The impact of large-scale parking capacity reductions on bicycle and public transportation demand

A Case Study for Rotterdam

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The Impact of Large-scale Parking Capacity Reductions on Bicycle and Public Transportation Demand

A case study for Rotterdam

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Preface

This thesis is the final milestone of my Master's degree in civil engineering at the TU Delft, within the track of Traffic & Transport Engineering. It was written during the period from 01-09-2024 to 31-04-2025, and represents both an academic culmination and a personal journey of growth.

The research was carried out in collaboration with Goudappel, as part of a broader initiative XCARCITY. The central focus of this thesis is on what happens to the public transportation and biking in a city when the parking capacity is reduced, a subject that aligns closely with both my academic interests and my passion for solving real-world challenges.

I would like to express my sincere gratitude to my academic supervisors; Maaike Snelder, Niels van Oort, and Jan-Anne Annema, As well as my company supervisor Arthur Scheltes for their valuable guidance, critical feedback, and unwavering support. Their expertise and mentorship were instrumental in shaping this thesis, and I am grateful for their patience and commitment.

With a special thanks to Lara Witte, who supported me throughout the practical aspects of the project. Her insights, feedback, and willingness to share her expertise have been vital to the success of this research.

In addition, I would like to acknowledge my fellow students, and colleagues for the engaging discussions, support, and moments of shared frustration and joy that made the process more enjoyable and motivating.

On a more personal note, I am deeply thankful to my friends the PEPA's. Your continued encouragement, understanding, and belief in me—even during the most stressful stages—provided the emotional foundation I needed to persevere.

Looking back, this thesis has not only been an academic endeavour, but also a meaningful period of self-discovery and learning. I hope the findings and reflections presented here offer a valuable contribution to the ongoing discussions in car-lite cities and may serve as inspiration or guidance for future research in this domain.

Adri Hooijer
Delft, April 2025

Summary

Urban planning in the Global North has historically prioritised the automobile, facilitating rapid economic growth but contributing to sprawling, car-dependent urban forms characterised by congestion, pollution, and a diminished quality of life. In recent decades, particularly in north-western Europe, increased awareness of the need for healthy and sustainable living has led to more stringent environmental standards. This shift has prompted a growing emphasis on urban densification and sustainable mobility, often pursued through car-lite strategies. Within this context, reducing parking capacity is increasingly viewed as a key strategy for discouraging car ownership while simultaneously freeing up urban space for other uses, such as, greenery, housing developments, and wider sidewalks / bicycle paths. However, due to the controversial nature of such measures, research on their city-wide impacts remains limited. Most existing studies focus on localised effects and often neglect the implications for alternative modes of transport. This thesis addresses that gap by investigating how large-scale parking space removal influences demand for cycling and public transport.

By examining whether these alternative modes of transport are capable of accommodating the potential increase in demand resulting from a reduction in car use, this study aims to provide insights into the spatial (re)distribution of usage across the network, and if a shift happens the extent to which existing cycling and public transport networks can absorb this additional demand, and the potential capacity constraints within these systems.

The city of Rotterdam was chosen as case study for this research. This city currently has a relatively high car-usage for Dutch standards, but still meets the preconditions (a dense mixed-use urban environment with a high quality active modes network) necessary to support car-lite initiatives, such as the removal of parking spaces. The study area within the city is defined as its most dense part, where the pressure on urban space is the greatest.

The study defines three intervention scenarios, ranging from the ‘realistic’ scenario where Rotterdam stops constructing new parking spaces right now, to the ‘ambitious’ scenario where Rotterdam becomes car-lite by common definition (less than 0.5 parking space per dwelling), with an intermediate scenario in between.

To test these different intervention scenarios a simulation model is used. A simulation model, provides a cost-effective and comprehensive approach to analyse system-wide network interactions. For this study, a static, macroscopic, multi-modal demand model is proved to be most suited because it can most effectively simulate route choices over a large urban network. After comparing candidate models, the V-MRDH model (A regional macroscopic, multimodal demand model) was chosen due to its high spatial detail, ability to implement parking restrictions, availability for this research, and its effective representation of the network of Rotterdam.

During the course of the study, it became evident that the simulation model alone could not fully answer the research question, as the redistribution of trips was limited to a modal shift without changes in destination. To address this, a supplementary estimation method was developed, combining the static spatial distribution from the model with the current understanding from literature and parking space data, together enabling a more realistic range of approximations.

The results show that removing parking spaces in Rotterdam leads to a measurable shift in travel behaviour, as was expected based on existing literature. In a realistic scenario with a 20% reduction (a reduction of 17,819 parking spaces) in parking spaces in the study area compared to the business-as-usual (BAU) scenario, it is estimated that in the evening rush hour a maximum of 2,566 motorists would

switch modes. Based on the mode split outcomes from the simulation model, this shift corresponds to an upper-bound increase of 2.8% in public transportation trips and 2.2% in bicycle trips, with lower-bound estimates being roughly one-fifth of those figures. Intermediate (40% reduction) and ambitious (60% reduction) scenarios scale these effects linearly, and are visualised in Figure I. Of the trips that switched modes 77% were short or medium distance trips and had destinations in the municipality of Rotterdam or the remainder of the MRDH. With the vast majority of the motorists that switched modes that had a destination in the municipality of Rotterdam switching to the bicycle.

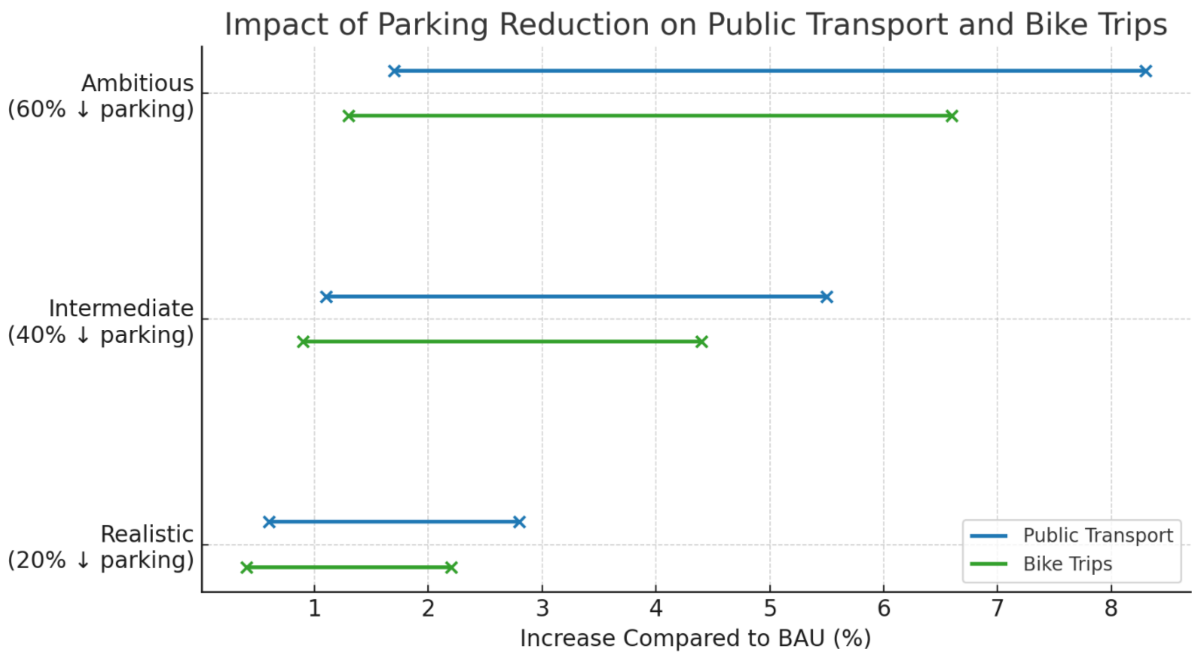

Figure I: Increase in bike and public transit trips leaving the study area in the evening rush hour.

While the observed increases in alternative mode usage may appear modest, they should be interpreted in the context of the chosen business-as-usual (BAU) scenario. In this chosen baseline, individuals are already more inclined to cycle or use public transportation due to existing policies that discourage car use and promote sustainable modes—reflecting broader trends in current mobility planning, and is in line with the plans of Rotterdam to focus on active mobility and public transportation. Moreover it is important to note that since these changes are observed in the trips departing from the study area in the evening rush hour, they do not include trips passing trough the study area.

In the intervention scenarios, the maximum average passenger load for metro and tram services, including the additional demand from former car users, remained below the lower bound of the recommended occupancy threshold of 85–95% of total line capacity. For the bus network, the maximum average load reached 89%, also within acceptable limits.

However, during the peak-of-peak period—the busiest 15 minutes of the rush hour—these values rose significantly. Metro load increased to 86.5%, tram load peaked at 98%, and on the busiest bus line, demand exceeded 100% of available capacity. These findings suggest that, while the average passenger load is unlikely to overburden the public transport network, certain lines may experience overcrowding during the most intense period of demand.

This study demonstrated that reducing parking spaces could lead to overcrowded public transportation in Rotterdam during the peak-of-peak period, but demand remained within manageable levels during the rest of the peak period. Since this study finds only an immediate strain on the public transport

networks following parking reductions in the peak-of-peak period, this thesis recommends to estimate these effects specifically before implementing large-scale parking capacity reductions. It furthermore recommends to focus attention on public transport planning at the strategic level, to account for a loss in the accessibility of the city by car. And lastly, proposes a specific direction for future model improvement, addressing the behavioural assumptions of the current modelling approach. This includes integrating parking constraints directly into the model's feedback loop by increasing resistance to zones where limits are exceeded, rather than applying only absolute constraints after the final iteration. Such an enhancement would improve the accuracy and policy relevance of similar studies in urban contexts.

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1 Introduction

For the past eighty years, urban planning policies, especially in the global north, have focused on facilitating the movement of cars, often at the expense of pedestrian-friendly environments and efficient public transportation systems (Farber & Páez, 2011; Turnheim, 2023). This car-centric approach aligns with mid-20th-century ideals of modernity, growth, and individual mobility. This fixation has led to the development of cities characterized by sprawling layouts, wide roads, and extensive parking lots, rather than compact, dense, and walkable neighbourhoods. The "Land-use transport feedback cycle" (Wegener & Fürst, 2004) is central to understanding this process, where land-use patterns and transportation systems reinforce each other, often resulting in cities designed for cars rather than people. Consequently, these developments have contributed to increased traffic congestion due to induced demand (Hymel, 2019), air pollution, and social inequities, as low-income populations often face limited access to efficient transit options (Iseki, 2016; Mohri et al., 2021).

1.1 Problem statement

In response to population growth and more stringent sustainability goals, cities in northwestern Europe have shifted their urban development strategies since the early 2000s. Instead of expanding car-centric suburbs, many cities now prioritize urban densification and sustainable mobility (Dembski et al., 2019). This shift has led to a growing focus on car-lite policies, which aim to reduce car dependency and promote walking, cycling, and public transportation (De Las Heras-Rosas & Herrera, 2019). The Netherlands has been actively participating in this transition, with several major cities actively implementing car-lite measures to improve liveability, enhance road safety, and generate positive public health outcomes (Peters, 2020).

Transitioning to a car-lite model is necessary to support this trend. High levels of automobile ownership extend beyond worsening congestion, poor air quality, and rising CO_2 emissions (HEI, 2010; Harrison et al., 2021) but also result in inefficient land use. Transportation modes differ significantly in terms of land consumption and corridor capacity (see Figure 1) (United Nations, 2013). In cities, where space is limited, cars are particularly inefficient, they require more space to move the same number of people as other modes and occupy substantial space when parked. For instance, cars in Dutch households are parked 96% of the time (Zijlstra et al., 2022) and parking spaces occupy roughly 11% of the public area in cities like Amsterdam (CROW, 2024).

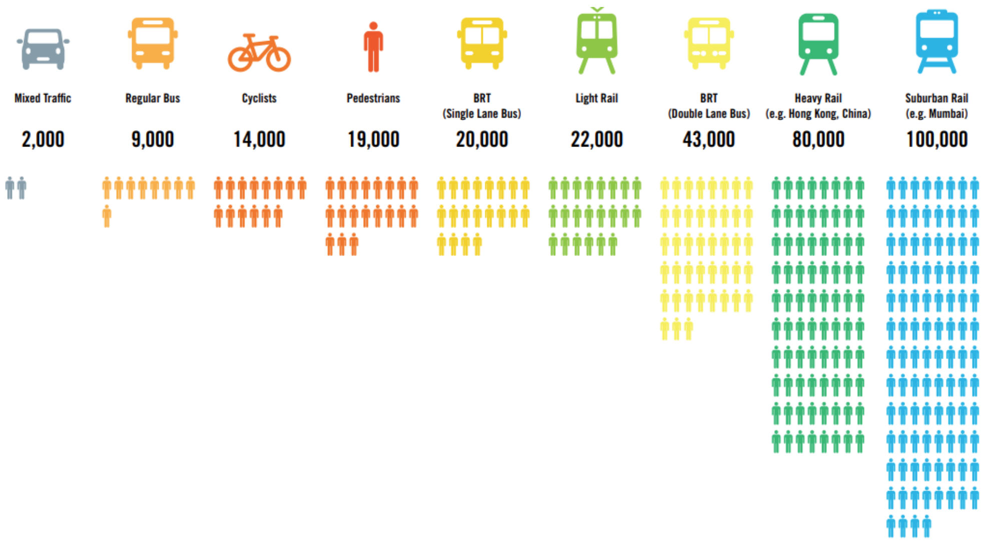


Figure 1: Transport mode space requirements. people per hour on a 3.5m lane in the city (United Nations, 2013)

This transition is particularly relevant given the projected population growth in combination with more stringent environmental norms (WHO, 2021). Between 2022 and 2040, the Dutch population is expected to increase by more than 1.4 million people, with growth primarily concentrated in the four largest cities: Amsterdam, Rotterdam, The Hague, and Utrecht (De Jong et al., 2022). This demographic trend of urban densification intensifies the need for sustainable urban mobility solutions that balance accessibility, environmental sustainability, and quality of life.

Car-lite measures can take many forms, but can, according to Jorritsma et al. (2023), generally be categorised in three main categories, namely build environment, roads & streets and parking policy. These categories can then be further divided into specific car-lite measures. Figure 2 shows the conceptual framework for achieving a car-lite city. An enlarged version of figure 1 can be found in Appendix F. Given that the urban fabric supports the use of active modes, with the provision of safe bicycle infrastructure and sidewalks in a dense, mixed use environment, as is the case in many Dutch cities, parking policy was identified as the most effective way to reduce cars in a city. (Jorritsma et al., 2023)

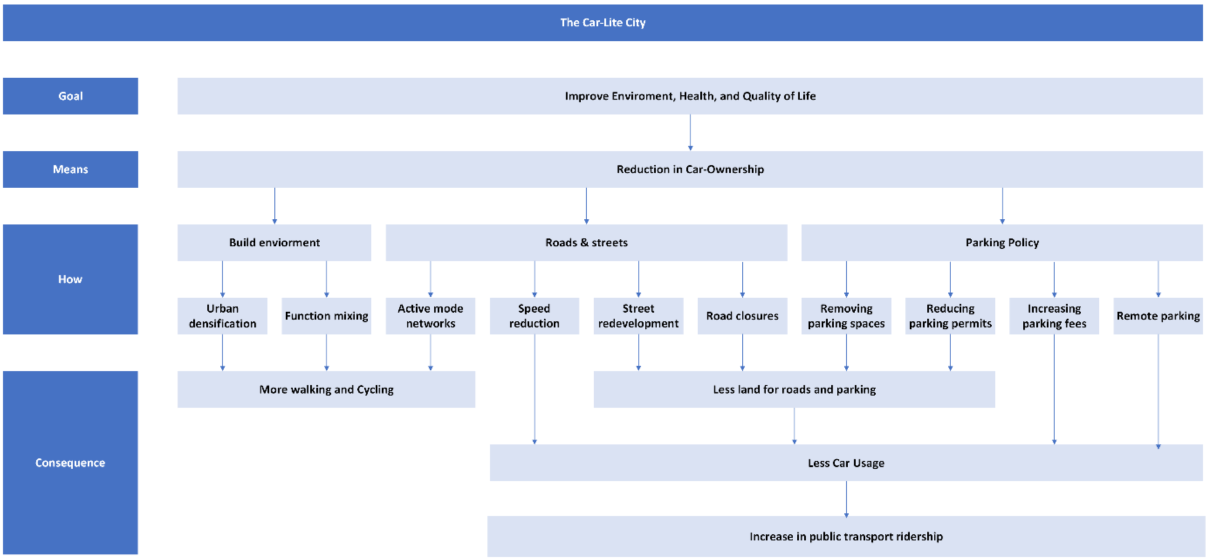


Figure 2: Conceptual framework car-lite city, form goal to consequence, as identified during the literature review.

