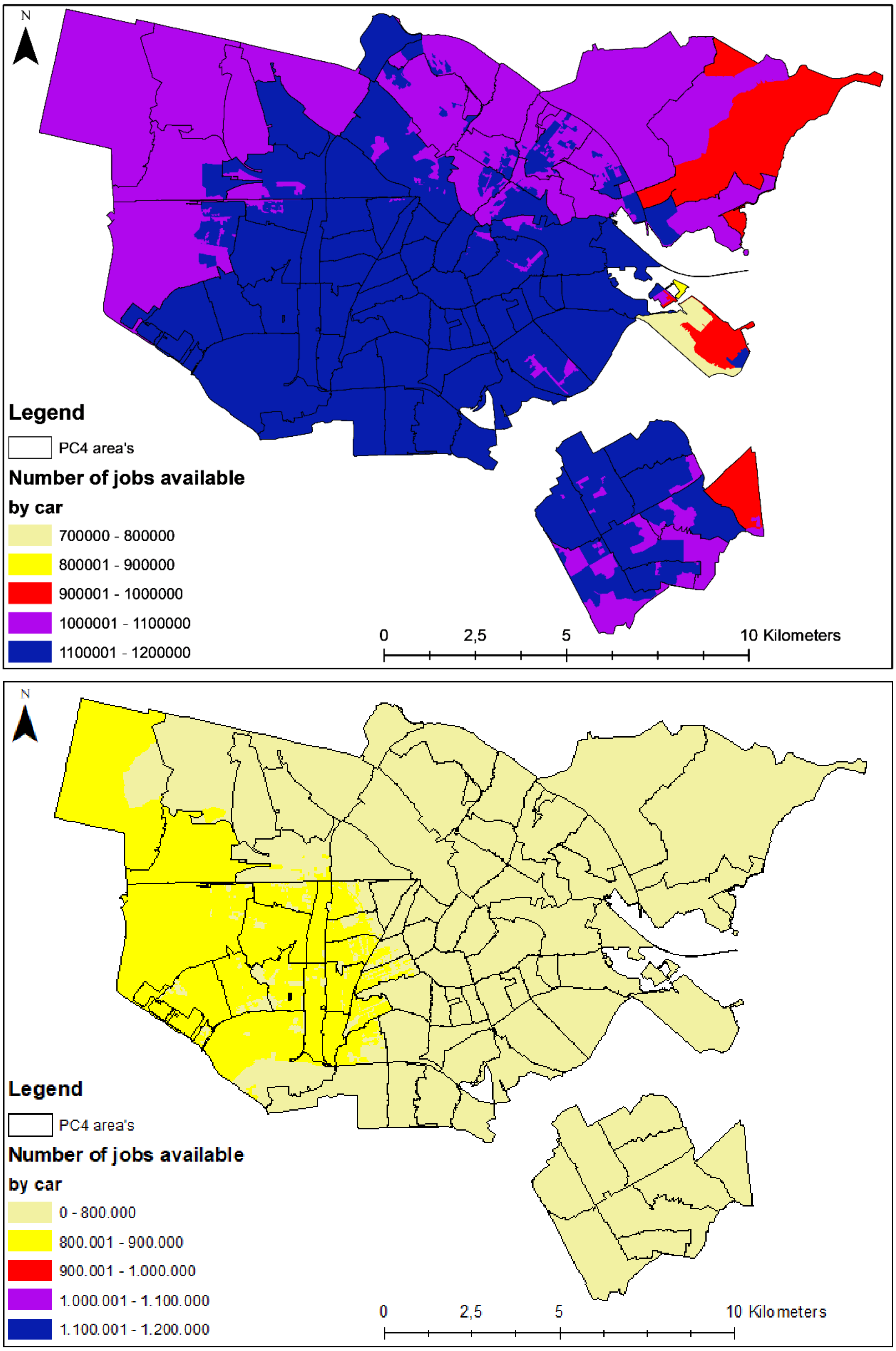


Figure 15: Histogram of available jobs by bike with and without crashes included



(a)

(b)

Figure 16: Job accessibility by car in PC5 areas[2], (a) without the inclusion of crash costs, (b) with the inclusion of crash costs

[2] PC4 boundaries are given since PC5 boundaries make figure unclear, accessibility is given per PC5

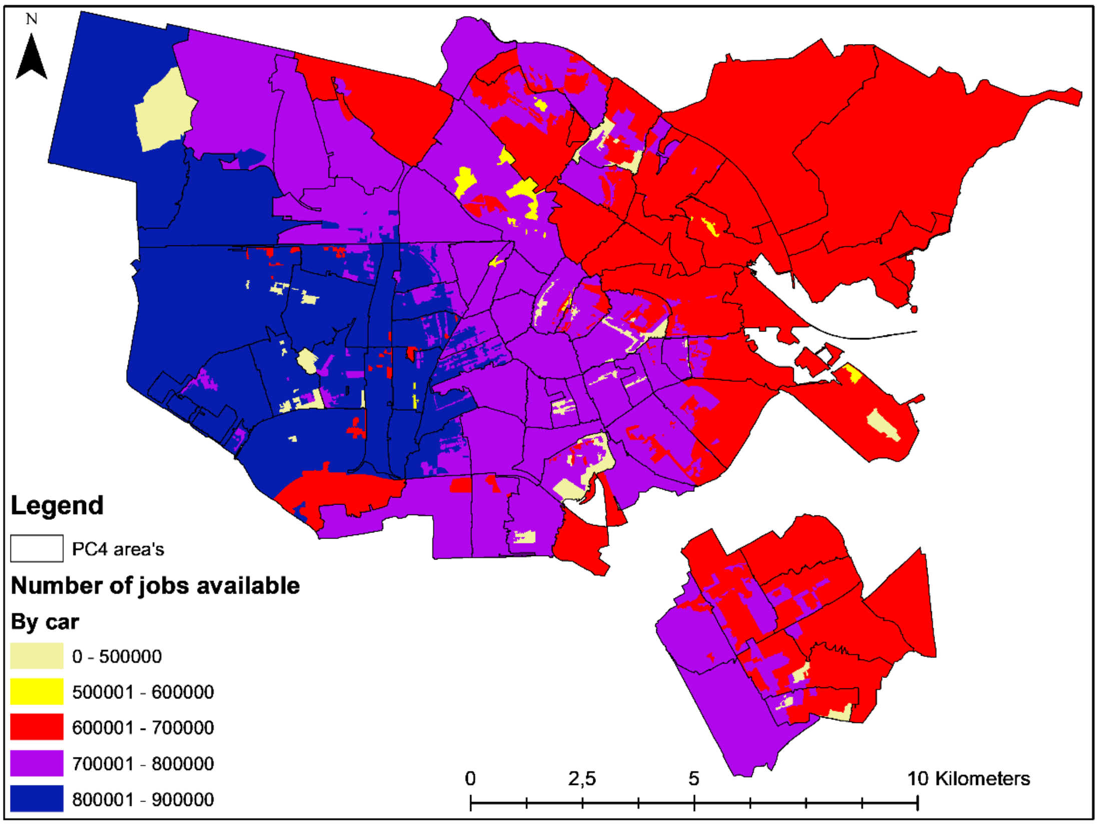


Figure 17: Job accessibility by car in PC5 areas with the inclusion of crash costs (adjusted legend)

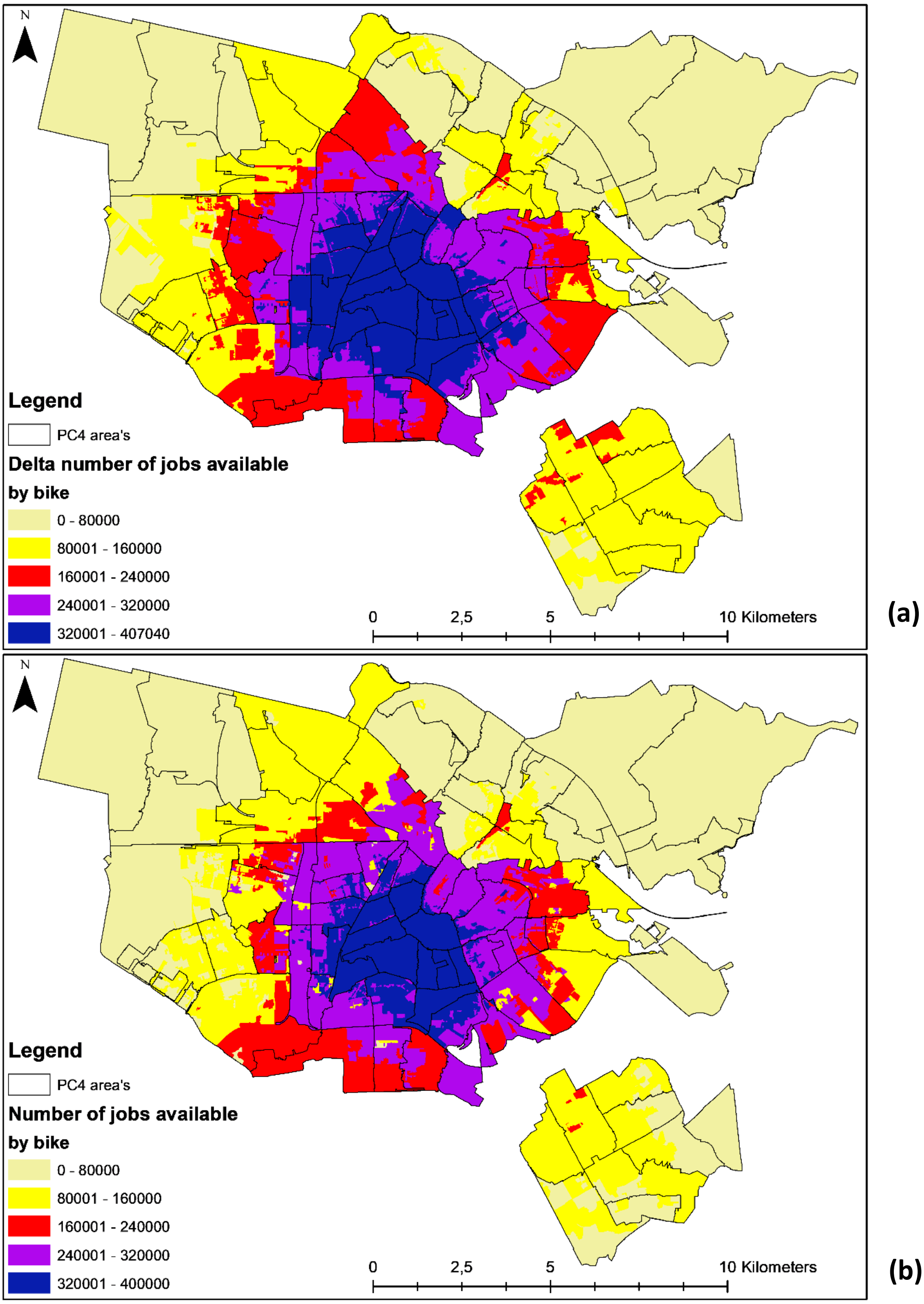


Figure 18: Job accessibility by bike in PC5 areas, (a) without the inclusion of crash costs, (b) with the inclusion of crash costs

6.2. Assessing the effects of speed limit reduction and improved traffic safety on job accessibility in Amsterdam

As described in section 2.2 any changes in speed limits may affect traffic safety and traffic characteristics. These effects subsequently can influence the accessibility of road users. To estimate the extent of these effects on accessibility a scenario analysis is performed. In this section the results of the second sub-research question, *“**How can changes in speed limits (and consequently traffic safety) influence job accessibility in different urban areas in Amsterdam?**”* will be given.

In comparison with the base scenario, the first three scenarios use the predicted traffic volumes, proposed new speed limit or predicted newly perceived crashes based on the power model. Scenario 4 combines all of the effects. Based on the different inputs together with the traffic safety model new predicted crash risks are determined.

Table 12 shows the average number of crashes expected on the roads in Amsterdam. The perceived crashes are based on counts over 5 years. The power model crashes are based solely on the perceived number of crashes, while the average crashes for the different scenarios are based on a combination of the traffic safety model and either the perceived crashes or the crashes from the power model. Based on this table a reduction in crashes can be expected for scenarios 3 and 4.

Table 12: Average number of crashes per type of crash and scenario

	Perceived Crashes	**Power Model**	**Base Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Car PDO crashes	0.566	0.547	0.567	0.563	0.567	0.549	0.546
Car KSI crashes	0.016	0.015	0.016	0.016	0.016	0.016	0.015
Bike PDO crashes	0.046	0.041	0.046	0.046	0.046	0.043	0.043
Bike KSI crashes	0.019	0.014	0.019	0.019	0.019	0.016	0.016

Table 13 provides an overview of the average number of jobs accessible per transport mode based on the situation of four different designed scenarios (see Table 6). Figure 19 and Figure 20 display the histogram of the distribution of the job numbers of the PC5 areas. Visualization of the number of jobs accessible per transport mode in scenario 4 is shown in Figure 21. In appendix D the accessibility of the other scenarios can be found. In general, the table, histograms and maps show very similar results as the base scenario for both car users and bicyclists. However, the tendency is that car users have a decrease in accessibility while cyclists have an improvement in accessibility. Still, car users can reach more jobs than other road users. This result was expected, since car users driving the speed limit are faster than cyclists and it is most likely that they have significantly higher accessibility, even after speed limit reduction. The results also show that scenario 1 has the largest negative effect on car users and no effect on cyclists. Scenario 2 has very minimalistic effects on both car users and cyclists. While scenario 3 has positive effects for both car users and cyclists. The combined scenario shows a reduction in accessibility for car users and the highest improvement out of all scenarios for cyclists. The histograms show some changes which are similar to the outcomes of Table 13. A closer look at the maps does show that for car users the areas with higher job accessibility (on the map in blue) have reduced. Bicyclists also show differences on closer inspection, however, in general, the accessibility is improved.

Table 13: Average number of jobs accessible per transport mode within a given threshold

Accessibility by …	Scenario 1 (New speed limit)	Scenario 2 (New car flow)	Scenario 3 (New crashes)	Scenario 4 (Combined effects)
Car, for given scenario	727,890	733,589	734,068	728,527
Car, for base scenario	733,733	733,733	733,733	734,624
Car, difference between given scenario and base scenario	-6,843 (-0.8%)	-144 (-0.02%)	335 (0.046%)	-5,206 (-0.7%)
Bike, for given scenario	211,677	211,717	213,536	213,595
Bike, for base scenario	211,677	211,677	211,677	211,677
Bike, difference between given scenario and base scenario	0 (0%)	40 (0%)	1859 (0.9%)	1918 (0.9%)