In 2023 Rye et al. reviewed 139 papers regarding parking policy in northwestern Europe, forty-seven (47) of those papers linked parking policies with a change in Modal split, but the majority was either about time restrictions, permits, fees and levies (24) or remote parking (17). With reduction of parking spaces at a local of citywide level being a still relatively new and controversial subject only three (3) papers where identified that linked a reduction in parking spaces with a change in modal split. With all of these papers primarily focusing on the change in car trips and omitting the consequences on the alternative modes. (Rijkswaterstaat., 2018; Lambe, B et al. 2010; Rye at al. 2022). Of these sources only Rijkswaterstaat gave an indication on the effect on alternative modes when the parking supply is reduced, but these where based on expert judgement. And they state that there is little to no research that confirm these figures. Earlier in 2017 the CROW identified almost 500 sources in the field of parking policy and notice an imbalance in the availability of knowledge for different interventions with the majority covering parking tariffs (as seen in Figure 3). The same lack of scientific papers covering capacity reductions, especially with regards to a potential increase in the use of alternative modes was also identified during this literature review.

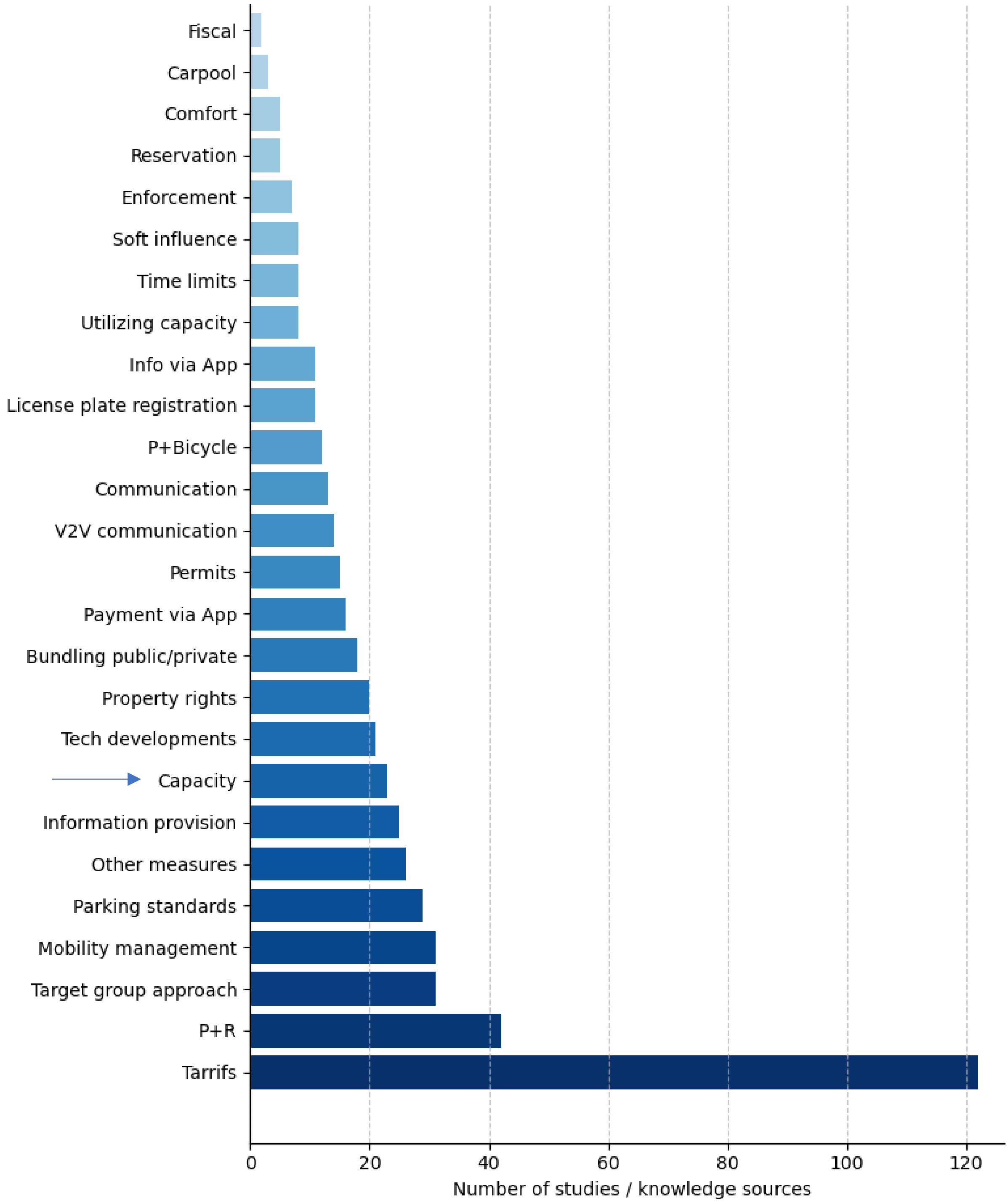


Figure 3: Imbalance of Parking Policy knowledge adapted from CROW (2017)

This research has shown that policies that reduce capacity can decrease car dependency at a local level, but two critical knowledge gaps, as identified in paragraph 2.6, remain. First, little is known about the, city-wide effects of large-scale parking reductions on the demand for alternative modes. Most studies focus on localized impacts, leaving uncertainty about how such policies influence travel behaviour across an entire urban network. Second, despite evidence suggesting that parking limitations can lead to increased public transit ridership, there is limited understanding if, and to what extent, transit systems must adapt in terms of capacity, frequency, and infrastructure to accommodate a potential shift away from car use.

1.2 Research objective and scope

This thesis examines the impact that the large scale removal of parking spaces has on the demand for public transportation and cycling, directly addressing the gap found in the previous paragraph. While much of the existing literature advocates for comprehensive policy packages or the simultaneous implementation of multiple measures to achieve car-lite cities (Hammadou & Papaix, 2015; Abbasi et al., 2023), this study deliberately narrows its focus to a single intervention, the removal of parking spaces. This single intervention will however be implemented in combination with an ambitious baseline scenario, that will be defined in paragraph 3.4.6. By isolating this measure this study aims to better understand the effects of this understudied measure.

To assess this policy, the research employs a case study approach, with Rotterdam chosen as the focus (see Section 3.2). The method for defining the boundaries of the study area with a major city is described in Section 3.3. The analysis is conducted using the V-MRDH simulation model, identified as the most suitable method (Section 3.4). Due to the included modes in the model, and time constraints, the research limits its scope to the examination of cycling and public transportation as alternative modes during the evening rush hour.

Guided by the sub-questions outlined in Section 1.3, this research aims to deepen the understanding of the relationship between parking policies and the demand for alternative transportation modes, ultimately offering insights and recommendations for urban planners pursuing sustainable, car-lite urban environments.

1.3 Research questions

The objectives described in section 1.2 lead to the following main research question:

How does the large scale reduction of parking spaces affect the demand of cycling and public transportation?

To answer this question, the research will address the following four sub questions:

a. Which specific areas in a city are most suitable to reduce parking spaces?
b. What is the effect of the reduction in parking spaces on the demand for cycling?
c. What is the effect of the reduction in parking spaces on the demand for public transportation?
d. How does the public transportation supply need to react to the change in demand?

1.4 Structure of the report

The remainder of the report will be as follows. Chapter 2 contains a literature review of car-lite policies in general, and goes into more detail into parking policy, this chapter identified the research gaps described in the introduction. Chapter 3 contains the methodology necessary to answer these research questions. It goes into detail about the case study- and model selection process, as well as quantifying a suitable study area, and gives a technical explanation of the V-MRDH model. Chapter 4 introduces the case study and presents the results found using the methodology. This is followed by the implications of the results on the bike and public transportation networks of Rotterdam. Chapter 5 discusses these implications and the limitations of the methodology and the results. Chapter 6 concludes the research, by answering the research questions and gives recommendations for future research and policy makers.

2 Literature Review

As stated in chapter 1 the objective of this thesis is to find out the effects that a large scale parking reduction has on the demand for alternative modes. Current scientific literature regarding parking policy seems to mainly focus on increased parking tariffs, or remote parking (P&R) (See Figure 3 for full list), with reducing the amount of parking spaces as a relatively new, controversial, and still understudied topic. (CROW, 2017; Rye et al., 2023)

As this thesis concerns research on car-lite cities trough the reduction of parking availability and the effects on bicycling and public transportation, this literature review will mainly reflect this, although it also examines parking in general, and the effects of a car-lite city. The literature review will serve as the basis for the methodology in chapter 3. Since parking policies are often made at the local level, and this research is focused on the Netherlands, literature and Gray literature such as governmental reports from this area are mainly used.

The literature review will begin by defining a car-lite city, and is followed by the goals of these car-lite cities. It then lists different car-lite measures, and highlights how these measures are currently used in cities. It then delves deeper into the specifics of parking policy, and starts with how parking policy influences land use-, and travel behaviour patterns. It then links parking policy to car-ownership as well as car-use, and highlights how space-inefficient cars in dense cities are. The literature review is concluded by listing the car-lite measures

The literature search is done both in English and in Dutch. Where Dutch is relevant because it is the local language of the area, and is mainly used for government reports. The search was done in Google (Scholar) and Scopus. During the search a combination of the following terms and their synonyms where used: *Car-lite, car-free, parking (reduction), modal split, travel behaviour, public transportation*. These searches yielded the initial list of literature which was extended using the snowballing technique. This method proved to be effective during pre-thesis where it was suggested by writing experts, therefor this method was also chosen for this thesis.

2.1 Defining car-lite

Autoluw is a Dutch term without a direct translation. It is often translated to car-lite, car-low or (nearly) car-free, all terms used interchangeably in literature. The term signifies a type of urban planning aimed at reducing car usage while not fully eliminating vehicle access. This creates an overlap between variants since all cities need to accommodate for emergency-, public transport and resupply vehicles, to move people and goods (Nieuwenhuijsen et al., 2018). This is reinforced by Melia et al. (2011) who states that all variants allow for hybrid and intermediate cases, but does define car-low developments as:

> *"Low car developments are residential or mixed use developments which offer limited parking, and are designed to reduce car use by residents."*

Dr. Steve Melia, 2011

With the difference to car-free developments being that they offer an immediate traffic free environment and are designed so all residents can live without owning a car. Car-lite developments, therefore, are characterized by two main features: limited vehicle access and designs that support reduced-car-dependent lifestyles. The term "limited" is context-dependent, requiring interpretation based on specific circumstances. The core idea is that parking restrictions and limited availability act to constrain car ownership. In other words, if more parking spaces were accessible, car ownership would likely increase, aligning more closely with the higher levels typical of the surrounding areas (Melia, 2014). By reducing on-site parking and enhancing access to public transportation and cycling infrastructure, these areas aim to mitigate the adverse health effects of car use as outlined in 2.2.

2.2 Goals of car-lite cities

In car-lite cities the reduction of cars is not the goal, but the means to a more liveable city. The goal of a car-lite city is to improve the safety, health and, quality of life for its residents. (Melia, 2014). This is done by removing cars from the streets and thereby minimizing the adverse effects of cars, including air pollution, noise pollution, reduction in physical activity and road accidents. (Nieuwenhuijsen et al., 2018)

Cars release greenhouse gases, such as carbon dioxide (CO_2), along with air pollutants like particulate matter (PM_x) and nitrogen oxides (NO_x). These pollutants originate both from tailpipe emissions, which are directly expelled through vehicle exhaust, and from non-exhaust sources. Non-exhaust emissions are evaporative fuel emissions, dust resuspension, brake and tire wear, and road surface abrasion, collectively termed non-tailpipe emissions (HEI, 2010; Harrison et al., 2021). Following their 2010 report the HEI published a new report in 2022 reviewing 353 studies in a wide range of countries to systematically evaluate the epidemiological evidence regarding the associations between long-term exposure to ambient traffic related air pollution (TRAP) and selected adverse health outcomes. And found a strong evidence to conclude that All-cause-, Circulatory-, and Ischemic heart disease mortality are linked to TRAP, in which chance, confounding, and other biases could be ruled out with reasonable confidence. But also found a likely association between TRAP and other causes, such as Asthma, Diabetes and lung cancer mortality (Boogaard et al., 2022).

Since there is now a much stronger body of evidence demonstrating how air pollution affects different aspects of health at even lower concentrations than previously understood, the WHO updated their 2005 advisory guidelines in 2021. In essence the advisory values for particular matter are halved, whilst the maximum NO_2 value is only ¼ of the previous advised value (WHO, 2021). In response the Netherlands updated their target values of “Het schone lucht akkoord” (The clean air agreement), with the original goal of meeting the former WHO air quality guidelines by 2030. With these new, more stringent air quality standards in place it is now, more than ever, time to rethink the place of the car in the city.

Cars and car related infrastructure are furthermore related to other undesirable environmental exposures most notably heat and noise (Nieuwenhuijsen et al., 2016). Exposure to traffic noise is a source of self-reported annoyance and a lead to a self-reported drop in quality of life (Welch et al., 2013), and while some studies found no significant evidence for the adverse effects of traffic noise on mental health (Hegewald et al., 2020), other studies found evidence that noise sensitivity is related to susceptibility to psychological ill-health (Stansfeld et al., 2021). Car usage is also associated with a lower levels of physical activity and active transportation (Wener & Evans, 2006; Mackett & Brown, 2011). Besides environmental exposures car related infrastructure can form barriers between neighbourhoods (Jorritsma et al., 2023). Lastly, car crashes are a direct cause of a large number of deaths and injuries (Papadimitriou, 2024; WHO, 2023) and are the leading cause of death for children and young adults aged 5–29 years (WHO, 2023).

In conclusion when automobiles are removed from the streets, there is strong evidence to support better health and safety for its residence and will ultimately yield a better quality of life.

2.3 Car-lite measures

Recent research by Jorritsma et al. (2023) classifies car-lite measures into three categories: built environment, parking, and roads & streets. The study by Jorritsma analysed their impact on car use and ownership by reviewing around fifty scientific studies and municipal evaluations. For the category the built environment, two prominent strategies, urban densification and functional mixing, were identified as effective in reducing both car use and car ownership, provided that viable alternatives to driving are available. This challenge is more pronounced internationally than in the Netherlands, where the well-established infrastructure for cycling and walking provides viable alternatives. Densification and mixed-use development are foundational, as they enable other measures to be effective by ensuring destinations are within accessible distances.

For the category roads & streets, the study identifies four measures: road closures, street redevelopment, speed reduction, and enhancement of cycling and pedestrian networks. While street redevelopment, speed reductions, and network improvements showed only modest local effects on reducing car use, street closures yielded significant reductions, albeit with the risk of traffic spillover onto nearby routes. None of these measures had a direct impact on car ownership. Finally, for parking measures, the study highlights four strategies: removing parking spaces, increasing parking fees, reducing parking permits, and implementing remote parking. The last three strategies have shown to reduce car use, and remote parking appears to have a potential impact on car ownership. The removal of parking spaces is the only measure with a clear negative effect on car ownership. Besides the space previously occupied by stationary vehicles can be used for other purposes (Jorritsma et al., 2023).

2.4 What can be learned from car-lite cities?

The previous section provided a theoretical framework for possible car-lite strategies. Current car-lite cities provide valuable lessons on balancing reduced car dependency with urban accessibility. This section examines several cities that have adopted one, or more of these car-lite strategies, highlighting the approaches they used, the challenges they encountered, and where available the outcomes of their initiatives.

2.4.1 Oslo

Oslo's car-free initiative is part of its ambitious 2016 climate and energy strategy. Oslo proposed an outright ban on cars in the city centre, which triggered significant public backlash. Local business owners voiced concerns that the ban could reduce customer access, impacting their revenue, while residents and accessibility advocates highlighted the need for better provisions for disabled drivers and emergency access. (Høynes et al., 2022)

To address these concerns, Oslo adopted a gradual approach. Starting in 2017, the city focused on removing on-street parking as a way to discourage car use without an immediate ban. By 2019, the city had removed 700 on-street parking spots—more than double the 300 spots removed by the end of 2017. This approach proved effective, with car traffic in inner city areas decreasing by 28%. Over time, public acceptance of these changes increased, as people began to experience the benefits of less traffic and more pedestrian-friendly spaces. (Høynes et al., 2022; McAskie, 2021)

2.4.2 Urban Mobility Trends in Europe

Amsterdam and Copenhagen are often recognized as leaders in bicycle usage among European capitals, which is largely a result of extensive, well-designed bicycle infrastructure (Fosgerau et al., 2023). However, this does not necessarily imply that these cities have exceptionally low car usage when compared to other European capitals. As illustrated in, while car usage and walking remain at relatively stable shares, a decrease in bicycle usage often corresponds with an increase in public transportation usage. This suggests that bicycles and public transit directly compete as primary alternatives to (medium-distance) car travel.

In cities where viable alternatives are limited, car usage tends to dominate. For example, despite a significant portion of Dublin's population having access to a rail station, car ownership and usage remain high. This is likely due to the fact that public transportation services do not align with the areas where people most need to travel (Caulfield, 2011).