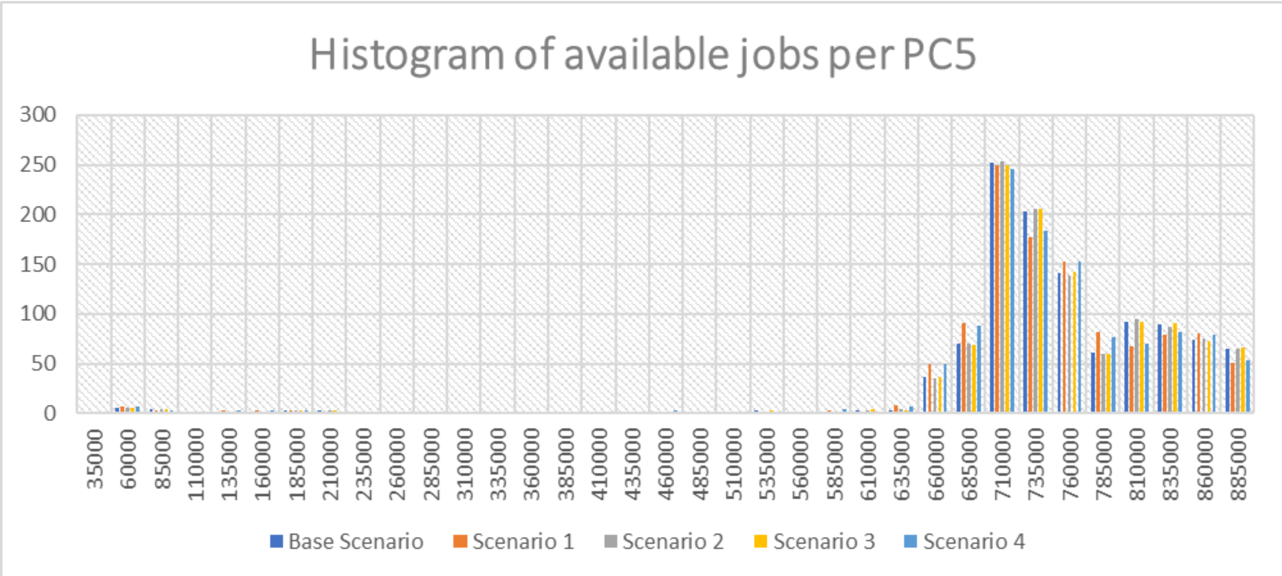


Figure 19: Histogram of available jobs by car for the different scenarios

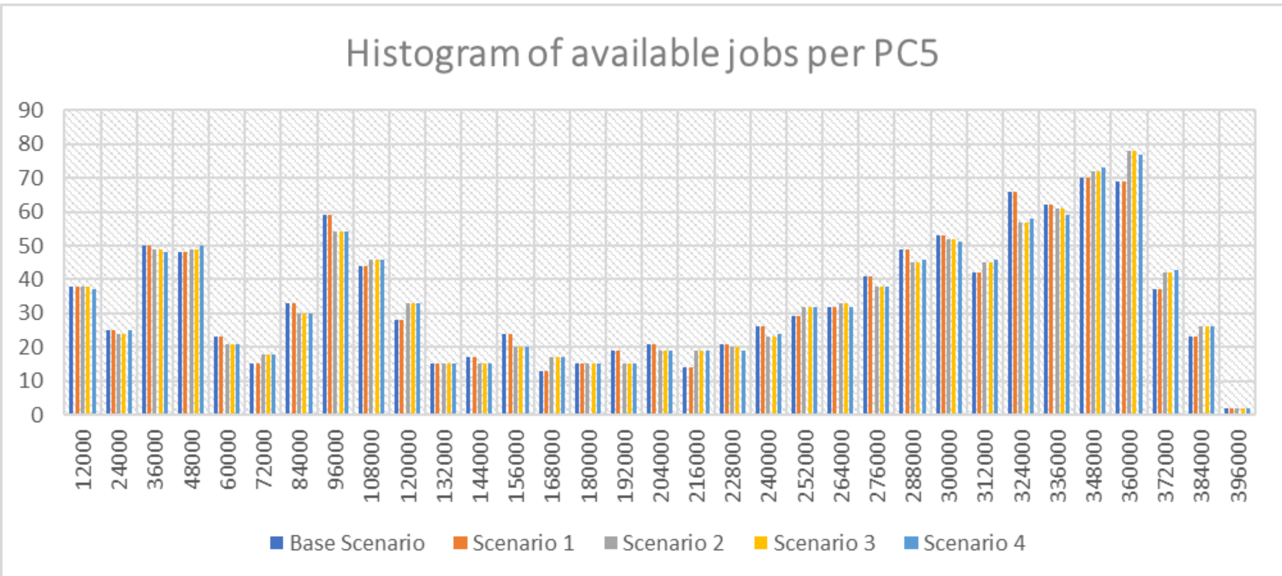


Figure 20: Histogram of available jobs by bike for the different scenarios

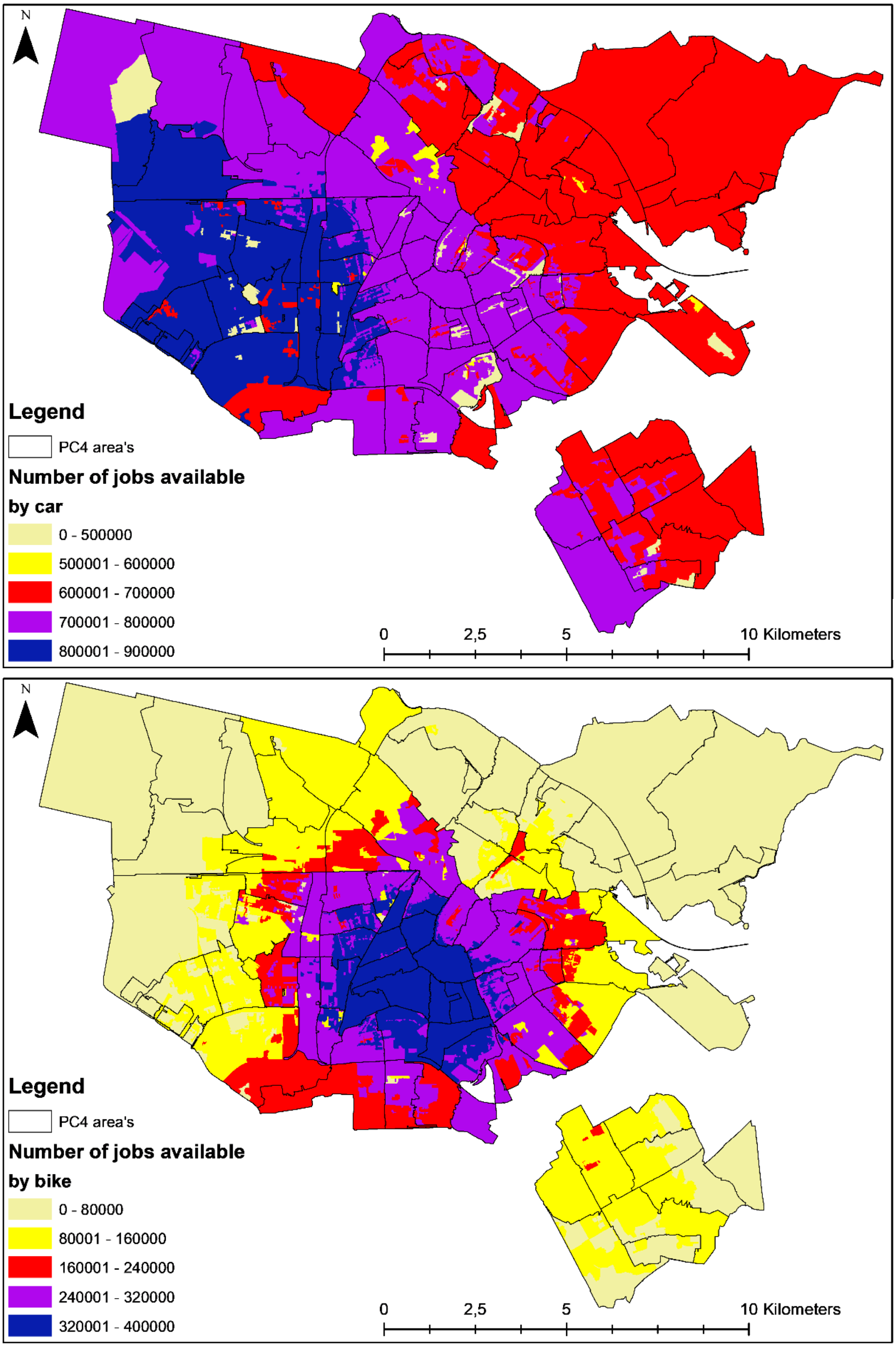
Comparisons between the results of different scenarios (Table 13) reveal that a reduction in traffic crash costs caused by reducing speed limits may positively affect job accessibility. This can be seen in the changes in the job accessibility of bicyclists. Because the job accessibility of cyclists is only influenced by changes in crash costs as a result of improvements in traffic safety. However, reducing speed limits changes the route choice which can decrease safety on roads without speed limit reduction and increase car traffic flow. Reducing speed limits can make changes in the accessibility of car users to jobs in two ways; 1) causing longer travel time that leads to a negative effect on accessibility, and 2) a smaller number of traffic crashes which results in lowering crash cost (positive impact).

To determine whether the changes in accessibility are significant a t-test is performed. The p values of the t-test can be found in table Table 14. As can be seen are the P values all greater than 0.05 indicating that the changes are not significant. This does not mean that the results of the scenario analysis are useless. The data still support the outcome of the scenario analysis and accessibility likely increases for cyclists and likely decreases for car users. However, the support is weak and shows merely an expectation of possible effects.

Table 14: P values of T-test comparing base scenario with scenario analysis

T-test	Scenario 1	Scenario 2	Scenario 3	Scenario 4
P value car	0.096	0.488	0.471	0.133
P value bike	0.500	0.497	0.357	0.353

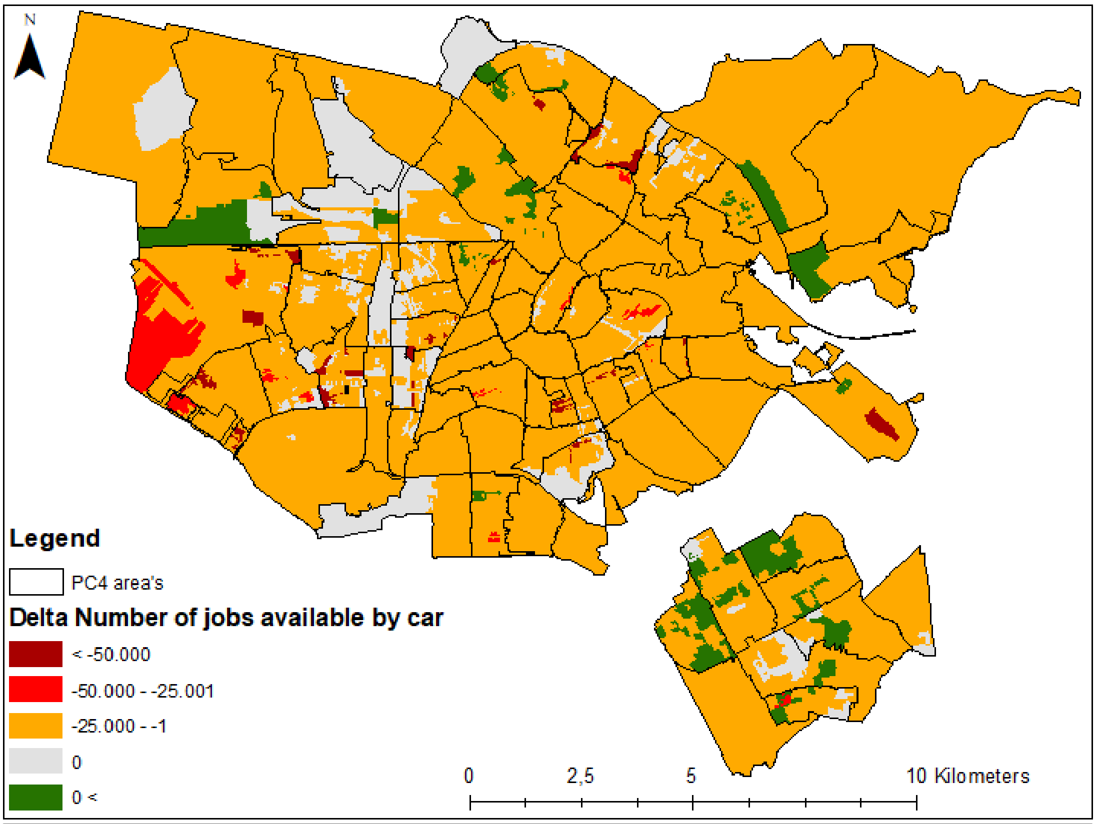
Figure 22a and b show the difference in accessibility for the different transport modes. For car users it seems that the reduction is very similar for the majority of Amsterdam, however, some regions experience no difference in job accessibility or even an improvement in job accessibility. For bicyclists, the majority of Amsterdam experiences an improvement in accessibility. Mainly in the North and district Amsterdam-Zuidoost, there are large areas where the accessibility stays the same as in the current situation. There are also in these areas some regions that even experience a reduction in accessibility.



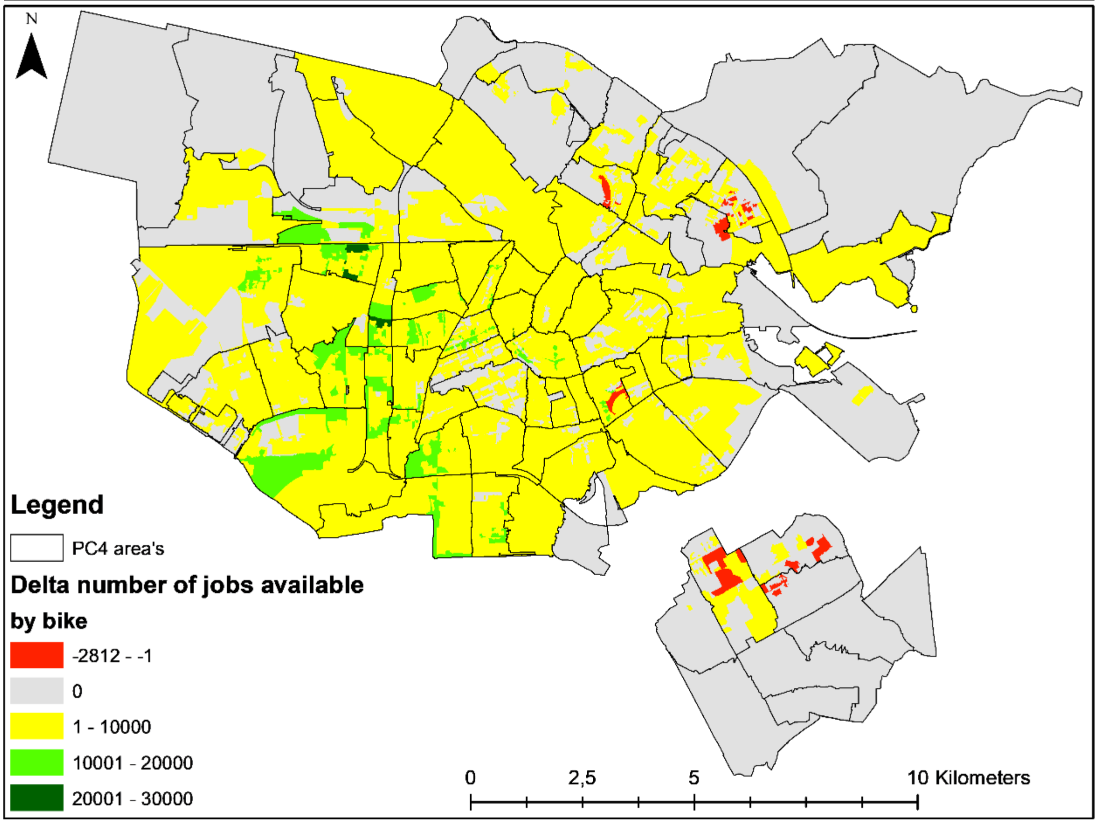
(a)

(b)

Figure 21: Accessibility scenario 4, (a) car, (b) bike



(a)



(b)

Figure 22: Accessibility delta between base scenario and scenario 4, (a) car, (b) bike

6.3. Analyzing the impacts of speed limit reduction policy on equity between different population groups

The findings in the previous sections revealed that the introduction of the same policy has had different impacts on accessibility levels in different PC5 areas. Therefore, in line with the last sub-research question: "***How can reducing the speed limits affect equity in accessibility between different population groups and regions?",*** this section presents the results of investigations on how speed limit reduction influences the equality of changes in job accessibility by different modes for different population groups.

6.3.1. Local Moran's I

To start local Moran's I analyses were performed using the current accessibility to show the clusters where currently the highest potential job accessibility is (Figure 23). This analysis reveals for car users a big cluster of areas with high potential job accessibility levels (in red) in the center and South of Amsterdam and clusters of low potential accessibility (in dark blue) in the Northeast and Northwest of Amsterdam. For bicyclists, the center of Amsterdam shows high potential job accessibility clusters. Whereas PC5 areas with low accessibility levels are clustered in the West and Northeast of Amsterdam as well as in the district Amsterdam-Zuidoost. The results are in line with the outcomes of the previous research questions.

Thereafter, local Moran's I tests were performed on changes in accessibility (Δ accessibility between base scenario and scenario 1) to examine the spatial distribution of changes in accessibility in the study region (Figure 24). A high cluster indicates for car users a positive effect on the accessibility changes while low clusters indicate a negative effect on the difference in accessibility. The results show high clusters for car users in the Northwest, Northeast, Southwest and Southeast. While low clusters are located in the North in the West and just Southwest of the center. For cyclists, a High-High cluster can be found West of the center, while in the North towards the Northeast, just South of the center and in the district Amsterdam-Zuidoost Low-Low clusters are located. Especially district Amsterdam-Zuidoost is interesting since for car users it seems beneficial for job accessibility to live there while for bicyclists it is disadvantaged to live there.

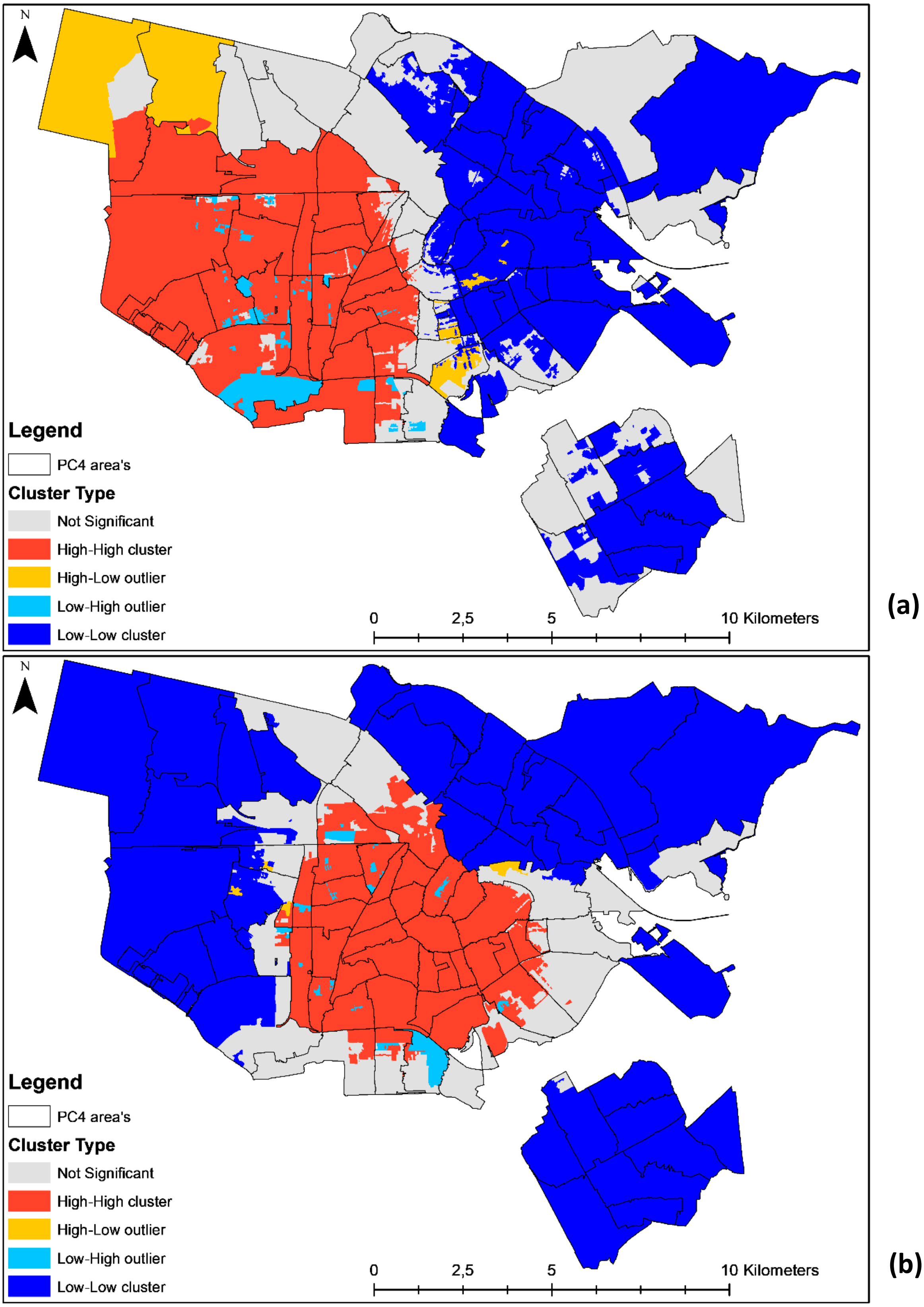
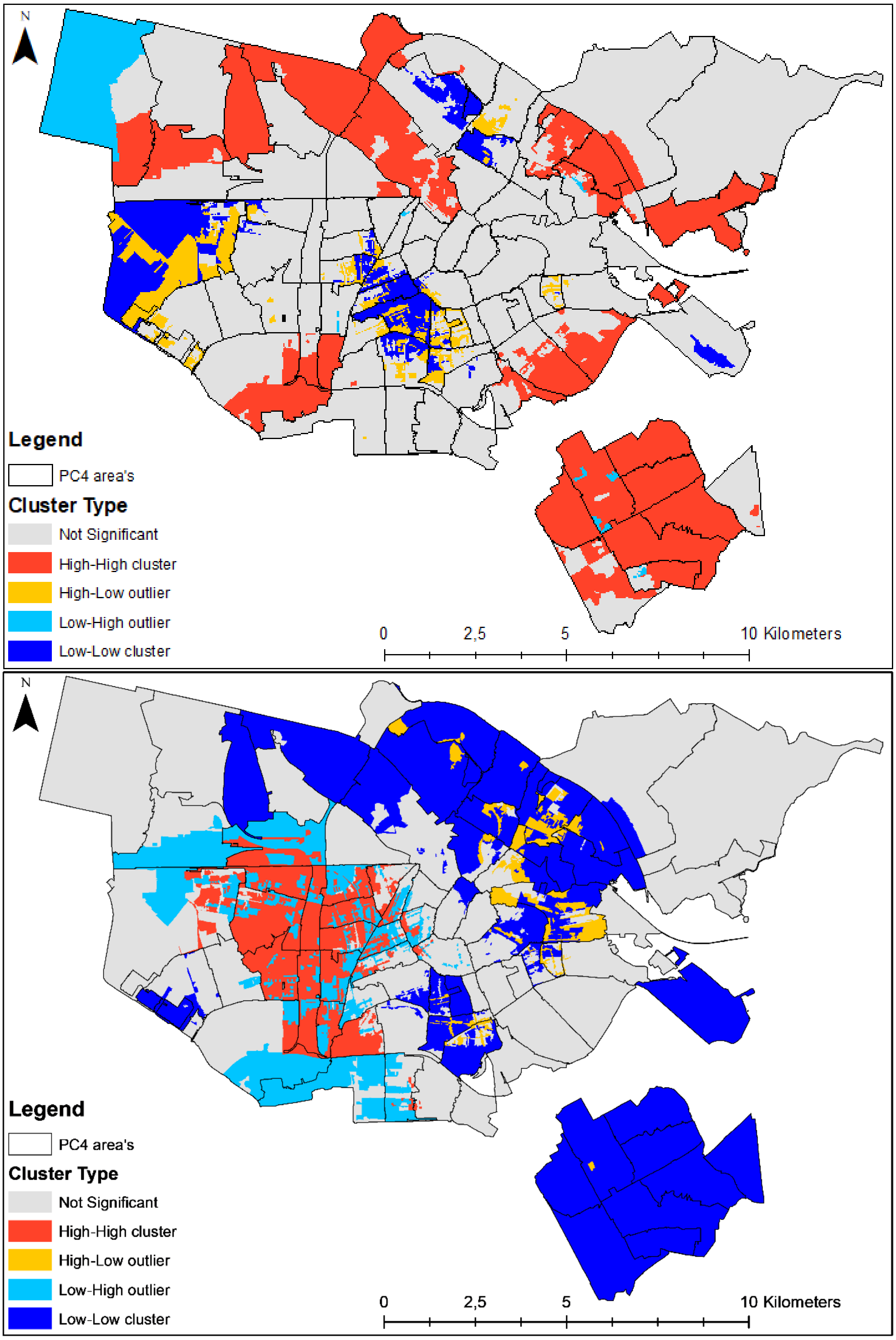