These cases highlight that it is important to provide viable alternatives to driving, but that with only providing alternatives car-use can only be reduced by a certain amount. Looking at Figure 2, In the case of Amsterdam there has been a declining trend in the trip-based modal split since 2015. This likely due to Amsterdam actively trying to discourage the usage of cars. From 2019 with the Agenda Amsterdam Car-Lite, with a package of 27 measures (Gemeente Amsterdam, 2019). What stands out is that even with these measures in place car-use seems relatively inelastic, responding slowly to policy interventions.

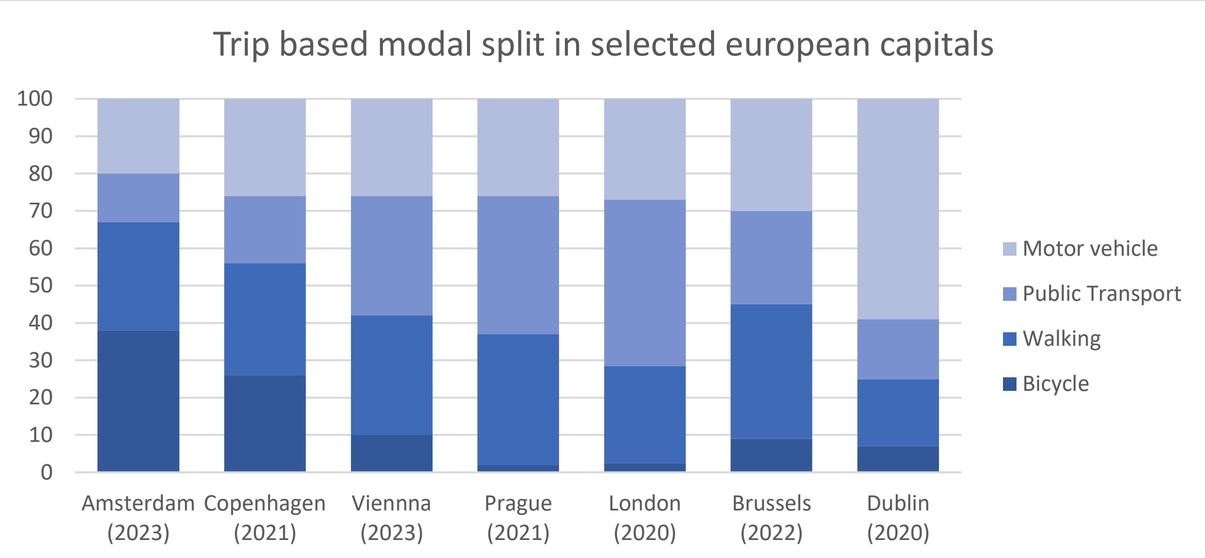


Figure 4: Trip based modal split in selected European capitals

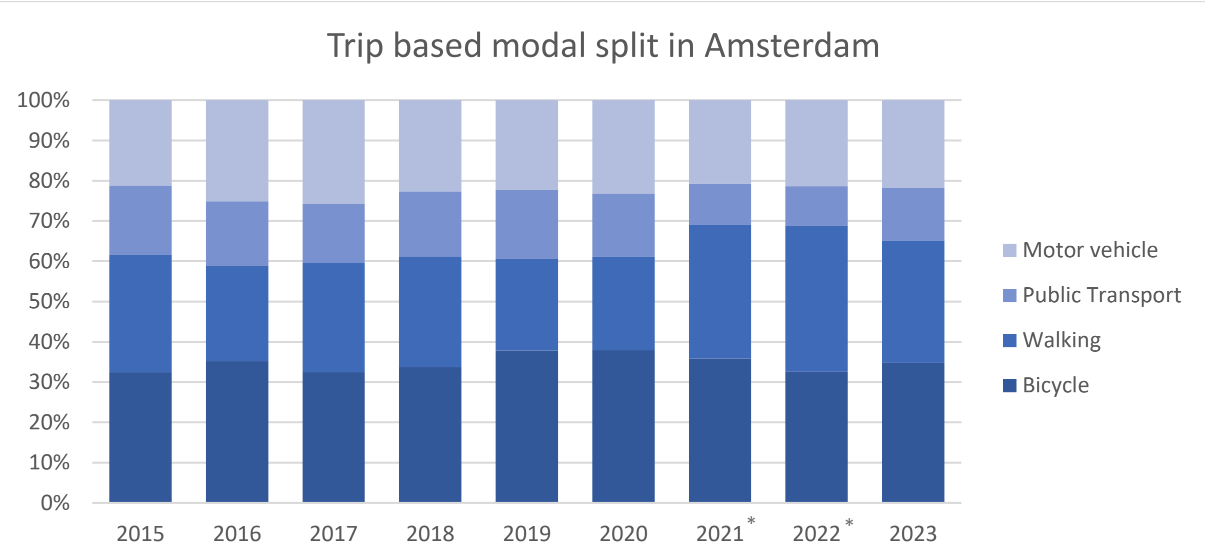


*Figure 5: Trip based modal split in Amsterdam 2015-2023 (CBS/OviN 2015 - 2017. from 2018 CBS/ODiN and Gemeente Amsterdam/afdeling V&OR); *Corona years*

2.5 Parking

As previous outlined in section 2.1 and 2.3, In a car-lite city, parking is an important tool in influencing the behaviour of people. This section will discuss the effects that removing parking has on car-ownership and car-use.

2.5.1 The Influence of Parking Space Limitations on Travel Behaviour

Parking availability plays a crucial role in shaping urban travel behaviour and transport system efficiency. According to Land-Use Transport Feedback Cycle (see Figure 6), land use changes, such as reducing parking spaces, have far-reaching consequences on accessibility, land-use decisions, and travel behaviour.

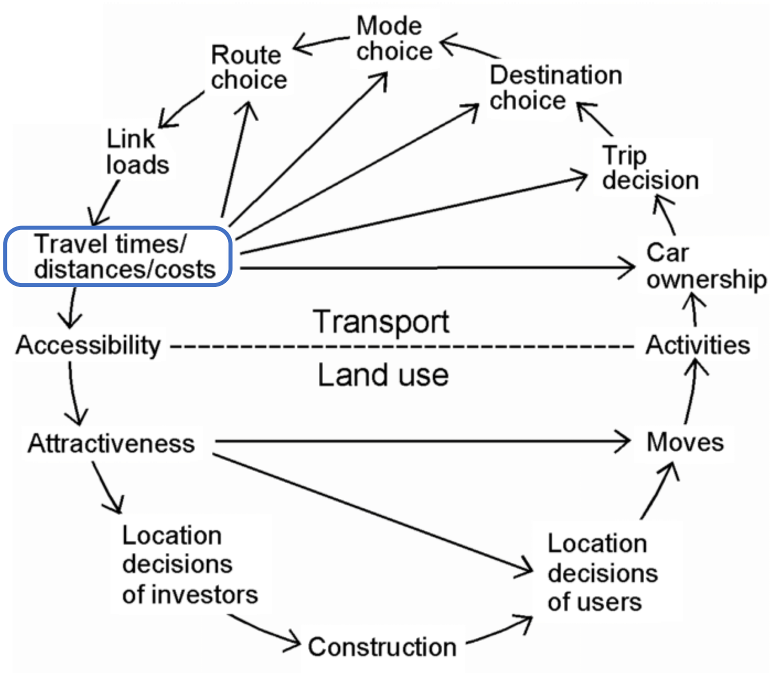


Figure 6: The land use-transport feedback cycle (Wegener & Fuerst, 2004)

The removal or limitation of parking spaces directly impacts accessibility, particularly for car users. Reduced parking availability in high demand areas increases the generalised cost of car travel, thereby discouraging private vehicle use. The CROW (2017) defines a high demand area as an area where the occupancy rate of the parking spaces is 83% or higher. Below that threshold they don't see a measurable change in accessibility when adding or removing a parking space. As accessibility decreases, the attractiveness of this location changes, influencing the location decisions of businesses, investors, and users. Over time, this can lead to shifts in land use, with higher-density developments and increased investment in public transport-oriented areas.

As accessibility and land-use patterns evolve, travel demand also adjusts. Travelers may change their route choices to avoid congested areas with limited parking or destination choices by opting for locations with better accessibility via alternative modes. Additionally, limitations on parking availability can serve as a push factor in reducing car ownership. Ultimately, these shifts contribute to a broader change in mode choice in the long term, as travellers increasingly opt for public transport or cycling.

According to the Dutch ministry of infrastructure and water management (Ministerie van Infrastructuur en Waterstaat, 2025) The exact effect of a parking measure on a city-wide level is strongly influenced by the specific measures taken and the impacted area's relative proximity to its competitors. But they state that there is a lack of research on this specific topic. However they provide some figures based on expert experience. According to them when removing a parking space 60% of motorists will park at different spot in the same area or in close proximity 20% choses for remote parking and only 20% choses a different mode, or doesn't make the trip. They do however not specify how this 20% is distributed between different mode types and non-users.

The CROW (2017) States that as a rule of thumb the following key figures regarding reducing the parking capacity could be used :

- Occupancy rate <83% = No effect
- Occupancy rate between 83%-95% = -0.5 parked car per removed space
- Occupancy rate >95% = -1 parked car per removed space

But they do again not state where those cars go to.

In conclusion, from a purely theoretical point of view using the land use-transport feedback cycle from Wegener and Fuerst (2004) one would expect that removing a parking space directly and indirectly influences mode choice, away from car use. Exact numbers regarding the extend and the redistribution are however hard to come by. The next paragraphs therefore explore the relationship between a reduction in parking spaces and a reduction in car- ownership and use.

2.5.2 Parking availability on the likelihood of car-ownership

As stated in the previous paragraph the provision of parking is one factor that influences the likelihood of car-ownership. This is further supported by scientific research. For instance, one study found that access to private or reserved parking triples the likelihood of car ownership (Christiansen et al., 2017). And numerous studies have shown a positive correlation between residential parking supply and car ownership (Guo, 2012; Christiansen et al., 2017; Yin et al., 2018; Albalate & Gragera, 2020; McAslan & Sprei, 2023).

However, the nature of this relationship is not always clear-cut. Some studies highlight that the relationship may be associative rather than causal, leaving the direction of causality uncertain (Christiansen et al., 2017; McAslan & Sprei, 2023). A common explanation is that higher car ownership prompts policymakers to implement higher parking minimums, making it challenging to determine whether more cars lead to more parking spaces or vice versa.

That said, Albalate & Gragera (2020) provide evidence of causality in the opposite direction. Using panel data from neighbourhoods in Barcelona, they found that the introduction of regulated residential parking spaces, and thereby indirectly increasing the residential parking supply, increased car ownership by 2.9% in treated areas compared to control areas. They also noted that this effect accumulates over time, reflecting the durable nature of car ownership decisions.

Nevertheless, causation may be less relevant for policies that actively remove parking spaces, as such interventions force a rebalancing of mobility behaviours. In this context, Weinberger (2012) argues that concerns about self-selection biases are secondary when implementing policies to reshape urban transportation systems. Moreover, reducing parking availability in transit-rich areas can discourage car-oriented households from occupying spaces that could be better utilized by transit-oriented residents, thereby optimizing the use of transit infrastructure (Weinberger, 2012). The takeaway should be that reducing the availability of parking in the study area reduces the car-ownership in that particular area, especially in the long term. This will be used to define more realistic scenarios in paragraph 3.4.6.

2.5.3 Parking availability on the likelihood of car-use

Parking availability influences car use in two key ways: directly and indirectly. Indirectly, parking availability affects car ownership, which in turn shapes car use. When parking is scarce, residents may be less inclined to own a car, as the difficulty and cost associated with parking make car ownership less practical. In this sense, car ownership acts as a mitigating variable, bridging the relationship between parking availability and car use. Lower car ownership reduces the likelihood of car use for daily travel, as residents may turn to alternative modes of transportation such as public transit, cycling, or walking.

This indirect effect is complemented by a direct influence of parking availability on travel behaviour, particularly among commuters. For those traveling to the area, research shows that in specific cases increasing parking costs and reducing parking availability can reduce car usage, shifting travellers to alternative transportation modes (Yan et al., 2018). In other cases research highlights that increased parking costs lead many commuters to shift parking locations rather than switch modes entirely (Shiftan, 2002; Marsden, 2006). This response is particularly common in cases where parking availability decreases or parking costs rise selectively within localized areas, rather than across broader regions. Or as Marsden (2006) states “Despite the observed sensitivity of drivers to increased walk time, there is evidence of unexpectedly long walk legs from free parking spaces being made indicating that the migration of parking problems will occur unless restrictions cover a wide area”.

Although parking pricing schemes have historically been regarded as the most effective policy measure (Higgins, 1992; Golias et al., 2002), recent studies suggest that parking demand may be relatively inelastic, with travellers often responding more strongly to parking availability and walking distance than to parking costs, especially in central locations (Chaniotakis & Pel, 2015; Mingardo et al., 2022).

2.5.4 Scarce urban space

All cars need a place to park. In fact, cars form Dutch households are parked 96% of the time. With an average size parking lot of about 12 square meters and 19 million parking lots, the Netherlands has around 225 square kilometres of parking lots, the same size as the city of Amsterdam (Zijlstra et al., 2022). And while space is most often not a problem in sparsely populated areas, it’s a problem in densely populated urban areas. In interviews with policy makers of the biggest Dutch cities, the lack of space in combination with creating a liveable city, is quoted as one of the main reasons for implementing car-lite policies (Jorritsma et al., 2023). Since space in big cities goes at a premium, cities as Amsterdam, Brussels and Paris are the first to take the controversial step to remove 11000, 65000 and 60000 parking spaces respectively (Jorritsma et al., 2023; *The Brussels Times*, 2019; Marchant, 2020).

2.6 Concluding literature review

The literature review can directly be used to answer the first sub question, what policies are effective to create car-lite zones? Table 1 gives an overview of different policies and measures that can be implemented to create car-lite zones and their effectiveness. The tables categories are based on the work by Jorritsma et al. (2023) as previously discussed in section 2.3, where the effectiveness is derived from the same work in combination with the findings of the literature review. The existence of cycling and pedestrian networks is added as a precondition since in section 2.4 it became apparent that car-lite measures only work when there are viable alternatives to driving. Form the literature review it also became apparent that removing parking spaces is clearly highly effective in reducing both car-usage and car-ownership (Guo, 2012; Chaniotakis & Pel, 2015; Christiansen et al., 2017; Yin et al., 2018; Albalate & Gragera, 2020; Høynes et al., 2022; Mingardo et al., 2022; Jorritsma et al.,2023)

Therefor there is chosen to use the removal of parking spaces as the basis for the car-lite policies in the case-study Rotterdam. Current literature offers a foundational understanding of how parking restrictions can reduce car usage. However, two gaps remain in understanding the broader effects of city-wide parking reductions on urban mobility and public transportation.

Table 1: Car-lite policies/ measures based on work by Jorritsma et al. (2023)

Category	Measure	Effectiveness
Built environment	*Urban densification*	*Precondition*
	Function mixing	*Precondition*
Roads & Streets	Road closures	Highly locally effective
	Street redevelopment	Moderate locally effective
	Speed reduction	Moderate locally effective
	Cycling and pedestrian networks	*Precondition*
Parking	Removing parking spaces	Highly effective
	Increasing parking fees	Moderate effective
	Reducing parking permits	Highly effective
	Remote parking (e.g. P&R)	Moderate effective

Firstly, while studies have identified (localized) impacts of parking restrictions on car ownership (Guo, 2012; Christiansen et al., 2017; Yin et al., 2018; Albalate & Gragera, 2020), they lack insight into the broader, city-wide effects on the modal split. Research has primarily focused on how parking reductions influence specific neighbourhoods or destinations, rather than examining how these restrictions may affect the overall distribution of travel modes across an entire city. This lack of a complete view of modal shifts suggests that more research is required to understand the effects of parking reductions on travel behaviour across a city-wide network.

Secondly, although there is strong evidence that parking availability influences car use, few studies have explored how large-scale reductions in parking may impact demand for public transportation specifically. While some research has shown a general relationship between parking limitations and increased transit ridership (Marsden, 2006), there is little clarity on the extent to which public transit systems in car-lite cities may need to adapt in terms of capacity, frequency, or infrastructure to accommodate a potential influx of former drivers. Further research is necessary to determine the adjustments required in public transportation planning to support cities with significantly limited parking, particularly as car-lite policies grow in popularity.

3 Research methodology

This chapter outlines the methodological framework that in this thesis will be used to obtain an answer to the sub questions and ultimately answer the main research question. First the research outline is described, then the case study selection is explained.

3.1 Research outline

Section 1.3 presented four research question. A method for answering the first question is provided in section 3.3, section 3.4 provides the method for answering questions 2 and 3. Section 3.5 provides a method for answering question 4. This section also provides a technical description of the chosen model. And defines the Business as usual (BAU) scenario, as well as the three intervention scenarios that will be used in the rest of the thesis.