Figure 23: Local Moran's I base scenario, (a) car, (b) bike



(a)

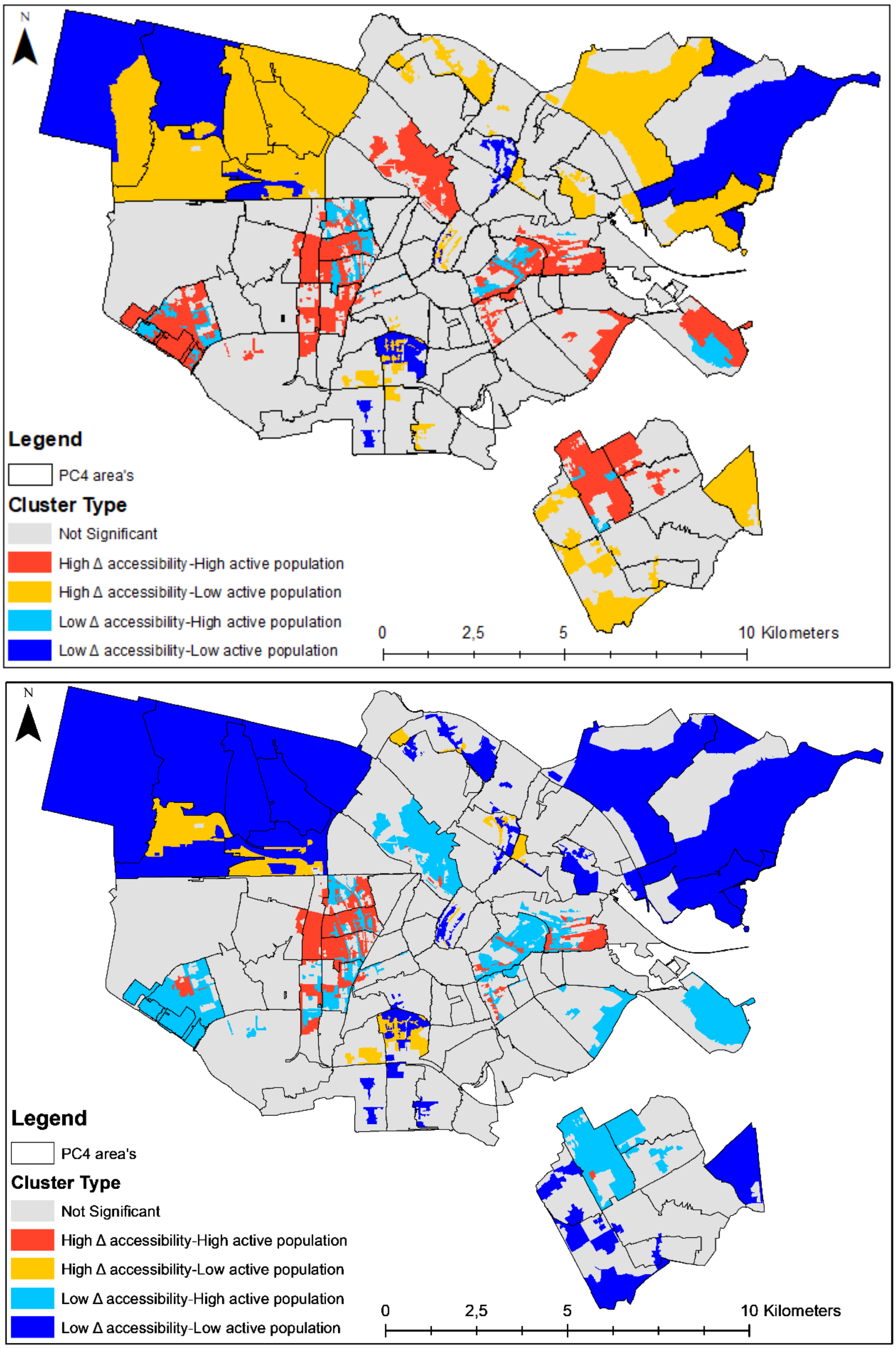
(b)

Figure 24: Local Moran's I difference between base scenario and scenario 1, (a) car, (b) bike

6.3.2. Bivariate Moran's I

Results of bivariate Moran's I between the selected socio-demographic and land use related variables, including active population (aged 15-65), median income, household size, percentage of male inhabitants, percentage of non-western immigrants and the Δ accessibility are illustrated in Figure 25-Figure 29. These variables are chosen based on the motivation given in section 5.2. The spatial distribution of the different variables can be found in Appendix A. For the bivariate Moran's I are four types of clusters. High-High clusters indicate clusters where the effect of change in accessibility is positive and the examined variable has a high value; this cluster group is shown by red color on the maps. High-Low clusters (orange) are high values for the changes in accessibility while the low value for the variable and a Low-High cluster (light blue) indicates a relationship the other way around. Low-Low clusters shown by dark blue color are clusters where the value of both the changes in accessibility and the examined variable are low. The Δ accessibility is the difference between the current accessibility and the predicted accessibility in scenario 4. High Δ accessibility indicates the positive effects of the change in accessibility while low Δ accessibility indicates the negative effects of the change in accessibility.

Figure 25a shows the results of bivariate Moran's I analysis to investigate the correlations between the Δ accessibility and the number of population aged 15-65 in the PC5 areas. It can be seen that in the Northwest and Northeast mixtures of Low-Low clusters (dark blue) with High-Low clusters (orange) are located, this indicates a low number of the active population who can experience both high and low effects of accessibility. In the other areas of Amsterdam, there are some High-High clusters with Low-High clusters which indicates that regions with a high number of active population can both experience positive and negative effects on job accessibility levels. These results indicate that for most of the PC5 areas the accessibility changes after speed limit reduction are independent of the number of active population. Figure 25b shows the results for the Δ accessibility by bicycle. The low active population regions in the Northwest and Northeast have a low improvement in accessibility. A High-High cluster (red) can be found West of the center, indicating that regions with a high number of active population benefit more from the speed limit reduction. The rest of Amsterdam is mainly Low-High clusters (light blue) which indicates that the large group of the active population experiences a decrease in accessibility. No clear relation can be found based on this map although it seems that living in a region with a high active population is more likely to be beneficial to the accessibility by bike.



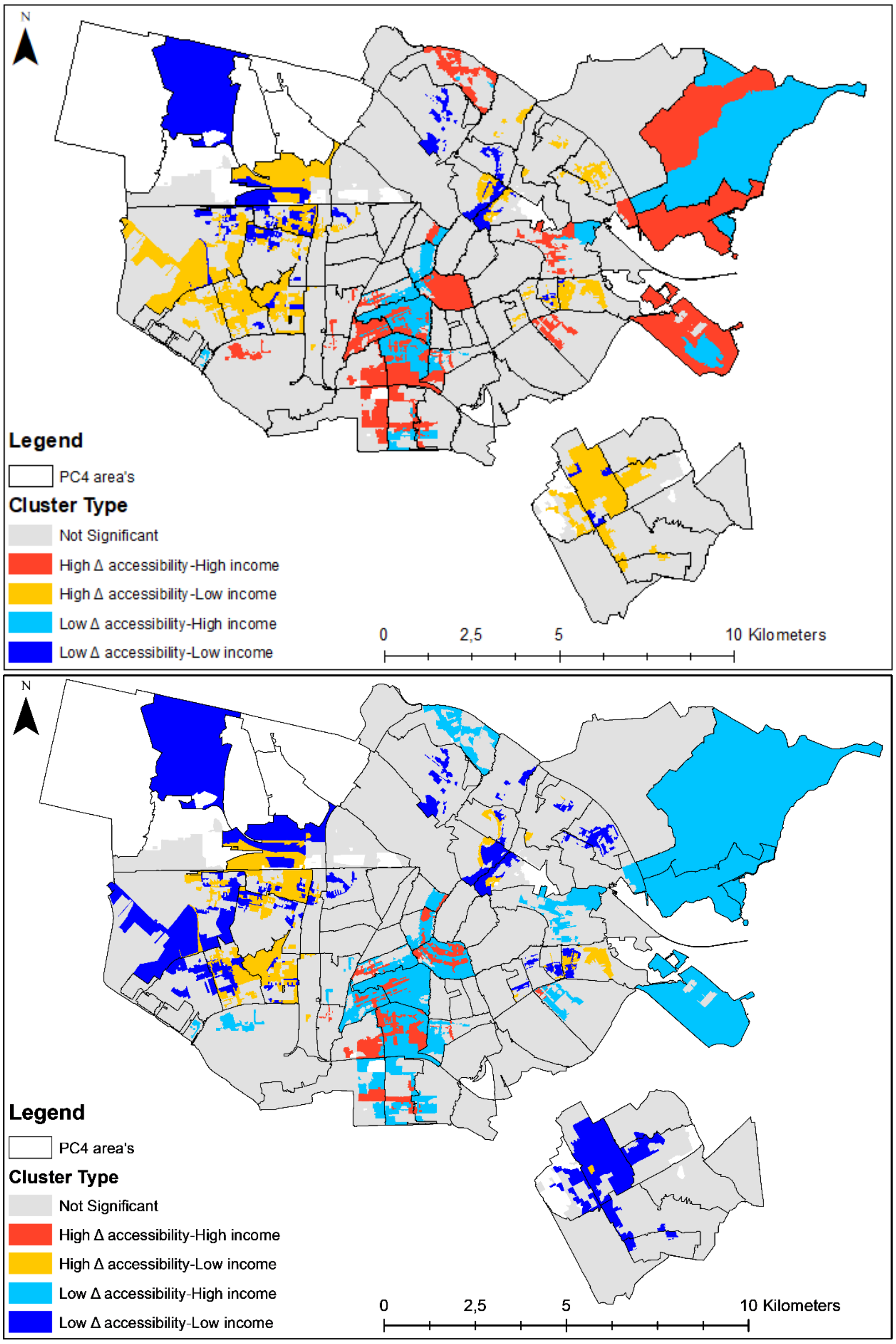
(a)