3.2 Case study selection

The selection of an appropriate city for the case study is important to assure the findings are relevant and applicable to other cities with the same challenges. The research is done as part of the XCARCITY programme in the Netherlands for the TU Delft, in partnership with Goudappel, a Dutch company. Therefor cities within this region had the preference. The city had to be sufficiency large, and needed to have the political will to reduce cars in the city. Partners of the XCARCITY programme have this political will and thus are prime candidates. With these requirements in mind three cities would qualify: Amsterdam, The Hague, and Rotterdam. Inside the municipality boundaries of these three cities, the car currently represents 23, 32 and 40 percent of the trip based modal split respectively. (Gemeente Amsterdam, 2023; MRDH 2023). Besides the highest car use, Rotterdam also has the highest parking mandates of the three cities, up to a minimum of 1.20 parking spaces for each dwelling > 120m^2 in the city centre, while Amsterdam does not impose parking minimums in the city centre at all. For context the highest minimum parking requirement in the city centre of The Hague is 1.00 parking spaces for each non-rental dwelling > 160m^2 (Gemeente Amsterdam, 2020; Gemeente Den Haag, 2021; Gemeente Rotterdam, 2022;) This combination of factors makes Rotterdam a particular interesting case study. Therefor in agreement with Goudappel and the TU Delft, Rotterdam was chosen as the Case study for this thesis.

3.3 Defining a study area

From the literature review it became clear that the removal of parking spaces works best in highly urbanised areas. In highly urbanised areas there is severely limited amount of urban space, facilities are close by and there are viable alternatives to driving. This paragraph will describe how a highly urbanised area will be defined. The outcome will define the study area and thus limit the scope of the project. There are different methods for defining what classifies as (highly) urban, For example by the CBS, PVL and independent consultancy firms. The methods by CBS and PVL were considered but since the metrics used by this method did not provide a good fit for application phase of the model but the methods and their respective drawbacks are presented in appendix B. The method used in this thesis is by consultancy firm ‘Studio Bereikbaar’, It uses the population and number of workplaces in, 500 by 500 meter squares, capturing the intensity of use of an area. Using this method ensures a quantitative approach to define a highly urbanised area in any city, where this data is available.

Method by Studio Bereikbaar

To obtain an urbanization mobility score of each region, for each 500 by 500 meter square the population and number of workspaces within biking distance are summed, where biking distance is defined as 3 km. The population and number of workspaces that are further away than 1.5 km are multiplied by a factor that linearly decreases from 1 at 1.5 km, to 0 at 3 km. A visual representation can be found in Figure 7. In formula form the weight factor $f(d)$ for any distance d between 1.5 km and 3.0 km is given by:

$$f(d) = \frac{3-d}{1.5}$$

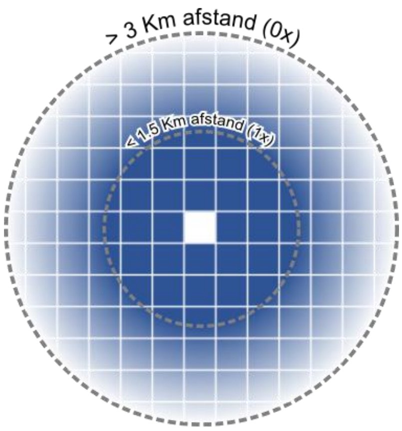


Figure 7: Urbanization mobility visualised

Meaning that a workplace at 2.00 km only counts as 0.66 workplace, and at 2.25 km as 0.5 etc. For each square $S_{i,j}$, where i and j are the index numbers of square S, The urbanization mobility score $U_{i,j}$ is consequently formulated as:

$$U_{i,j} = \sum\nolimits_{d \leq 1.5} P_d + W_d + \sum\nolimits_{1.5<d\leq 3} (P_d + W_d) \cdot f(d)$$

Where:

- P_d is the population at distance d
- W_d is the number of workspaces at distance d
- $f(d)$ is the distance-based weight factor

The urbanization mobility of the whole area, region or municipality is the average of all the urbanization mobility scores of all the squares within this area. This can then be classified in six predefined urbanisation codes namely as can be seen in

Table 2.

Table 2: Urbanization classification by Studio Bereikbaar

Urbanization code	Urbanization class	Urbanization score
S6	Highly Urban	>2000
S5	Urban	900-2000
S4	Suburban	600-900
S3	Low Suburban	400-600
S2	Town like	200-400
S1	Rural	<200

Using this classification method it is expected that each city has a cluster S6 zone in its most urbanised areas. This cluster can then be used to define the boundaries of the study area. The Rotterdam cluster for year 2024 can be found in Figure 8. This method is used in paragraph 4.1 to define the study area for this research.

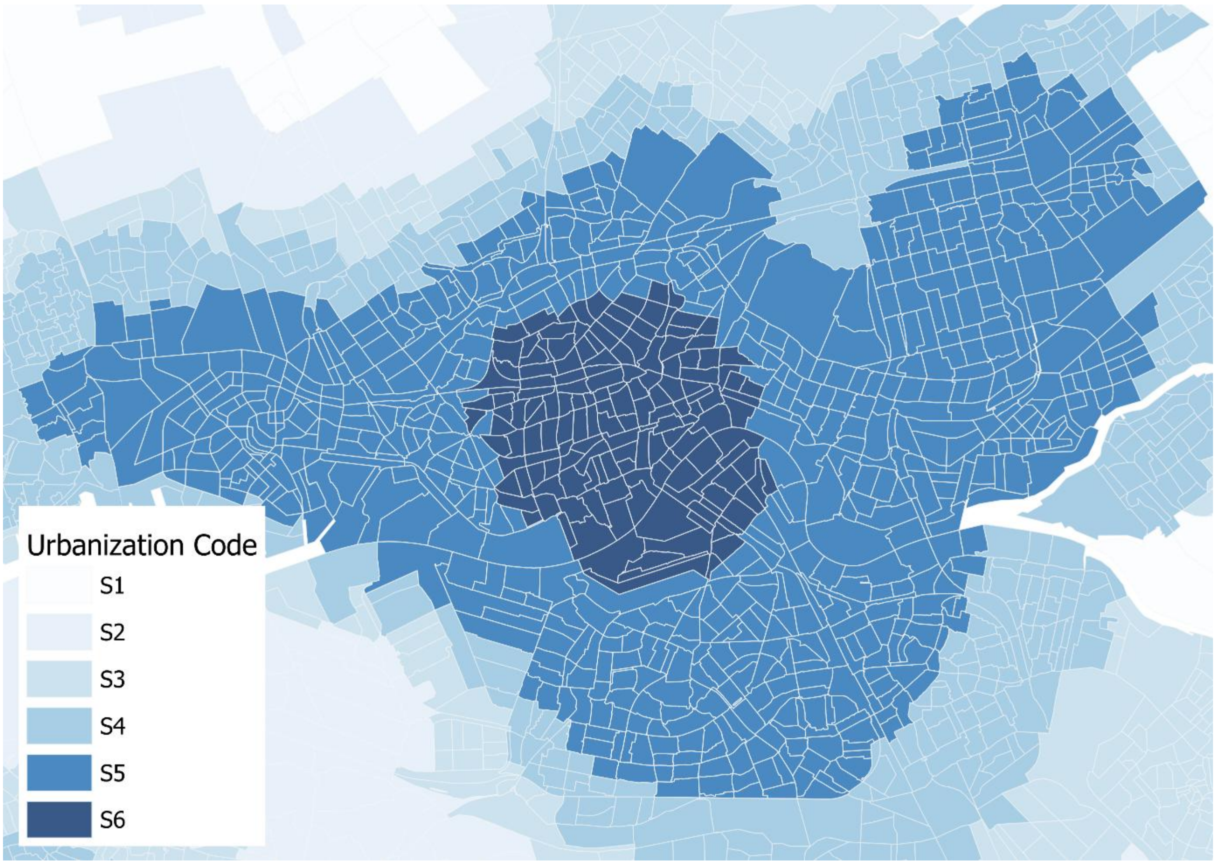


Figure 8: Visualisation of urbanisation Rotterdam trough method by Studio bereikbaar.

3.4 Effects on alternative modes using simulation models

To gain an insight into the effects caused by the implementation of parking restrictions on the alternative modes in the city, a variety of methods can be used, such as surveys, interviews, real-world experiments, or simulation models. Studies on the topic of parking restrictions using surveys (e.g. Kirschner & Lanzendorf, 2020) or interviews (e.g. Lambe et al., 2017) often capture the amount of support for these restrictions, with the availability, or extension, of alternative modes as variables. Conducting a survey could give insight into the stated choice between car, bike, and public transport to a certain set of destinations when parking is reduced, but will fail to capture the full range of system-wide effects and interactions.

Real-world traffic experiments that test restrictive policies, on the other hand, will capture the full range of (first-order) system-wide effects and interactions, but are costly and often face heavy public resistance. One recent example is the test with the controversial implementation of the modal filter on the Weesperstraat in Amsterdam (Gemeente Amsterdam, 2024). These experiments are often meant to assess what actually happens when a (restrictive) policy is implemented. Prior to implementation, stakeholders and traffic simulations typically generate a range of expectations regarding both the potential positive and negative effects. The real-world experiment allows for a direct comparison between these expectations and observed outcomes, providing valuable insights into behavioural adaptations, changes in modal split, and overall network performance.

A simulation model offers a comprehensive and cost-effective alternative, and is often used prior to real world experiments, making it the most suitable method for an exploratory study assessing the effects of parking restrictions on alternative modes. Unlike surveys or interviews, which capture individual preferences rather than system-wide responses, simulations allow for a full analysis of network interactions. They provide flexibility to test multiple scenarios, varying the extent of parking restrictions, the availability of alternative transport modes, or additional infrastructure changes, without the financial and political risks associated with real-world experiments.

This section remainder of this section will provide a method for answering the sub questions: What is the effect of the reduction in parking spaces on the demand for cycling? and What is the effect of the reduction in parking spaces on the demand for public transportation?

3.4.1 Model selection

In the previous paragraph, simulation models were identified as the most suitable method for assessing the effects of parking restrictions on alternative modes. In this paragraph, the specific traffic simulation model is selected that best addresses the following sub-question: What is the effect of the reduction in parking spaces on the demand for cycling?

Because this study focuses on the effects reducing parking spaces on alternative modes, it is crucial that the model is multi-modal, and possesses the ability to limit the amount of available parking. Additionally, the model must be capable of simulating route choice over a large network to capture system-wide effects and interactions.

Calvert et al. (2015) provided an overview of different model types and the behavioural choices they can handle (see Table 4) as well as the variables they can predict (see Table 5). For this research, the ability to predict mode of travel and route choice is essential, with modal split being the key variable.

Based on these requirements, a demand model appears to be the most suitable option. However, demand models do not inherently predict route choice. Fortunately, Calvert et al. (2015) note that demand models can serve as inputs for assignment models, whether using a macroscopic, mesoscopic, or microscopic assignment approach. Since this study does not require detailed analyses of speed, lane, or headway choices, a static macroscopic model is sufficient. This type of model is the least resource-intensive, which is beneficial for simulating a large network.

Table 3: Types of models and behavioural choices they are able to deal with (Calvert et al., 2015, p. 17)

Category	Trip/ destination	Mode of travel	Departure time	Route choice	Speed choice	Lane choice	Headway choice
Demand model	X	X	X	-	-	-	-
Macro model - static	-	-	X	X	-	-	-
Macro-model - dynamic	-	-	X/-	X	X	-	-
Meso-model	-	-	-	X	X	X/-	-
Micro model	-	-	-	X	X	X	X
Data driven model	X	X	X	X	-	-	-

Table 4: Types of models and traffic flow variables that can be predicted (Calvert et al., 2015, p. 18)

Category	Modal split	Route proportions	Travel time / average speed	Lane distribution	Volumes
Demand model	X	-	-	-	-
Macro model - static	-	X/-	X/-	-	X
Macro-model - dynamic	-	X/-	X	-	X
Meso-model	-	X/-	X	X/-	X
Micro model	-	X/-	X	X	X
Data driven model	-	-	X/-	X/-	X/-

In addition to requiring a multi-modal static macroscopic demand model that can simulate route choice and limit parking spaces, it is advantageous to utilize an existing, validated traffic model rather than developing one from scratch. This approach not only conserves resources but also ensures methodological robustness. Moreover, because this study examines network-level effects in Rotterdam, the chosen model must include a detailed representation of the city's network.

Based on these criteria, three candidate models emerge: the Netherlands Regional Models (NRM), the Dutch National Model (LMS), and the V-MRDH model used by the municipalities within the MRDH (which includes Rotterdam). All three are static, macroscopic, multi-modal demand models with the capability to restrict parking, and each incorporates Rotterdam's network to varying degrees. Among the national models, NRM-West offers a relatively detailed network for Rotterdam. However, the V-MRDH provides an even higher level of spatial granularity—with 3392 and 7786 zones respectively—although it treats walking solely as a first/last mile option in combination with public transport, whereas NRM-West considers walking between zones as an independent modality (De Romph & Cellissen, 2022).

A key differentiator between these models is their ability to simulate parking restrictions effectively. In an independent review, Snelder and Vonk Noordegraaf (2022) found that the NRM is only partially suitable for studies focusing on restrictive policies related to car ownership and parking limitations. In contrast, the technical report by Goudappel. (2023) confirms that the V-MRDH is well-suited for studies that involve ambitious mobility policies with stringent parking limits. An overview of the difference between the selected models is given in Table 5.

Considering its higher spatial detail, its ability to implement parking restrictions, and its overall suitability for assessing system-wide effects at the network level in Rotterdam, the V-MRDH model is selected as the most appropriate simulation tool for this thesis.

Table 5: Comparison between selected simulation models

Category	V-MRDH	NRM-West	LMS
Version	3.0.2	2021	2021
Demand model	Yes	Yes	Yes
static macroscopic model	Yes	Yes	Yes
Included modes	Car, public-transport, bike	Car, car passenger, train, Bus/Tram/Metro, Walking	Car, car passenger, train, Bus/Tram/Metro, Walking
# of model zones	7786	3392	1600
Ability to limit parking	Yes	Yes, with limitations	Yes, with limitations
Periods of day	Morning peak, evening peak and rest of day for all modes	Morning peak, evening peak and rest of day for car and public transport, 24 hour period for rest of modes	Morning peak, evening peak and rest of day for car and public transport, 24 hour period for rest of modes
Special density network Rotterdam	High	Medium	Low

3.4.2 The V-MRDH model

As mentioned above V-MRDH, specifically version 3.0.2, will be used in this thesis as at the moment of writing it was the most recent version of the model. The parking module was introduced in version 3.0 published at the end of 2023. The model runs in the most recent version of the Omnitrans software at the time of writing, version 8.1.0 This model will be used for predicting the effects of parking space removal on the modal split. For the purposes of this thesis the modal split will be defined as the ratio between people in private vehicles, public transit, cycling, and walking (only for trip chains), all other modes are omitted, since they are not included in the V-MRDH model.

The V-MRDH, is a macroscopic traffic model, and is based on a fully multi'-modal system for the entire 24-hour period on an average workday, with peaks (a morning and evening peak of two hours each) and off-peak hours (the rest of the day) being separately distinguished. It consists of the following elements:

I. *Modes of transport*: car, public transport, bicycle, (and freight traffic);
II. *Time periods*: morning peak, evening peak, rest of the day (combined into an average workday 24-hour period);
III. *Trip purposes*: work, business, education, shopping, social/recreational, and other.

To be able to run these time periods separately, they are implemented independently

The traffic model assumes the main mode of transport when estimating the transport mode in the matrix. Within the public transport modelling, there are trip chains because pre- and post-transport (walking and/or cycling) are separated and made visible. Additionally, the model uses a P+R module, where car trips are transferred to the public transport system via a Park & Ride facility. The study area of the traffic model is the entire Rotterdam The Hague Metropolitan Region. The model also calculates trips outside the study area, but at a less detailed level (Goudappel, 2023).

3.4.3 Technical explanation V-MDRH

This paragraph explains the matrix estimation procedure of the V-MRDH 3.0.2 traffic model, the explanation is based on the technical report by Goudappel. (2023), but some parts are summarised and others extended. The model consists of four essential steps,

I.	Trip generation & attraction	(Where do people come from and where do they want to go?)
II.	Resistance calculations	(How hard is it to reach the destinations?)
III.	Trip distribution	(Who goes where and with what type of mode?)
IV.	Trip assignment	(What route do they take?)

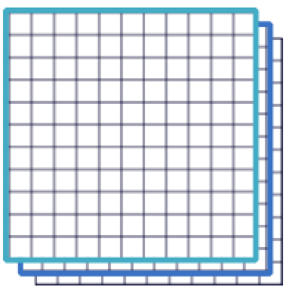
A visualisation of these steps is given in Figure 9. The core of this model is a simultaneous multi-constraint gravity model used for step III, which determines origin-destination matrices based on the input data obtained from step I & II. The model is based on Newton's law of gravity: the greater the resistance between two points, the fewer movements will occur between them. Model zones with many spatial functions have more mass and thus generate more attraction than zones with fewer functions. This relation is given by equation [*3.1*]

$$T_{i,j,m,p} = G \cdot \frac{P_{i,p}^{\alpha} A_{j,p}^{\beta}}{f(c_{i,j,m,p})} \qquad [3.1]$$

Where:

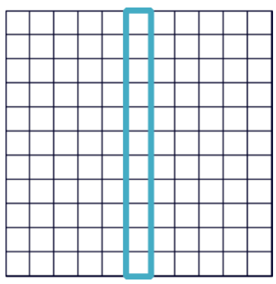
- T_{ijmp} = The amount of trips T from model zone i to model zone j for mode m and purpose p
- $P_{i,p}$ = Production in zone i for purpose p
- $A_{j,p}$ = Attraction in zone j for purpose p
- $f(c_{ijmp})$ = Impedance function based on the generalised cost from i to j for mode m and purpose p
- α, β, G = Balancing and scaling factors based on calibration with data from the ODiN

The application of the multi-constraint element of the model allows additional conditions for estimation, such as parking limits and adhering to origin-destination patterns from measured data, to be considered alongside the choice of destination, destination accessibility, and available transport options. A constraint can be applied for each combination of model zones, three simplified examples are given below. (Goudappel, 2023)



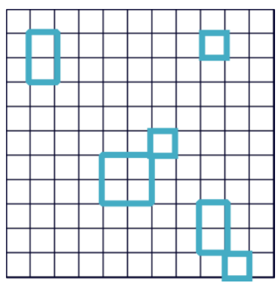
Modal split constraint

$$\frac{\sum_{ij} T_{ij,car}}{\sum_{ij} T_{ij,transit}} = \frac{MS_{car}}{MS_{transit}}$$



Parking constraint

$$\sum_{i} T_{ij,car} \leq PL_j$$



Trip length constraint

$$\sum_{ij \in C_k} T_{ij} = TD_k$$

Where:

- MS = The observed model split
- PL_j = The parking limit of model zone j
- TD_k = The amount of trips to distance class k; for example 0-3km.

Resistance calculations

The networks for each mode and transit time tables from the input of the resistance calculations. In this model resistance (or ease of connection between to zones) is expressed in generalised costs (€). The generalised costs, for each mode and purpose are given by equation [*3.2*].

$$C_{i,j,m,p} = L_{i,j,m} * VoD_{i,j,m,p} + R_{i,j,m} * VoT_{m,p} + P_{j,m} \qquad [3.2]$$

Where:

- $C_{i,j,m,p}$ = Generalised costs from model zone i to model zone j for mode m and purpose p
- L_m = Trip length between i and j in km for mode m
- $VoD_{m,p}$ = Value of Distance in €/km for mode m and purpose p
- $R_{i,j,m}$ = Trip duration between i and j in minutes for mode m
- $VoT_{m,p}$ = Value of Time in €/min for mode m and purpose p
- $P_{j,m}$ = Parking costs in destination zone j, only for mode $m = car$, otherwise 0, in €

In Intrazonal cases that is when $i = j$ for all modes m and all purposes p the intrazonal impendence C_{ii} is half of the average of the three smallest values in row i. Together this outputs of a set of matrices with generalised costs between each pair of nodes, for all modes m and all purposes p. These then can be used in the trip distribution step as input of the deterrence function. These matrices are also referred to as skim matrices. (Goudappel, 2023)

Trip distribution

In this step both the trip production & attraction as well as the skim matrices as combined together to distribute the trips between zones with formula [3.1] as previously described in this paragraph. The deterrence function used by the model is the lognormal function (Goudappel, 2023). Given by equation [3.3].

$$f\left(C_{i,j,m,p}\right) = \alpha \cdot \exp\left(-\beta \cdot \ln^2\left(C_{i,j,m,p} + 1\right)\right) \qquad [3.3]$$

All trips are then balanced in 50 iterations such that, whilst simultaneous adhering to all given contains:

$$\sum_{j,p,m} T_{i,jm,p} = P_i \quad \text{and} \quad \sum_{i,p,m} T_{i,j,m,p} = A_j \qquad [3.4] \text{ and } [3.5]$$

This process yield the final production and attraction matrices for each zone to each other for each purpose and mode that will be used in the final step that assigns these trips to links of the network.

Trip assignment

The method for trip assignment is different per mode. Car traffic is sensitive to road congestion and is assigned in 20 steps. In each step 1/20 of the total is assigned to the network. In each step all 1/20 of the total amount of cars take the quickest route between zone i and j. Thus, when one route becomes slower due to congestion the cars in the next step will automatically choose for the best alternative route.

Public transport is assigned using multi-routing technique Zenith. This method allows travellers to reach their final destination via multiple routes. The distribution across these routes depends several impedance factors, all expressed in time, including access time, waiting time, travel time, egress time, and transfer time. Some of these components are weighted differently, a full table of all weights can be found in the report by Goudappel. (2023, p. 33, table 1.10)

Lastly cyclists between zone i and j are split equally between three routes since an all or nothing method assignment to the shortest route resulted in an extreme bundling of cyclists that is not observed in the real world. Instead 1/3 is assigned to the route with the lowest travel time, 1/3 is assigned to the route with the least distance, and 1/3 is assigned to route with the lowest generalised costs where both distance and time account for 50%. This way the spread among possible routes is greater and aligns more closely with the observed data.

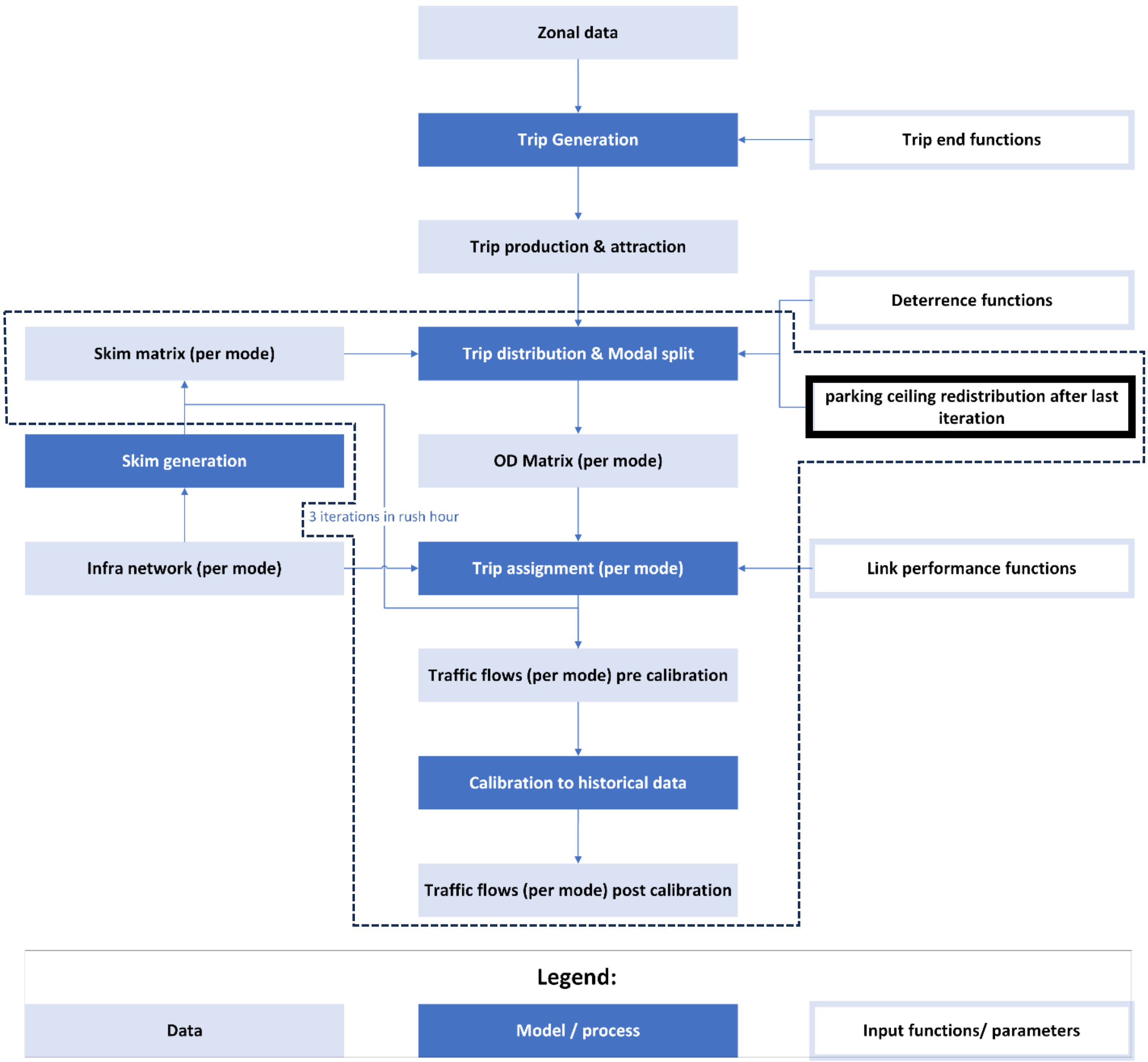


Figure 9: V-RMDH framework adapted from Goudappel, 2023. In solid black the changed input. In striped black the affected steps.

The model processes the three periods included in the model, morning rush, evening rush, and the rest of the day, independently from each other. For each period, attraction and production figures are recalculated, and the distribution functions are custom to that specific time. During peak hours, an iterative matrix estimation procedure is applied: after the first iteration, new travel time matrices are generated that account for road congestion (which alters the resistance between any two points), this feedback loop is repeated twice for a total of three iterations. This approach ensures that congestion affects not only route choice but also mode and destination choices.

3.4.4 Parking data in the Netherlands

For this study, current parking figures are required. Since these figures are not tracked in the Netherlands, multiple studies have tried to estimate the number of parking spaces in the Netherlands (Van Dijken et al., 2002; Kennisinstituut voor Mobiliteitsbeleid, 2018; Van Der Tuin et al., 2021) with varying definitions and methodological approaches. Early work based on 2000 data estimated around 8.9 million *public* parking spaces (Van Dijken et al., 2002). Further assessments by the Kennisinstituut voor Mobiliteitsbeleid (KiM), indicate that the *total* number of parking spaces might range between 14 and 18 million. More recently, the TNO-led Urban Tools Next II project, which employs advanced GIS-based methods, estimated about 18.8 million *total* parking spaces. (Van Der Tuin et al., 2021) Given that the TNO estimate is a comprehensive and up-to-date reflection of parking capacity, and the data is available for this research these estimates will be used.

In the study by Van der Tuin et al. (2021) A large portion of the parking spaces in (public) parking lots was found in the Open Parking Data dataset of the Dutch National Parking Register. Other parking spots are well represented in the 'Basisregistratie Grootschalige Topografie' (BGT). For parking spaces on private property at homes and businesses, the Cadastral Base Map and GIS methods were used. Finally, for unmarked parking options along the street, estimates of parking capacity were made using the National Road Database (NWB). then applied the found parking capacities as a case study on the VRMDH 2.6, an predecessor of the model that will be used for this thesis, and found the results to be plausible and within the range of expectations.

Some cumulative outcomes of this study that are used in chapter 4 are given in : Cumulative data for neighbourhoods Rotterdam

3.4.5 Calculating the parking limits

Paragraph 3.4.4 described discussed different sources of parking data. To calculate the parking limit the V-MRDH model uses data that was collected by TNO as part of the Urban Tool Next II programme (Van der Tuin et al., 2021).

The number of parking spaces found by this study then formed the basis for the parking limits in the new VRMDH 3.0 model. First the total number of parking spaces is distributed over the time periods included in the model namely, morning peak, evening peak, rest of the day. An apriori run without the parking limit found that the distribution of cars over the time periods was 13%, 75%, 12% respectively. The same distribution is used for the parking limits over the time periods. This distribution over the parts of the day is necessary since they are all simulated separately and do not interact with each other. This way of calculating the parking limit means the model is 'reserving' parking spaces for a specific time period. Lastly the number of parking spaces is multiplied by a turnover rate, to account for the fact that one parking space could be used by multiple vehicles in one time period. They found this turnover rate to be 1.35 on average, but varies per parking zone, in the range from 0.82 to 2.01. A visualisation of the realisation of the parking limit is found in Figure 10.

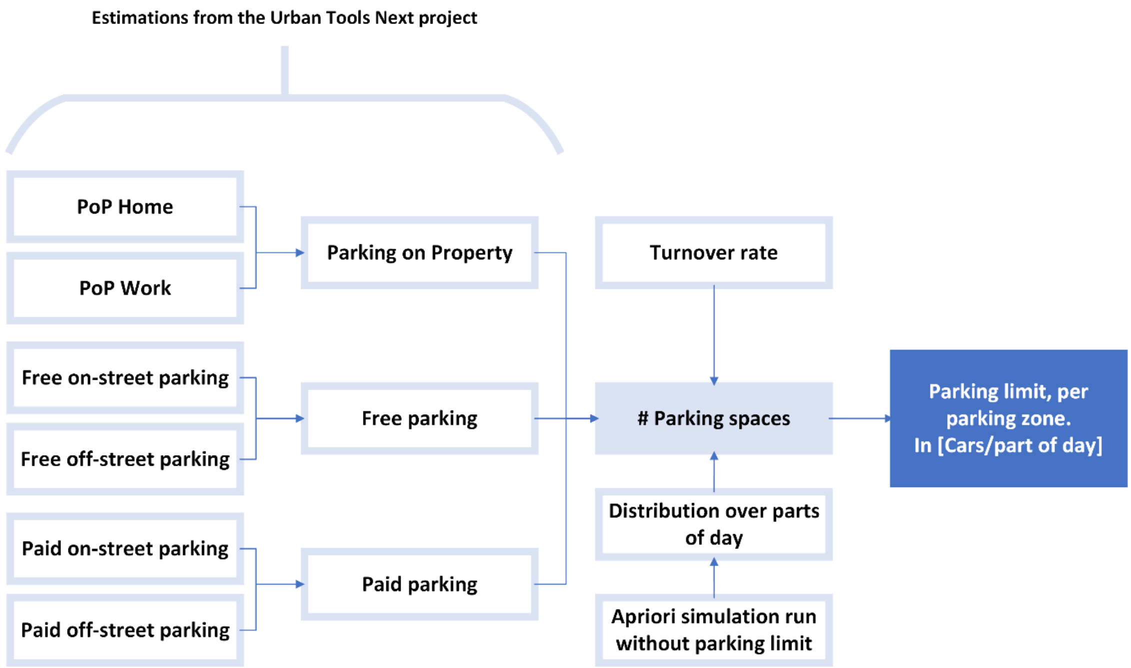


Figure 10: Calculating the parking limit

This way of calculating the parking limit has two limitations. Firstly, since the number of parking spaces is the aggregated sum of all types of parking spaces, removing more, or less of a specific type of parking space is not possible. This means that for this research parking spaces are removed equally over PoP, Free- and paid parking. Secondly since a distribution factor is used the parking limit 'reserves' parking spots for a specific time period. For example, in the evening rush hour no more than 12% of the total available parking spots can be used. This means that for this thesis when the total parking limit is lowered by 10.000 cars, this will result in a maximum reduction of 1.200 cars in the evening rush hour.

3.4.6 Scenarios

To establish the relationship between the percentage of available parking spaces and the modal split, it is necessary to systematically vary the availability of parking. There is a particular interest in exploring the full spectrum of possibilities in order to identify any tipping points, where a significant shift from private vehicle use to public transportation occurs. To explore this spectrum of possibilities it is necessary that multiple scenarios will be tested. However, there is a trade-off between precision and computational cost. A preliminary test yielded a run time 131 hours for the full 24 hour model, with the computational resources available for the project. Given the time constrains for completing this thesis there was chosen to compose three intervention scenarios.

Defining scenarios

To assess the effects of parking space removal, the baseline (Business As Usual, BAU) is compared with three intervention scenarios. These scenarios represent different levels of intervention, ranging from realistic to ambitious parking reduction. These three scenarios will be compared against the business as usual (BAU) scenario where no extra parking limitations are applied. To summarise these scenarios will be:

1. BAU
2. Realistic scenario
3. Intermediate scenario
4. Ambitious Scenario

The next step is to quantify these scenarios, therefore it is necessary to define what is realistic and ambitious.

Realistic Scenario: Rotterdam Stops Building Parking Spaces

To assess the feasibility of this scenario, one can examine Rotterdam's past actions on a smaller scale. Between 2008 and 2020, Rotterdam removed 3,000 parking spaces from its city centre (Gemeente Rotterdam, 2020). According to the parking data in paragraph 3.4.5, the city centre contained approximately 15,000 parking spaces on municipal grounds (see Table 11 in 4.2.3 for a breakdown by type). This means Rotterdam eliminated roughly 20% of its on-street parking spaces in the city centre over 12 years. Given that the total number of parking spaces in the city centre was around 28,000, this represents a 10% reduction in overall parking availability.