(b)

Figure 25: Bivariate Moran's I between Δ accessibility ((a) car, (b) bike) and total active population

The second variable that has been analyzed is the median income. As the results of cluster analysis on Δ accessibility and median income shown in Figure 26, the correlations between median income and Δ accessibility are in the East and South of the center a mixture between High-High (red) and Low-High (light blue), indicating that high income can both be beneficial or disadvantaged. In the West, it is a mixture between High-Low (orange) and Low-Low (dark blue). Thus, both high-income and low-income can experience a high or low decrease in accessibility, thus no relation can be seen based on the map. For bicyclists, the high-income regions are mainly clustered by Low-High (light blue) indicating that they experience a minimal increase or even a small decrease. The cluster in the West shows again a mixture between High-Low (orange) and Low-

Low (dark blue) thus low-income bicyclists do not solely benefit from speed limit reduction. Indicating that there is no relation between the accessibility change due to speed limit reduction and the median income apart from a slightly more negative effect for high-income regions. This is not surprising since the location with an increase in accessibility are both high- and low-income regions



(a)

(b)

Figure 26: Bivariate Moran's I between Δ accessibility ((a) car, (b) bike) and median income

Figure 22 depicts the clusters between Δ accessibility and average household size. There are in the Northeast and Southwest High-High (red) clusters mixed with some smaller Low-High (light blue) clusters. In the center of Amsterdam the majority is part of a High-Low cluster (orange) with a few low-low (dark blue) clusters. This indicates that in areas with larger households accessibility mainly experiences positive effects. But the same can be said for the smaller households in the center of Amsterdam. For bike users the Northeast is completely a Low-High cluster (light blue) while the Southwest is Low-High mixed with High-High (red). The Center of Amsterdam shows a more or less opposite effect in comparison with the car users. A larger Low-Low cluster mixed with smaller High-Low clusters. This means that in general both the larger households and the smaller households experience more negative effects when it comes to bicycle accessibility than positive effects. Thus, indicating that there is no relation between the Δ accessibility for bicycle users and the size of the average household.

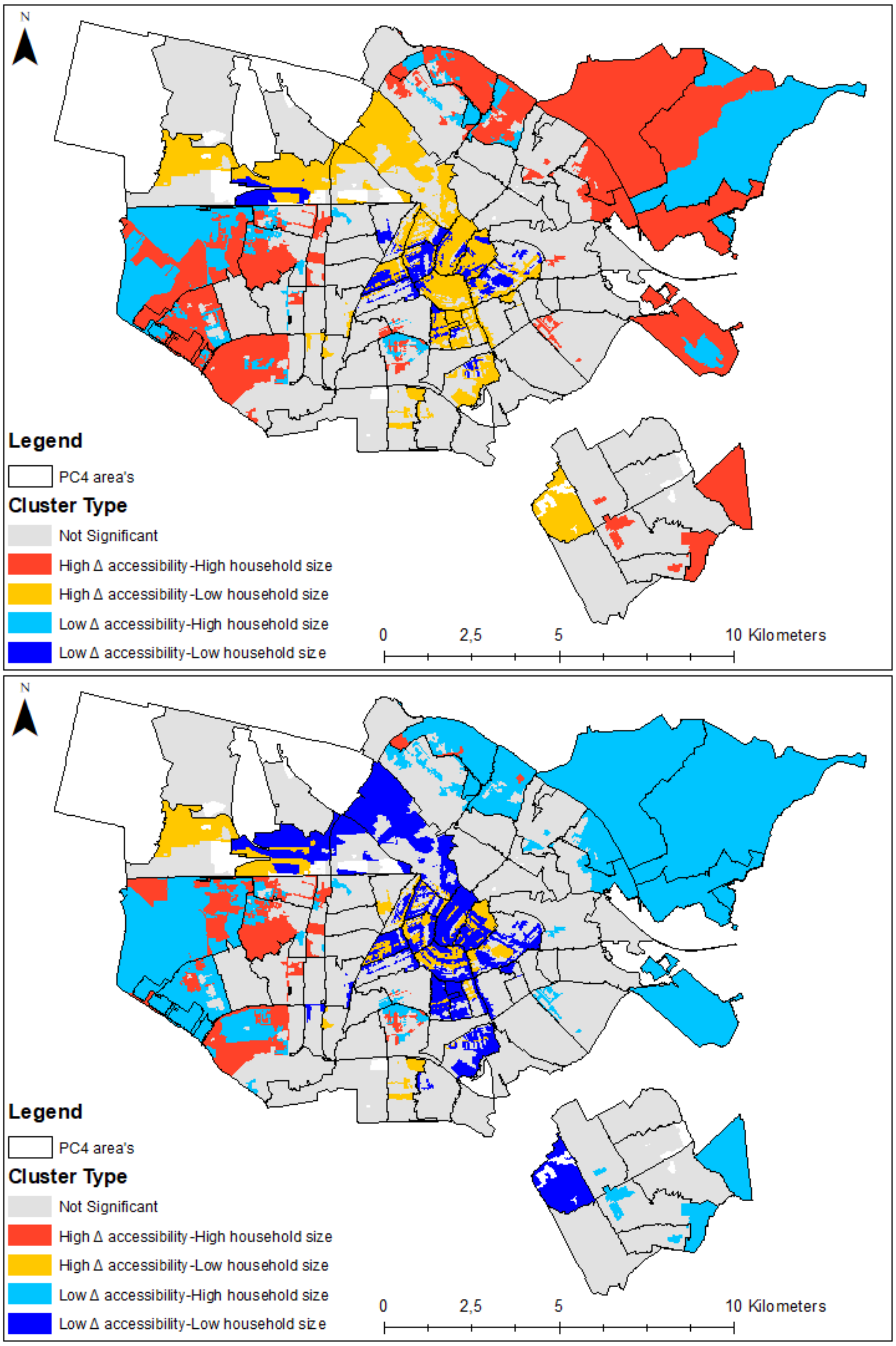


Figure 27: Bivariate Moran's I between Δ accessibility ((a) car, (b) bike) and average household size

The percentage of male inhabitants (Figure 23) shows mainly a High-High cluster (red) in the Northwest, in the Center of Amsterdam and half of the district Amsterdam-Zuidoost. The other cluster types are sparsely attendant across the city. This would mean that in Amsterdam that regions with a higher percentage of men are beneficial when it comes to the speed limit reduction for car accessibility. For bicyclists the opposite is perceived. The locations with high percentages of man are experience negative effects when it comes to bicycle accessibility given by the Low-High clusters (light blue). While the other clusters are sparsely attendant in Amsterdam. This would imply that regions with a high percentage of males experience more reduction in accessibility by bike.

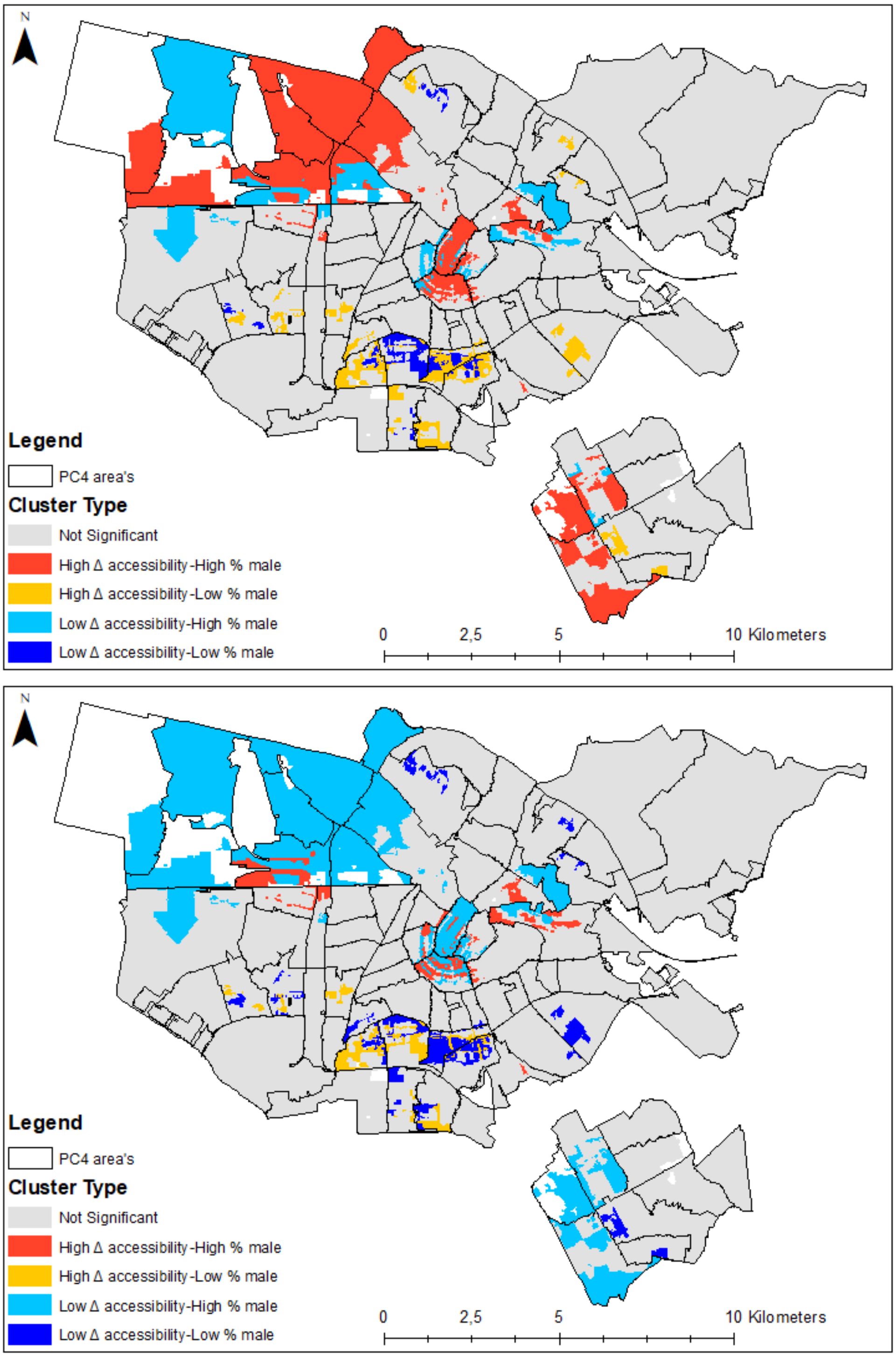


Figure 28: Bivariate Moran's I between Δ accessibility ((a) car, (b) bike) and percentage of male inhabitants

The percentage of non-western immigrants (Figure 24) shows in district Amsterdam-Zuidoost mainly a high-high cluster (red), in the west High-High is mixed with Low-High (light blue). The center of Amsterdam, the Northwest and the Northeast are High-Low (orange) with low-low (dark blue) clusters. Despite that all cluster types are attendant it seems that in general the cluster types indicating a positive effect on accessibility are larger for both high and low percentages of non-western immigrants. This implies that there is no difference in equity for car users based on immigration background. Bicyclists show an opposite pattern where the more attendant clusters are Low-High clusters and Low-Low clusters. This indicates that independent of the percentage of non-western immigrants the tendance is negative for bicycle accessibility, but again no changes in the equity for bicyclists.