Projections for the V-MRDH model suggest that, under a business-as-usual (BAU) scenario, Rotterdam plans to add 10,000 new parking spaces within the study area. With approximately 90,000 parking spaces currently in this area (Zone A in Figure 31), a 10% reduction compared to the BAU scenario would effectively mean that Rotterdam stops constructing new parking spaces.

Given the city's ambition to allocate more space for walking, cycling, and public transportation, alongside efforts to reduce car traffic (Gemeente Rotterdam, 2020), halting the construction of new parking spaces appears to be an achievable goal.

Ambitious scenario: Rotterdam's parking supply becomes car-lite by common definition

In the ambitious scenario Rotterdam becomes car-lite by common definition. With many cities defining car-lite parking norms often as below 0.5 parking space per residential dwelling (Sprei et al., 2020). With 22230 residential dwellings in the Centre of Rotterdam in 2024 (Centraal Bureau voor de Statistiek, 2024) this would mean that maximum amount of *total* parking spaces in the city centre would equal roughly 11000. With currently in total roughly 28000 parking spaces in the city centre (see Table 11 for the breakdown by type). This means that ambitious scenario sees a decrease of 60% in parking spaces compared to the BAU scenario.

Intermediate scenario

In the intermediate scenario, Rotterdam adopts a more gradual transition reducing the amount of parking spaces while still accommodating some level of car ownership and use. This could involve a parking space target somewhere between the current 28,000 spaces and the ambitious scenario's 11,000 spaces. For this research the intermediate scenario will be defined as a reduction of 40% compared to the BAU scenario.

Choosing the forecast year

The scenarios mentioned in the previous paragraph will be variations on the 2030 forecast of the existing situation. The baseline of the V-RMDH represents the situation in 2020 (pre-COVID). By selecting a year from the recent past, the model could be calibrated and validated using observed data. Beyond this baseline, the model incorporates five pre-validated forecast scenarios:

I. 2030 WLO high;
II. 2030 urban reference;
III. 2040 WLO low;
IV. 2040 WLO high;
V. 2040 urban reference.

The WLO forecasts are widely used as a foundation for policy decisions related to the physical living environment in the Netherlands. Developed by the Netherlands Environmental Assessment Agency (PBL) and the Netherlands Bureau for Economic Policy Analysis (CPB), these scenarios outline two main trajectories:

I. *High*: This forecast combines relatively high population growth with strong economic growth of approximately 2% per year.
II. *Low*: This forecast assumes limited demographic development accompanied by moderate economic growth of about 1% per year.

(Centraal Planbureau voor de Leefomgeving, 2015)

In addition to the WLO scenarios, the V-RMDH includes urban reference forecasts, which are derived from WLO High. These forecasts are designed to be more consistent with policy objectives, particularly in densely urbanized regions. Unlike WLO forecasts, they integrate policies not yet formally adopted and emphasize changes in travel behaviour and preferences. (Metropoolregio Rotterdam Den Haag, 2024) Since the case study is set in the most urbanised part of Rotterdam in the near future, the 2030 Urban Reference forecast was deemed the most suitable as a basis for further analysis. The implications of this choice are discussed in section 5.2.

3.5 Method for determining the impact on the public transportation

In this final step of the methodology all previous steps are combined to find the effect of the intervention scenarios described in the previous paragraph on the public transportation and bicycle network. The full process is visualised in Figure 11. This thesis will evaluate the impact on the three levels of public transportation planning; Operational, tactical, and strategic.

To evaluate the impact of the intervention scenarios on the operational planning, this study adopts a method focused on vehicle load as the key performance indicator, specifically during the peak-of-peak period—the time of highest passenger demand within the broader peak hours. The analysis compares vehicle occupancy levels of the intervention scenario to the BAU. By isolating the peak-of-peak period on the most critical link of the metro, bus, and tram network, the method captures the most critical operational stress on the network. Average load, and occurrences of overcapacity are examined to identify shifts in utilization patterns attributable to the intervention. This approach provides actionable insights into how the intervention influences the efficiency and comfort of public transport services during periods of maximum pressure.

To evaluate the impact of the intervention scenarios on the tactical planning, this study first establishes a year-on-year baseline growth without the impact of the intervention scenarios. Then the impact of the intervention scenario is determined and compared with the current growth of the network.

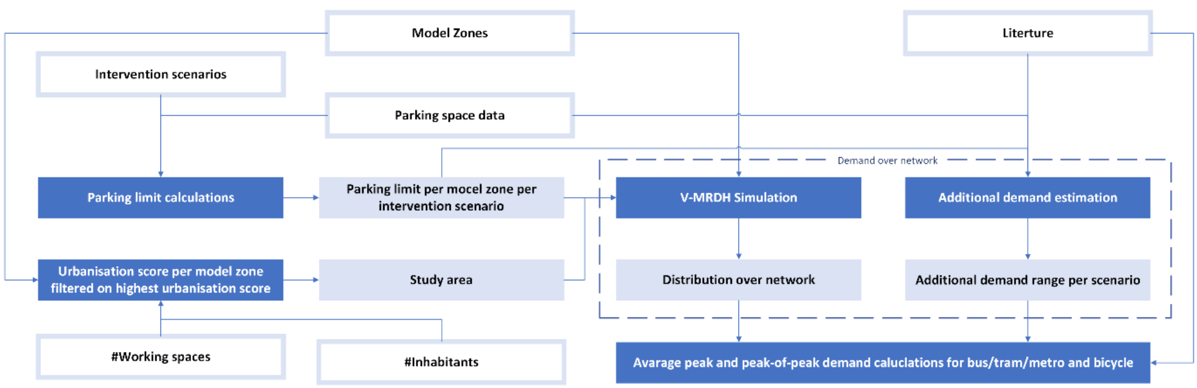


Figure 11: Visualisation of the workflow

4 Case study Rotterdam

Rotterdam, located in the South-Holland province of the Netherlands, is the country's second largest city with a population of 665.000 as of 2023 (CBS). Bombed in the second world war, the city was built form the ground up during the 1950s to the 1970s. The extensive destruction of the city centre allowed for the implementation of new, open, and modern spatial infrastructure, making the city unique in the Netherlands. Over the years, the city became known for its car centric planning and some even call it "The city rebuild for cars" (Not Just Bikes, 2020), but this is in line with the vision for the city of 1950's.

> *"Rotterdam will be spacious, it will have the elegance of a metropolis: the speeding traffic, the broad boulevards, all the tall buildings will generate a sense of bustle that blends harmoniously with modern life."*

Rein Blijstra, in Het Vrije Volk 13-11-1952

The car centric planning phase that followed during the 1960s and 1970s is still felt to this day, and this is translated into Rotterdam having the highest car modal share, and highest minimum parking mandates of the four biggest Dutch cities, and was one of the main reasons this cities was selected as a case study in section 3.2.

With a city rebuild for cars it seems obvious that the urgency to allocate more space to active modes remained absent for longer than in historic city centres such as those of Utrecht or Amsterdam. However, the vision for Rotterdam has changed over the decades, the growing awareness of the negative health impacts of car-centric cities, and the desire for more liveable public spaces have prompted a significant shift in priorities. And since 2005 Rotterdam has implemented integral policies to give the city a new identity away from the city rebuild for the car towards a city lounge at the river (Bakker, 2017). And to this day Rotterdam is building a future where people, rather than vehicles, are the focus of urban design. As can be read in the city's mobility programme (Gemeente Rotterdam, 2020).

This case study will examine one aspect of this ongoing transition. It will explore how limiting the availability of parking spaces affects the biking and public transportation trips in the city. And will explore the implications, and gives recommendations to the public transportation operator on the operational and strategic level.

4.1 Definition of the Study area

In Section 2.6, three preconditions were identified as necessary before other car-free initiatives, including the reduction of parking spaces, can be effective. These were a dense urban environment, mixed-use neighbourhoods, and high-quality pedestrian and cycling networks. Jorritsma et al. (2023) noted that the last two are primarily a challenge in an international context, as they are well developed in most Dutch cities.

Therefore, Section 3.3 presented a quantitative, generalized method to identify parts of the city that are sufficiently dense and active to support car-free initiatives. Applying this method to Rotterdam resulted in Figure 6. This resulted in an area where the preconditions for car-lite initiatives are met.

To reduce complexity and smooth variability, the standard output of the V-MRDH model aggregates the 7786 × 7786 matrix into a 65 × 65 origin-destination (OD) matrix, A visualisation of the matrix compression zones is provided in Appendix C. The parking constraint described in Paragraph 3.4.3 is applied at this aggregated level. However, to better reflect localized parking pressures, five zones were separated. These zones were: Kralingen, Charlois, Hillegersberg, Prins Alexander, and IJsselmonde (Goudappel, 2023).

Overlaying these aggregated zones on the urbanization map of Rotterdam yields Figure 9. Examining this figure reveals that these parking zones do not perfectly align with the areas of highest urbanization. Only one zone, Zone A - Rotterdam Centre - fully overlaps with S6, four other zones partially overlap with S6 together they are labelled A through E, with the following names:

A. Centrum
B. Delfshaven
C. Noord
D. Kralingen Oost
E. Feyenoord

To assess whether these are realistic zones for implementing parking space limitations, they can be compared to areas in Rotterdam where parking constraints are currently in place. Figure 10 illustrates these areas, with Zone A defined as highly urbanized. Comparing this to Figure 9, one can observe that while the areas are not an exact match, they align closely. This indicates that the generalized method produces realistic zones for implementing parking space limitations, at least in the case of Rotterdam.

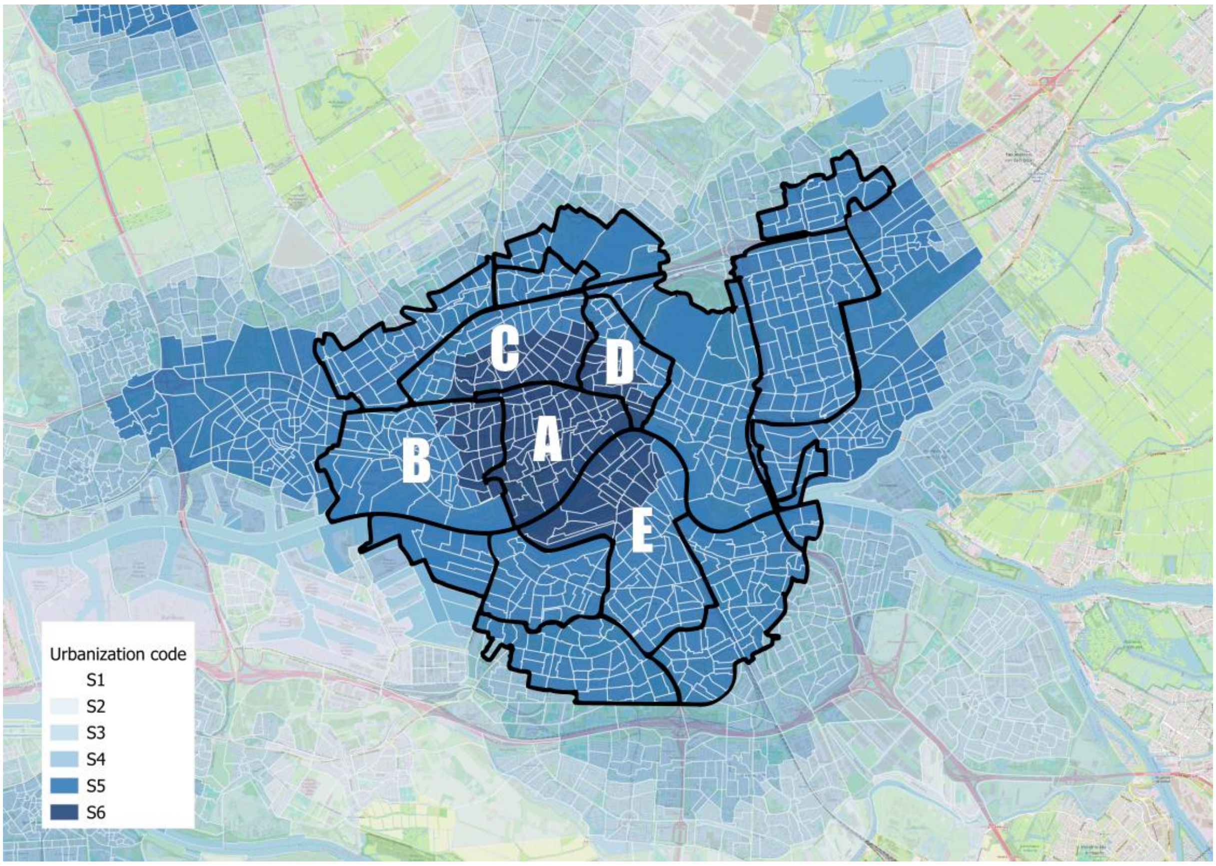


Figure 12: Parking areas overlayed on urbanization zones

Figure 13: Area types as used in "Beleidsregeling Parkeernormen auto en fiets gemeente Rotterdam 2022"

4.2 Results

This section presents the findings on how the removal of parking spaces influences alternative transportation modes in urban areas. And thereby answering sub questions b and c introduced in section 1.3. The results are structured as follows: First the outcomes based on the V-MRDH model are presented, afterwards a calculation is made to estimate the effect on the alternative modes. The implications of the effects are discussed in Chapter 5.

4.2.1 Application of the model

The V-MRDH model used in this thesis is central to analysing the effects of parking space removal. To support reproducibility, all aspects of the simulation, form setup to export, are documented. A detailed description is given in Appendix D.

4.2.2 Outcomes of the V-MRDH model

The V-MRDH traffic simulation model was used to evaluate the impact of parking space removal on the alternative modes in Rotterdam. The V-MRDH was chosen as most suitable model in paragraph 3.4.2, a technical explanation of the model can be found in paragraph 3.4.3. The scenarios as defined in paragraph 3.4.6 were simulated using the steps described in Appendix D.

Table 13 to Table 16 in Appendix G show the simulation results of the different scenarios. Results indicate a 2.3% increase in bike trips, and a 3.7% increase in public transportation trips compared to the BAU scenario, for every 20% decrease in car trips.

As defined in paragraph 3.4.5, the parking limit is expressed as a restriction on car trips. In the BAU scenario, parking pressure is at 100%, making the decrease in the parking limit and the decrease in car trips directly proportional (1:1 equivalent). Note that according to the model 100% of the excess car-trips are redistributed within the same zone to public transport and biking, These findings are not consistent with earlier literature as found in paragraph 2.5.1, that says that some people will choose a different destination when the accessibility of a place decreases. The implications and potential solutions will be further discussed in paragraph 5.1.1.

Despite this limitation, useful insights can still be derived from the results. Notably, the distribution of shifted trips between biking and public transport remains consistent, regardless of the extent of the parking reduction. In the city centre, the modal shift ratio equals 45:55 (Bike: Public Transport),

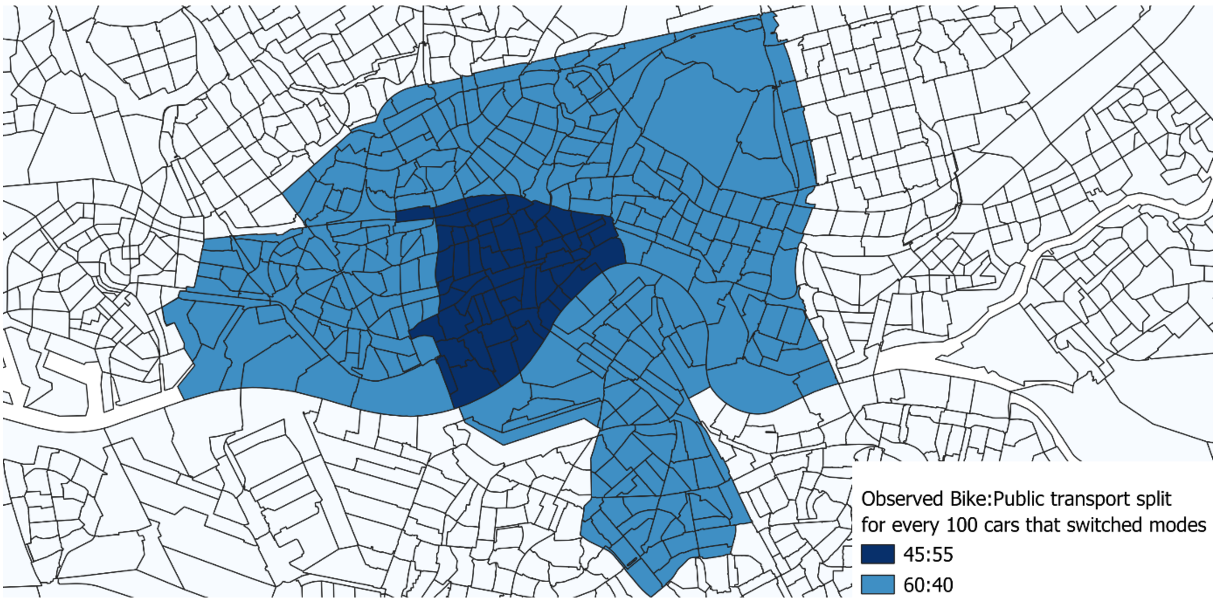


Figure 14: Observed split in model results between bike and public transport

whereas in the surrounding neighbourhoods, this ratio is 60:40. This suggests that the relative attractiveness of each mode is location-dependent, influenced by factors such as public transport availability and cycling infrastructure. This is consistent with earlier literature as found in paragraph 2.5.1.

Moreover Figure 16 shows the most relevant row of the difference between the 65x65 OD-matrix of the BAU scenario and the intermediate scenario for mode car and all purposes since the rest of the matrix does not change by approximation, the full matrix can be found in Appendix J. This shows that according to the model when reducing parking spaces in one area only the car trips to and from that area are influenced. Since Rotterdam is a big employer and this OD-Matrix is for the evening rush hour, most people want to leave Rotterdam hence this row shows the difference in departures from the study area. The opposite is true in the morning rush hour. An analysis of the data shows that 42% of removed car trips are removed from within the boundaries of the municipality of Rotterdam, 34% of the removed car trips were from the remainder of the MRDH, and 23% of the removed car trips were from the remainder of the Netherlands. This is visualised in Figure 15.

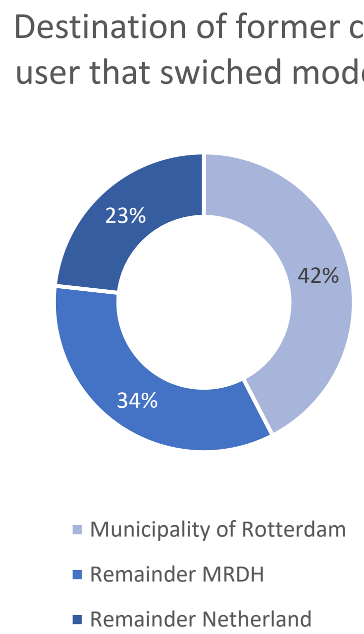


Figure 15: Destination of former car users that switched modes

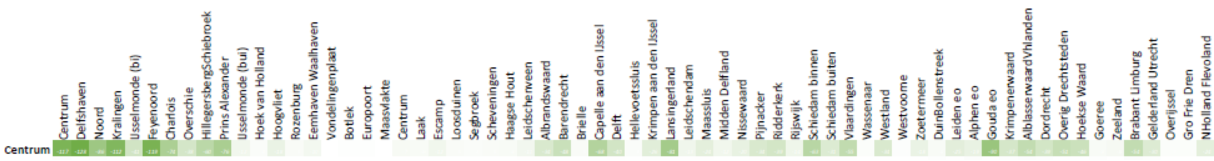


Figure 16: Difference in car departures form study area BAU-Intermediate scenario. Colour indicates intensity of decrease.

Moreover the data form the OD-Matrices can be used to visualize the destination of trips leaving the study area in the evening rush hour, and the destination per mode of the people that switched modes in the Intermeadate scenario in a Sankey diagram, the result is shown in Figure 17. From this figure it becomes clear that altough car trips reduce by 40% in the intermediate scenario, the increases in public transportation and biking trips is relatively small due to the original skew in the modal split. This skew is a result of the choice of BAU scenario, where there is already a reduction in car-trips due to other polocies that stimulate public transportion and decourage car use. The implications of this choice are futher discussed in section 5.2.

Another insight is that for all scenarios all public transportation lines Bus/tram/metro/train grow by roughly the average amount, exact percentages for lines in the city centre can be found Appendix C. This is further explored in section 4.3 that shows that in the busiest sections of the network around 3% of the lines total capacity is occupied by former drivers in the intermediate scenario.

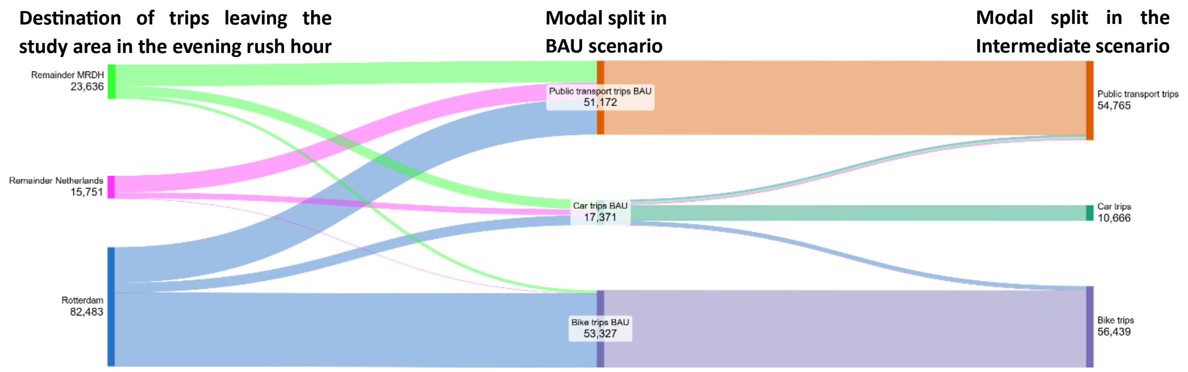


Figure 17: Sankey diagram of destination of trips, and modal splits in BAU and Intermediate scenario

4.2.3 Estimation based on parking space data.

To support the estimations of the V-MRDH model this paragraph provides a supplementary method to the simulation model. And derives an answer to the research questions b and c based on available parking data in combination with existing literature.

Parking data form Van de Tuin et al. (2021) was in paragraph 3.4.4 selected for this study. The cumulative relevant collected data by this study is presented in : Cumulative data for neighbourhoods Rotterdam. The parking spaces are divided in three categories Parking on Private Property (PoPP), free (street) parking spaces, and paid (street) parking spaces. Using this data it is estimated that the municipality of Rotterdam has around 790.000 parking spaces. 125.000 (16%) of which are paid and 615.000 are free (78%) (street parking, parking lots and parking garages). The remaining 50.000 (6%) are parking spaces on private property. A breakdown per neighbourhood can be found in Table 19. The distribution of parking spaces becomes different however when only considering (highly) urbanised areas now 49% of parking spaces are paid, indicating a larger scarcity of space. A breakdown per neighbourhood can be found in Table 20.

To estimate the effect of a large scale parking reduction on the alternative modes in the city the three scenarios defined in 3.4.6 can be used. Table 11 includes all neighbourhoods in the study area as defined in section 3.3. but only for zones where the urbanization level is S6. These figures will be used in the scenarios to estimate the effect on the Public transportation.

Table 6: Amount of parking spaces in study area neighbourhoods in Rotterdam from data by van der Tuin et al. (2021)

Zone name	PoPP	Free Parking	Paid Parking	Total
Rotterdam Centrum – S6	13235	1396	13580	28212
Delfshaven – S6 Only	1824	410	14643	16877
Noord – S6 Only	1238	1607	11389	14234
Kralingen Oost – S6 Only	563	219	6835	7617
Feynoord – S6 Only	4061	5217	12879	22156
Total	20921	8849	59325	89095

Realistic scenario

In the realistic scenario 20% of the parking spaces in the study area are removed. From Table 6 it becomes apparent that there are 89095 total parking spaces in the study area. Meaning that in this scenario a total of 17.819 parking spaces are removed in Rotterdam. Or about 60% more than the 11.000 parking spaces that a similar sized city as Amsterdam is removing. (Jorritsma et al., 2023).

When using the method described in 3.4.5 to calculate the parking limits it is found that in total 12.830 vehicles can have the study area as their destination. Runs with the simulation model have shown that more than 95% of parking spaces are already filled in the baseline scenario in the study area, meaning that reducing the parking limit with one, one less vehicle will park in the study area according to the rules of thumb used by CROW (2017) as found in the literature review in paragraph 2.5.1. With this information a lower and upper bound for the increase in alternative modes can be found.

Upper bound

In the upper bound 100% of travellers keep the same zone as their destination, and only switch modes, the method currently used by the V-MRDH model, meaning that 20% of 12.830 will switch to other modes. Model runs have shown that the alternative mode distribution in this case is 45:55 for Bike and Public transit respectively for the city centre. Using this ratio of the 2566 cars that will switch modes 1411 will choose public transport and 1155 will choose for biking.

In Table 17 it can be found that in the baseline 2030 scenario 50994 trips leave the study area by public transportation in the evening rush hour. 1411 more passengers more would mean an maximum increase in passenger of 2.8% leaving the study area by public transportation compared to the BAU scenario.

In Table 18 it can be found that in the baseline 2030 scenario 52837 trips leave the study area by bike in the evening rush hour. 1155 passengers more would mean an maximum trip increase of 2.2% leaving the study area by bike compared to the BAU scenario.

Lower Bound

For the lower bound key figures based on expert experience can be used as found in the literature review in paragraph 2.5.1. According to the Dutch ministry of infrastructure and water management (Ministerie van Infrastructuur en Waterstaat, 2025) when removing a parking space with an existing parking pressure of 95% or greater 60% of motorists will park at a different spot in the same area or in close proximity 20% choses for remote parking and only 20% choses a different mode, or doesn’t make the trip. With exact figures depending on the size of the impacted area. Since motorists are on average only willing to walk about 200 meters for most trip purposes (Van Der Waerden et al., 2015) the study area encompasses an large area the amount of motorists that will park at a different spot in the same area or in close proximity is probably lower than 60%, hence only 20% choosing a different mode will be used as the lower bound. Meaning that the lower bound is can be defined as 1/5 of the upper bound.

Intermediate and ambitious scenario

In the intermediate and ambitious scenario 40% and 60% of the total number of parking spaces are removed respectively compared to the BAU scenario. Since both the upper and lower bound are defined with the only dependent variable being the absolute amount of removed parking spaces, they scale linearly with the absolute removed amount of parking. Combined with the realistic scenario this yields Table 7, the upper and lower bounds of this table are visualised in Figure 18.

Table 7: Effect on alternative modes when parking spaces are removed

	Realistic	Intermediate	Ambitious
Relative amount of parking removed compared to BAU scenario	20%	40%	60%
Absolute amount of parking removed compared to BAU scenario	17819	35638	53457
Upper bound increase in public transportation compared to BAU scenario	2.8%	5.5%	8.3%
Lower bound increase in public transportation compared to BAU scenario	0.6%	1.1%	1.7%
Upper bound increase in bike trips compared to BAU scenario	2.2%	4.4%	6.6%
Lower bound increase in bike trips compared to BAU scenario	0.4%	0.9%	1.3%

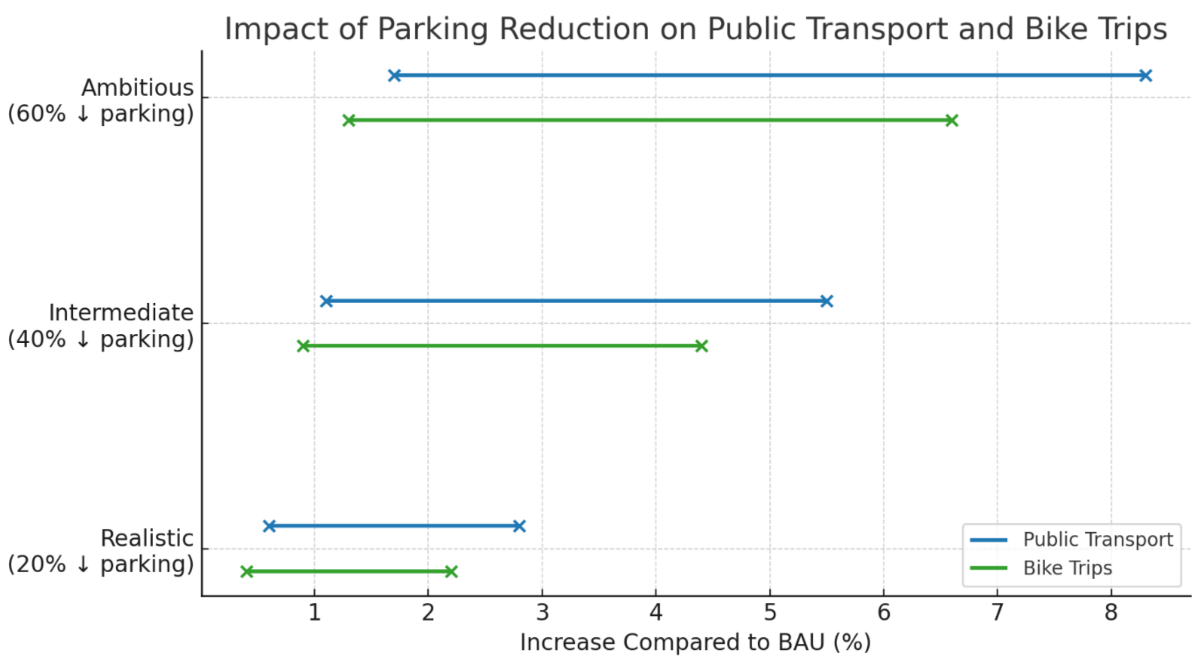


Figure 18: Impact of parking reduction on public transport- and bike trips

4.3 Implications of the results

The previous section estimated the effects of reduced parking spaces on alternative modes of transport. Understanding the impact of these outcomes is crucial for policymakers and engineers to develop appropriate responses. This section quantifies the consequences for the public transportation network of Rotterdam based on these findings. This will be done based on the different levels of operation of the public transportation network (operational, tactical and strategic) in order form the short to the long term.

4.3.1 Operational Level

For the operational level this paragraph examens the impact the influx of former drivers has on the day to day operations of the public transportation network. In the intermediate scenario, the *upper*-bound estimate suggests an increase of 2,822 additional passengers leaving the study area compared to the business-as-usual (BAU) scenario. However these additional passengers are not evenly spread along the peak period between 16:00-18:00, and most people leave work just after 17:00, as can be seen in Figure 19. When only looking at passengers that depart between 16:00-17:59, the same two hour period that the simulation model uses 31.5% departs between 17:00-17:14, also called the peak-of-peak period, a full list of percentages can be found in Table 8.

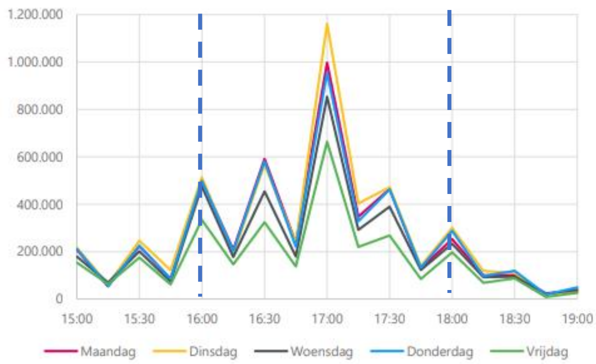


Figure 19: Number of travellers in the evening rush hour from their regular or extern work location (departure time) in 2024 (N=7511). (Goudappel and Ipsos I&O; 2025)

Time	amount	percentage
16:00-16:14	500000	13.4%
16:15-16:29	200000	5.4%
16:30-16:44	600000	16.1%
16:45-16:59	200000	5.4%
17:00-17:14	**1175000**	**31.5%**
17:15-17:29	400000	10.7%
17:30-17:44	475000	12.8%
17:45-17:59	175000	4.7%
Total	3725000	100%

Table 8: Percentage of travellers departing in 15 minute time intervals on Tuesday derived from Figure 19

According to the V-MRDH model, independent the level of intervention the most significant absolute increase in passenger volume occurs between the metro stations Oostplein and Gerdesiaweg, served by metro lines A, B, and C. This section experienced an in the intermediate scenario an average increase of 470 passengers, representing approximately 17% of all trips that switched to public transport.

Given that the evening rush hour in the model spans two hours, this translates to an additional 230 passengers per hour on average between these stations. In the BAU scenario, each metro line (A, B, and C) operates with a frequency of six trains per hour, resulting in a total of 18 metro services per hour. During peak hours, RET typically deploys SG2 rolling stock in a double-unit formation, as shown in Figure 20.

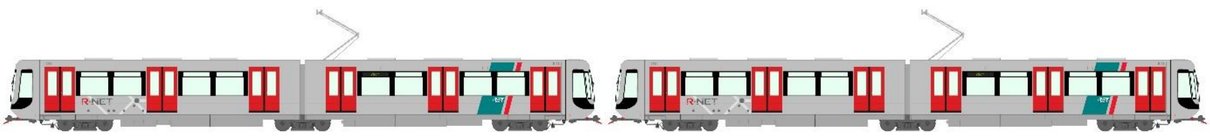


Figure 20: RET - Dubble unit rolling stock SG2 (RET, n.d.)

According to RET (n.d.), a double-unit SG2 train has a seating capacity of 128 and a standing capacity of 306, bringing the total capacity to 434 passengers per train. Assuming a worst-case scenario where metro services are already operating at full capacity in the BAU scenario, accommodating the additional demand from reduced parking spaces would require increasing the frequency of one of the metro lines by one train per hour.