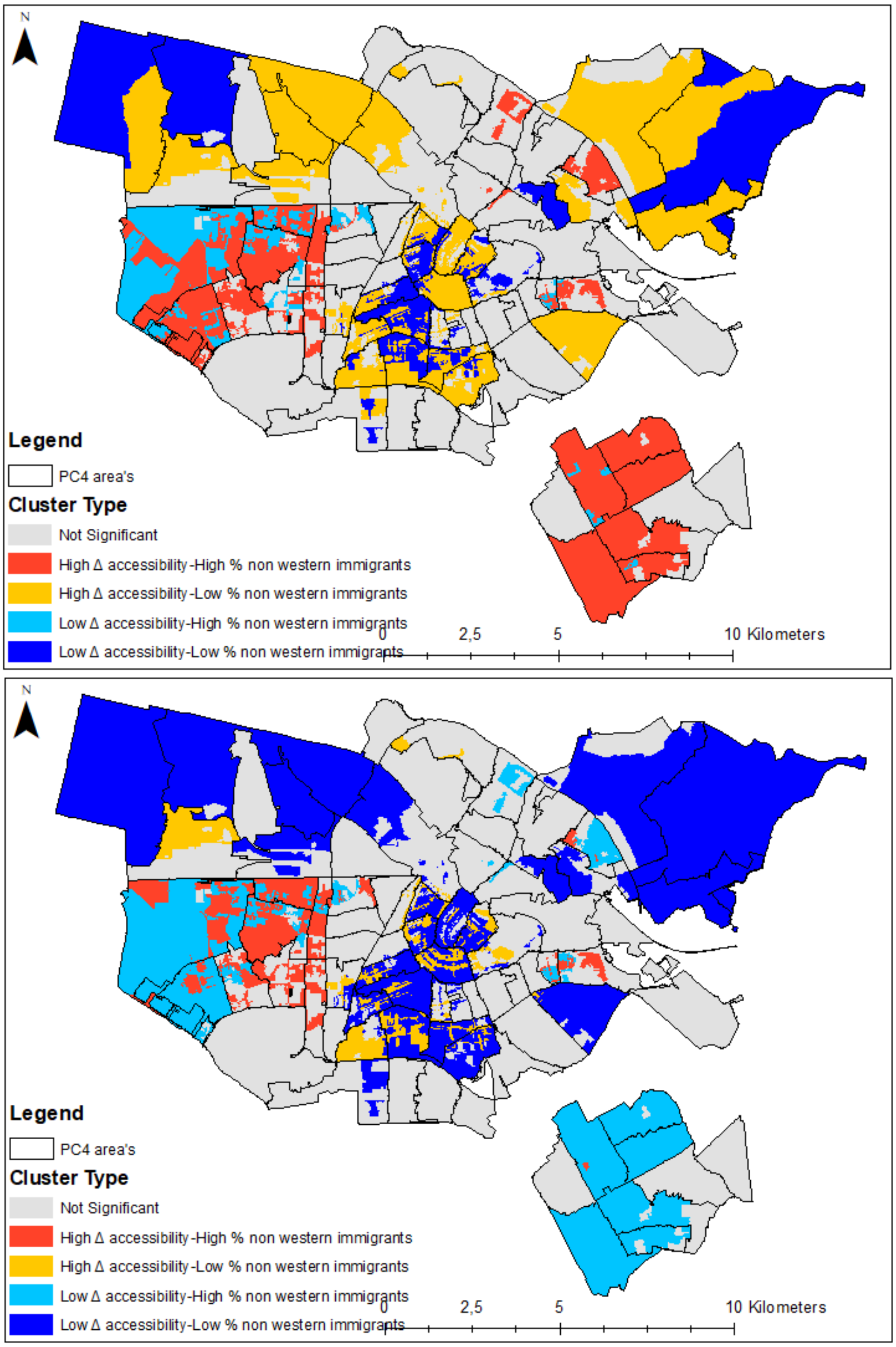


Figure 29: Bivariate Moran's I between Δ accessibility ((a) car, (b) bike) and percentage of non-western immigrants

7. Discussion

This chapter reflects on the research. First, an interpretation of the results is given, then the practical implications are explained and lastly, this chapter gives the limitation of the research and possibilities for future research.

7.1. Interpretation of results

The main findings of this research are summarized in this section. In the initial situation of the model, when accessibility was determined without traffic crashes, the center of Amsterdam has the highest accessibility rates, both for car users and cyclists. The same results were found in (Cheng & Bertolini, 2013). The spatial pattern does change for car users when the traffic crash costs are integrated into the accessibility model. When the crash risks are taken into account the West of Amsterdam has the highest job accessibility for car users. While the spatial pattern for cyclists remains more or less the same and the highest accessibility is still in the center of Amsterdam. The comparisons between the outcomes of the two models show that including the crash costs decreases accessibility for both car and bicycle users. These reductions are quite significant with 34.0% for accessibility by car and 12.3% for accessibility by bicycle.

Results of the scenario analysis revealed that speed limit reduction for the sake of traffic safety improvements can result in changes in the potential job accessibility by both car and bicycle. In all but one scenario the accessibility of car users on average decreases, but there are some regions where it remains the same as in the base scenario or even increases. When only the speed limit is taken into account (scenario 1) the reduction is the largest. The effects of change in car flow (scenario 2) are very minimalistic but show a negative effect while the effects of reduced crashes (scenario 3) also show minimalistic effects but they are positive for accessibility. Overall, an average reduction in the accessibility of 0.8% is found when the base scenario is compared with scenario 4, in which all effects are taken into account. However, the t-test showed that the results are not significant which means that the changes are an indication and not certainty of how the accessibility will change. The results can be explained since speed reduction has mainly two effects on accessibility. Firstly, the benefits of speed limit reduction are that there are fewer crashes and thus less potential risk of a crash (Vis, Dijkstra, & Slop, 1992) (Janssen & Verhoef, 1989) (Engel & Thomsen, 1992), and therefore the crash costs decrease. Secondly, this policy makes car speeds lower (Vadeby & Forsman, 2018), thus travel times are longer for car users, which increases travel costs (Niedzielski & Boschmann, 2014). Based on this research it seems that the negative effect, reducing the speed, is much larger than the positive effect, increased safety, for accessibility.

For bicyclists, the speed limit reduction has, in general, a positive effect but for some regions it remains the same as in the base scenario or even decreases. The effects of only the speed limit reduction (scenario 1) are zero. Since the speed limit does not affect the traffic safety model prediction for crashes and the speed of bicyclists is not influenced by the speed limit they experience no effects based on only a reduction in the speed limit. When the new car flow is solely used (scenario 2) the changes are very minimal and show a slight increase in the average accessibility while the effects of reduced crashes (scenario 3) also have the largest effects on the accessibility for cyclists. Overall, on average an accessibility improvement can be expected of about 0.9%). An overall improvement is not surprising since based on the scenario analysis. The accessibility is almost only influenced by the changes in crashes while the changes in car traffic volume have very minimal effect. It can be explained since the speed limit reduction does not have any effects on the bicyclists' speeds and travel times in this research. Based on the traffic safety model only car volumes could negatively change the crash risks. While the power model only has positive effects on the crash risks when reducing the speed limit. However, as shown in Figure 13 speed limit reduction will result in increased traffic volumes on some roads leading to higher exposure to crash risk for cyclists. This explains why some regions experience a decrease in accessibility by bike.

When performing the local Moran's I it was clear that there is a cluster forming of the current accessibility, where people living in the Southwest have high job accessibility by car and people living in the center of Amsterdam have high potential job accessibility by bike. Cluster forming was also found when performing Moran's I analysis for the differences in accessibility between the base scenario and scenario 4. This shows that the change in accessibility is not equally distributed. For car users there are four clear High-High clusters visible where accessibility decreases are the smallest or even increases in accessibility are perceived, these are located Northeast, Northwest, Southeast (including district Amsterdam-Zuidoost) and Southwest. The Low-Low clusters, indicating the largest decrease in accessibility are located North, West and South of the center of Amsterdam. For bicyclists, one large High-High cluster, with large improvements in accessibility, can be found West of the center. The Low-Low clusters, with minimal improvements or decreases in accessibility, can be found North Northwest and in the district Amsterdam-Zuidoost.

The main finding for the bivariate Moran's I is that for both car users and bicyclists on active population, median income, household size and percentage of non-western immigrants there is not a clear indication that one population group is more beneficial than others. Since independent of the change in accessibility the value of the variable was high or low. Or high and low changes in accessibility could be found in both low and high values of the variable. For the percentage of male inhabitants, it seems that a higher percentage of males live in regions with positive effects on car accessibility. While also in the regions with high percentages of males there are negative effects on cycling accessibility. This was expected since females are more bicycle users (Miralles-Guasch, Melo, & Marquet, 2016). Therefore, safety improvements will have less effect on regions with lots of males since there are likely to be fewer bicycle trips and thus less possibility of improvement on safety and accessibility.

7.2. Practical implications

The findings of this research revealed that reducing the speed limit reduces in general job accessibility by car. The job accessibility for bicyclists in general experiences a positive effect when the speed limit is reduced. Some regions experience reductions in job accessibility by bike, which can be due to the increase in traffic volume and crash risks on the roads that do not have a speed limit reduction. Thus, a solution to overcome this loss could be a mode shift from car to bicycle, which is expected when travel times by cars increase. Nonetheless, the results also showed that the average accessibility by car in PC5 areas will be higher than accessibility by bicycle, even after speed limit reduction (explain why). Thus, despite longer travel time by car as a result of reducing the speed limits, the accessibility of an individual remains the highest when traveling to and from their job by car.

From an equity point of view, the results show clusters of high accessibility in the West of Amsterdam for car users, while for cyclists the clusters of high accessibility are in the center of Amsterdam. The main reason for that is the high number of jobs located in the city center area. The fact is that transport policies on their own do not change the location of jobs and it will therefore be near impossible to have a completely equal distribution of job accessibility all over the city. However, in combination with land-use policies, it is possible (Straatemeier & Bertolini, 2008). Also, transport policy can be used to affect accessibility levels in the city without changing the location of jobs and therefore can be used to create a more equal distribution of accessibility. As is shown by the scenario analysis where the clusters of Δ accessibility were found outside of the center.

Specific results from the bivariate Moran's I analysis revealed that car users in a high percentage of male regions are positively influenced by their accessibility while the same regions are negatively influenced by bicycle accessibility. The other variables tested in the bivariate Moran's I analysis showed no real negative or positive equitable effects from the speed limit reduction.

7.3. Limitations and further research

The main limitation of this research is the lack of real speed data. No data was available for the situation with the speed limit reduction. Therefore, the decision was taken to use the speed limit as the traffic speed. This may not always be realistic especially around intersections where congestion could occur which increases travel times. Secondly it implies that the speed limit is obeyed and that the traffic speed will reduce on the roads that have a reduction in the speed limit, according to Vis, Dijkstra & Slop (1992) this will not always be the case, especially when no other incentive measures are taken to reduce the speed.

Another limitation that could be changed for future research is the estimated crash risk costs. The current simplistic traffic safety model uses only a few variables to predict the number of crashes. In future research the traffic safety model could be improved by including more variables. For this research it was deemed too time-consuming to create a traffic safety model with much more variables since the focus was not on the traffic safety model, but on the effects of speed limit reduction on accessibility. Using an advanced traffic safety model, the results would most likely differ in a numerical sense, but it is believed that the overall outcome would follow a similar pattern on the impacts on job accessibility as seen in this research.

The used crash data (BRON data) is the traffic safety data registered by the police for the years 2015-2019. It is known that especially for light bicycle crashes the data is under-registered (SWOV, 2010). As traffic crashes happen randomly (i.e., they are probabilistic phenomena) it is possible that the estimated crash risks on roads are over or underestimated when incomplete data is used. A solution could be to use a different data source, such as ambulance-registered data, however, this is often not freely available.

Moreover, the geographical scope of this research is limited to the Amsterdam municipality. It means that only jobs located within the municipality of Amsterdam and the 16 km boundary are taken into account. Even though, people living outside of this boundary also have access to jobs in Amsterdam or the residents in Amsterdam might work outside of this region which could increase their accessibility and the overall equity in job accessibility. This shortfall can be alleviated by the fact that Amsterdam and the boundary are a large area, and it is likely that a majority of the inhabitants of Amsterdam also work in the chosen region.

Furthermore, this research applied the contour measure to estimate job accessibility. Whilst this method is undemanding on data and easy to interpret, it does not give the combined effect of the land use and transport component and does not take competition or individual perceptions into account (Geurs & van Wee, 2004). Therefore, future research may try to conduct a similar analysis by using different contours to overcome the arbitrary choice of a single contour, or use a more advanced accessibility model, such as the well-known gravity model in which the access to opportunities in a zone is determined for all other zones, where more distant zones have diminishing influences. The gravity-based model overcomes the shortcomings that were earlier mentioned for the contour measure (Geurs & van Wee, 2004).

For future research based on the equity effects of speed limit reduction the chosen sociodemographic could be adjusted. The current chosen variables are broad and future research could split the variables into multiple groups, such as for the different age groups, to show more effects.

The last limitation is that the findings of this research cannot be generalized to other (Dutch) cities. Because the difference in accessibility depends on the layout of the city (Tillema, 2019) and which roads are reduced in speed limit and also the location of jobs. This will be different from city to city. However, the methodology applied in this research can be applied in other case studies to investigate the accessibility and the effects of speed limit reduction or different transport policies for different cities.

8. Conclusion

This research aimed to investigate the effects of the implementation of traffic safety policies, such as speed limit reduction, on job accessibility and equity in job accessibility by car and bicycle. A case study on assessing speed limit reduction effects from 50 to 30 km/h in the urban areas in the city of Amsterdam was conducted. The main outcome of the research is that despite the positive effects of speed limit reduction on the safety of road users, the implementation of this policy has a negative effect on the accessibility of car users. That is due to the major effect of this policy on the travel time by car. On the other hand, the speed limit reduction policy has a positive role in improving the job accessibility of bicyclists, as a result of a significant impact of this policy on cyclists' safety improvements. From an equity perspective, the implementation of the speed limit reduction policy benefits regions with a high percentage of males when it comes to car accessibility but has negative effects on bicycle accessibility in the regions with a high percentage of males.

To conclude this research first the sub-research questions will be answered and lastly, the main research question will be answered.

8.1. How can traffic safety indicators be integrated into accessibility models?

This research used the monetary value of crash risks to be able to integrate traffic safety outcomes into an accessibility model. Two job accessibility analyses were performed by excluding the traffic crash costs and by including these costs in the accessibility model. The results of these analyses reveal that exclusion of the unavoidable traffic safety costs from the accessibility analysis results in the overestimation of accessibility by both modes of transport.

8.2. How can changes in speed limits (and consequently traffic safety) influence job accessibility in urban areas in Amsterdam?

With the help of the designed scenario analysis, the effects of reducing speed limits in urban areas on job accessibility were analyzed. A reduction in speed limit increases the safety of all road users, which has a positive effect on accessibility. However, the results showed that because lowering the speed limit increases travel time by car, job accessibility decreases for the majority of car users. The reduction of speed limits is beneficial for most cyclists in terms of an increase in job accessibility levels by taking the traffic crash risk costs into account. That is because bicyclists do not have longer travel times since their travel time is not affected by speed limit reduction. Whilst these groups of road users benefit the most from the decline in crash risks that leads to an increase in their job accessibility.

8.3. How can reducing the speed limits affect equity in accessibility between different population groups and regions?

Based on Moran's I analysis it can be said that for all transport modes there are clusters of high and low accessibility. This indicates that accessibility is not equally distributed over the study area. Some regions benefit more than others from the speed limit reduction which was shown by the local Moran's I for the Δ accessibility which implies that the transport policy does not have an equal effect on all residents. When comparing the change of accessibility with the number of active population, median income, average household size and the percentage of non-western immigrants, using the bivariate Moran's I there was no clear indication that a certain population group benefits more than another, but using the same analysis between change in accessibility by car and the percentage of male inhabitants, it seemed that car users living in the regions with a higher percentage of males experience a positive effect in accessibility while the same regions experience negative effects for accessibility by bike.

8.4. What are the effects of speed limit reduction on job accessibility and equity in the urban areas in Amsterdam?

This research showed that reducing the speed limit in Amsterdam has negative effects on the accessibility for car users. Based on the conceptual model (Figure 2) several relationships are causing the effects. The speed limit reduction increases traffic safety, since the speed reduction, as is shown by the traffic safety model and in Table 12, reduces the number of crashes. However, this increases the travel impedances, since travel times increase. Despite the increased traffic safety which decreases travel costs the overall travel impedances for car users are higher after the speed limit reduction. This causes job accessibility to decrease. However, the decrease is only minimal and statistically insignificant and therefore only an indication. Based on scenario 3 accessibility improves when safety on the road improves, however, again the changes in accessibility are insignificant which only implies that a reduction in traffic crashes causes an improvement in job accessibility, but it cannot be said with certainty. The final arrow of the conceptual model that was researched is the relation between job accessibility and spatial equity. This research showed that there are visible locations within the city of Amsterdam that have clusters of high accessibility and clusters of low accessibility which implies that job accessibility is not equally distributed over the city. The road safety policy to reduce the speed limit does not seem to cause inequity in the city since the difference in accessibility reduction did not show particularly that certain locations benefit significantly more than other locations. Also, for specific population groups or areas within the city, the measure does not seem to have an unequal effect. Only people in neighborhoods with a higher percentage of males seem to be more advantaged when it comes to car accessibility but are disadvantaged when it comes to cycling accessibility.

To answer the main research question of this research. The effects of speed limit reduction on job accessibility in the urban areas of Amsterdam can be summarized as follows. Speed limit reduction will cause the accessibility of car users to decrease. Despite the reduction in crash risks, which leads to a decrease in travel costs, causes speed reduction increases in the overall travel costs. Beneficiaries of speed limit reductions are bicyclists. Their risk of being involved in a traffic crash declines on most roads. This improves their safety and their accessibility.

When looking into specific population groups who are affected by the speed limit reduction there could not be found any specific relationship that can be generalized over the study area. However, it seems that in the high percentage of male areas a smaller decline in accessibility by car can be expected compared with other areas. For bicyclists, these areas can experience a smaller improvement in accessibility.

In short, this research shows that reducing speed limits from 50km/h to 30km/h can have both positive and negative aspects for road users. Therefore, to decide whether the policy should be implemented or not cost-benefit analysis could be used to determine which factors, especially for car users, are more important, a decrease in accessibility or an increase in traffic safety. It is important to note that the changes in accessibility are insignificant and therefore merely indicative, which is positive since the reduction in speed limit will improve traffic safety without significant effects on accessibility.

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