When assuming that the metro has some rest capacity as is the case according to the V-MRDH model, and as supported by data from the RET (2024) (See Table 9), the removal of 40% of the parking spaces in the study area in Rotterdam translates to an *average* increase of 13 passengers per vehicle. Between those stations, or 3% of the lines total capacity on average. In the 15 minute peak-of-peak period this number is increased to 33 additional passengers per metro. In other words in the peak-of-peak period about 7.5% of this lines *total capacity* will be filled with former drivers. Li and Hensher (2013) defines an acceptable peak rate for commuting services as 85-95% of the total capacity, where standing allowance should be treated as an additional component of capacity. and Adding 7.5% to occupancy rates found in Table 9, does exceed the lower bound of this range for metro line B, resulting in 86.5% capacity usage.

Table 9: Occupancy rate, busiest point on line, November 2023, during scaled down service. (RET, 2024)

Mo-th Line	Hour Direction	16:00-17:00	17:00-18:00
A	Schiedam	44%	38%
	Binnenhof	59%	56%
B	H v Holland	78%	52%
	Nesselande	79%	58%
C	De Akkers	64%	52%
	De Terp	62%	46%

Tram

The same calculations can be made for the tram where the biggest increase is between Tiendplein and 1e Middellandstraat. This increase of 94 passengers or 47 per hour is on average divided over the lines 1, 7, and 11. With each a frequency of 4 per hour, for a total of 12 trams per hour between those stations. The rolling stock on these lines is the Citadis II as depicted in Figure 21. Each tram has a capacity of 56 seats and a standing capacity of 124 bringing the total capacity for each vehicle to 180 (RET, n.d.). Again assuming that these lines are already operating at full capacity, the increase could be handled by one more vehicle.

When assuming that this line has some spare capacity, as is the case according to the V-MRDH model. In this scenario the busiest link has a link load of 1679 in the evening rush hour in the defining direction, as can be seen in Figure 35. In the peak-of-peak period this means that 529 passengers travel between those station pairs. With a capacity of 180 per tram and 3 trams in this 15 minute time window the total capacity between those stations in this 15 minute period is 540 passengers. Meaning that in the busiest time the line is at 98% of capacity exceeding the upper recommended limit.

Figure 21: RET - Citadis II Rolling stock (RET, n.d.)

Figure 22: VDL Citea SLF-120E Rolling stock (RET, n.d.)

Bus

Lastly, these calculations can be also be made for the bus. The biggest increase in bus passengers is for BRT line 44 on the section between Dijkzigt and Katendrechtse Lagedijk. In the intermediate scenario this line will see an increase of 41 passengers, or about 21 per hour. With a spits frequency of 8 busses per hour between those stations. The RET operates busses of the type VDL Citea SLF-120E on this line one is shown in Figure 19. This type of bus has 33 seats, and a standing capacity of 47, for a maximum capacity of 80 people (RET, n.d.). again assuming that the line operates at full capacity one more vehicle will suffice, even allowing for all passengers to be seated. According to the model in the intermediate scenario, this line will have an passenger intensity of 1134 in the evening rush hour, as can be seen in figure Figure 36. With an rush hour capacity of 1280. This means that this line has in the intermediate scenario a total rush hour occupation of 89%. Since this exceeds 85%, and the seat occupancy is at

215%. it is recommended that this line will see an increase in frequency, or a switch to a articulated bus. However since each bus will have on average about 3% more passengers more in the intermediate scenario compared to the BAU, this could already be recommended for the BAU scenario.

4.3.2 Tactical level

At the tactical level, the passenger growth resulting from removing parking spaces can be compared to the network's natural expansion. Figure 23 shows RET's passenger numbers, and while the growth rate varies depending on the period examined, the data from 2010–2019 (pre-pandemic) reveals a stable average annual increase of 2.4% (R^2 = 0.975). In an intermediate scenario, the impact from eliminating parking spaces is estimated to fall between 1.1% and 5.5%. Since not all parking spaces will be removed in a single year, this additional growth will be distributed over several years. For instance, if the municipality begins removal immediately and finishes by the forecast year used in the model, 2030, the entire process would span five years. Under the worst-case scenario, this translates to an extra yearly growth of roughly 1.1% per year. Although this increase is notable, it represents an upper bound and remains significantly lower than the extremes observed during the corona pandemic. Consequently, continuing with business as usual at the tactical level should be sufficient to accommodate the expected rise in passengers.

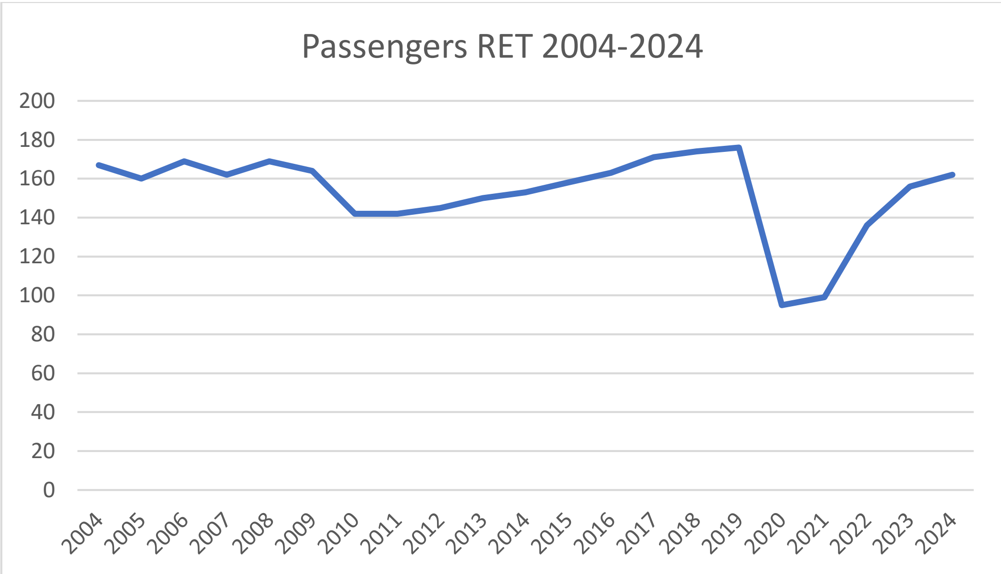


Figure 23: Passenger numbers (in millions) of RET over time. (Combined figures of RET transportation plan, 2008, 2011, 2012, 2013, 2020, 2022, 2025)

4.3.3 Strategic Level

The strategic level, defines the overarching goals, targets, and policies that guide the evolution of public transportation network. Although the intervention scenarios assumed no immediate alterations to the public transportation network—thus leaving this level out of direct outcomes calculations—the literature reveals several broader implications.

Reducing parking spaces should be viewed as one component of a comprehensive package of car-lite measures. When such initiatives are implemented in together—rather than in isolation—they can generate effects that surpass the simple sum of their parts. For instance, integrating parking reductions with improved public transport services, enhanced cycling infrastructure, and pedestrian-friendly urban design can encourage modal shifts more effectively, leading to significant reductions in private car dependency (Hammadou & Papaix, 2015; Abbasi et al., 2023).

A central implication of these measures is the need to maintain, or even improve, overall urban accessibility. As car-lite policies reduce the availability of private vehicle access, it becomes crucial to densify the public transport network, to shorten ingress and egress distances. Expand Park & Ride capacities, to ensure travellers have the option to leave their vehicles outside the city. And to extend the networks reach, to give peripheral areas easy access to the transit network of Rotterdam.

4.3.4 Bike

In the ambitious scenario, bicycle traffic is projected to increase by 6.6% compared to the BAU scenario. The busiest cycle path in Rotterdam is the one leading to Rotterdam Central Station. This 4.25 m-wide two-way cycle path, at its most congested section and in the busiest direction, sees 6,274 bike trips during the evening rush hour—equivalent to 3,137 bicycles per hour. This finding aligns with a 2016 experiment by the Fietsersbond, which identified this as the busiest cycle path in South Holland based on bike counts.

Estimating the capacity of a cycle path is more complex than that of public transportation. However, one study (Seriani et al., 2015) estimated that a 2 m-wide one-way cycle path reaches saturation at 4,657 bicycles per hour. Applying this to the analyzed cycle path, the busiest flow in the ambitious scenario corresponds to approximately 68% of the estimated saturation flow.

A notable discrepancy in the model is that most north-south bike traffic is routed via the Westersingel, whereas in reality, the Municipality of Rotterdam reports that the majority of this traffic uses the Coolsingel (Gemeente Rotterdam, 2020). See Figure 37. These results suggest that improving cycling infrastructure along this route could help distribute north-south bike demand more evenly between the two corridors, potentially alleviating perceived congestion on the Coolsingel.

Moreover, unlike public transportation users, cyclists do not concentrate on a limited number of routes to the same extent. As a result, the overall increase in bicycle demand is distributed across a larger number of links, making the absolute increase in the ambitious scenario relatively small compared to the BAU scenario. Figure 38 illustrates this by highlighting only the links that experience an increase of more than 15 bicycles per hour—revealing that only a handful of links see such growth. Considering that the total increase in bike trips within the study area is 3,465, it is evident that these few links do not account for the majority of the increase.

When combining this observation with Figure 39, which highlights streets experiencing a bike demand increase above the average 6.6%, it becomes clear that while the increase is distributed across the entire network, the highest relative growth is concentrated in the city center. However, in absolute terms, this often amounts to no more than 15 additional bicycles per hour. This is further supported by the fact that over 90% of trips shifting from car to bike have destinations within the Municipality of Rotterdam, as visualized in Figure 17.

Lastly, zooming out the broader implications of this policy, in the ambitious scenario 60% less car trips will have the study area as their destination, according to the CBS (2022) in 2021, 39.1% of all killed cyclists in the Netherlands were killed in a collision with a car, or van. With less cars on the road, the risk of such fatal accidents could be significantly reduced, contributing to improved cyclist safety.

5 Discussion

This study found that for every 20% reduction in car trips produces roughly a maximum 2.3% increase in bike trips and a 3.7% increase in public transportation trips compared to the business-as-usual scenario, since this did not align with existing literature, an alternative method found an increase in the range of 0.6%-2.8% for public transport trips and 0.4-%2.2% for cycling trips, leaving the study area in the evening rush hour. The following sections will explore the implications of these findings, encountered limitations of the study and potential solutions, and suggestions for further research.

5.1 Limitations of using the VMRDH model

This section discusses the implications of the VMRDH model in the context of the study's objectives, as well as its limitations, which may affect the interpretation and generalizability of the results.

5.1.1 Overestimating zones generation potential

Ideally, changes in parking availability would be reflected through adjustments to the zonal data. However, the parking limits are currently incorporated as a redistribution function at the last iteration step (See Figure 9). This approach avoids introducing a feedback loop in which a zone's attractiveness is reduced based on the number of filled parking spaces, which would significantly increase the model's complexity and computation time.

While this method simplifies the model, it also introduces a limitation: a reduction in parking spaces does not influence the destination choice. This assumption is reasonable for minor changes in parking availability, as small reductions are unlikely to lead travellers to choose different destinations. However, for significant decreases in parking spaces, this assumption becomes less realistic. In reality, a reduction in parking spaces would be expected to increase resistance to car travel. Instead, the model predicts a higher-than-expected shift to public transport and cycling for these zones.

One scenario in which these results would be more realistic is if all city centres simultaneously reduced their parking availability. In such a case, differences in car accessibility between cities would be minimized, making the decision to travel primarily a mode-choice problem rather than a destination-choice problem.

During this thesis another way to address this limitation was explored. One could implement the parking ceiling as shown in Figure 24. Instead of introducing a new feedback loop that affects the attractiveness of the zone, the resistance to the zone can be altered, so the existing feedback loop could be reused. In this version of the model the generalised cost function (equation [3.2]) includes a cost component $PL_{j,m,p}$ for an exceeded parking limit of the destination zone j. The modified equation is given in [5.1].

$$C_{i,j,m,p} = L_{i,j,m} * VoD_{i,j,m,p} + R_{i,j,m} * VoT_{m,p} + P_{j,m} + PL_{j,m,p} \qquad [5.1]$$

In each full model iteration, the total demand for zone j is compared to the parking limit. When the demand exceeds the parking limit, a cost $PL_{j,m,p}$ that grows with a to be determined function (e.g. linear, logarithmically) based on the exceeded amount is added to the generalised costs for car travel ($m = car$). This component $PL_{j,m,p}$ could be dependent on the purpose p of travel, where for example, business trips are less sensitive to high parking pressure than shopping trips, but this is optional.

An exploratory a code was written to test this modified method with the model. One test was performed with a $PL_{j,m,p} = \ln{(exceeded\ amount)}$. A natural logarithm was chosen as function to prevent feedback driven oscillation between simulation runs. This resulted in promising results as can be seen in Figure 41 in Appendix J, with zones outside the study area actually becoming busier as a result of the removed parking spaces in the study area, but still an overall decrease in car trips.

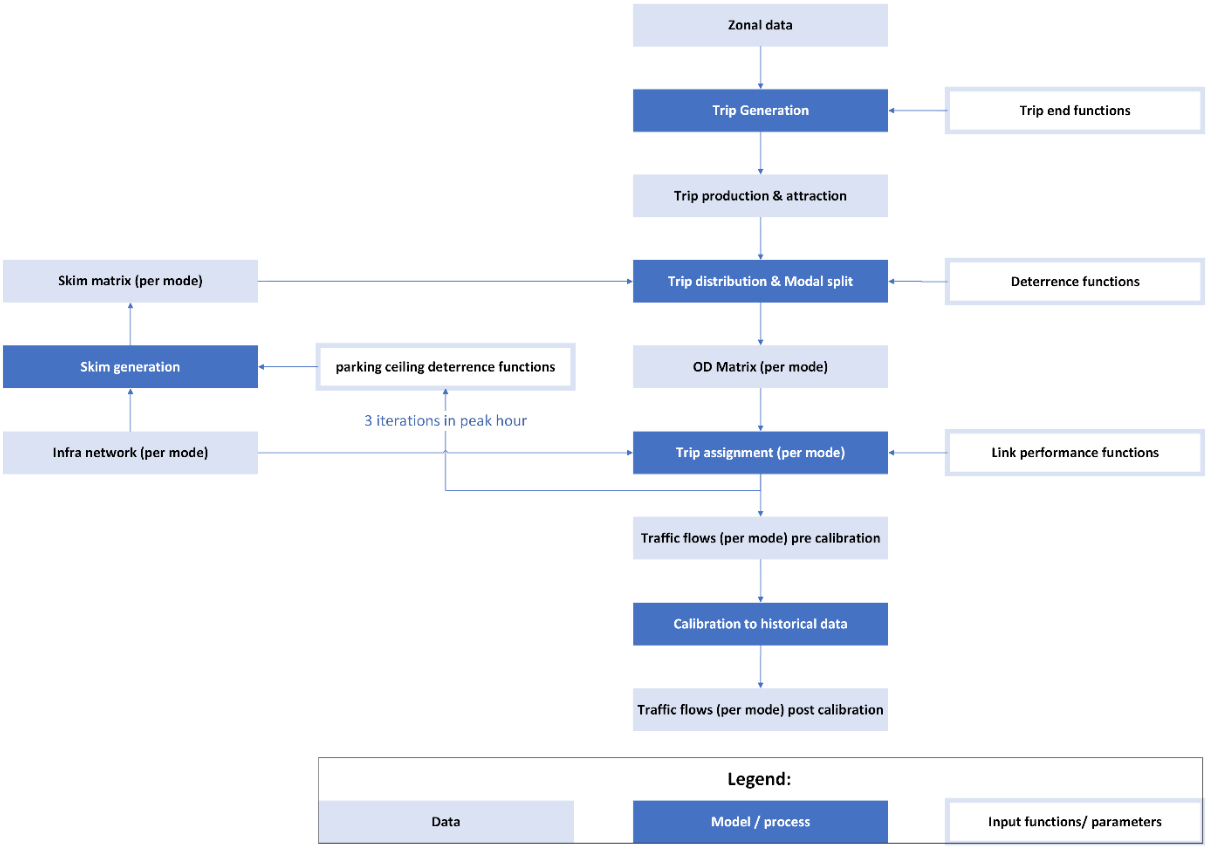


Figure 24: Altered framework V-MRDH model where the parking ceiling is incorporated in the feedback loop.

Procedure 1: Add Extra Resistance for Exceeding Parking Limit

```
IF iteration > 1 (only when there is a previous iteration) THEN
  - Open the OtSkimCube and OtMatrixCube
  - Retrieve the car matrix from the previous iteration for the specific time period
  - Define a factor for different travel purposes (work, shopping, education, other)
  FOR EACH parking_limit_zone (zoneArray, timeHash) DO
    - Get the parking ceiling limit for the specific time period
    - Calculate the total inflow and outflow to/from the parking zone based on the previous iteration
    IF total inflow > parking ceiling limit THEN
      - Calculate the difference (how much the limit is exceeded)
      FOR EACH travel purpose (work, shopping, education, other) DO
        - Retrieve the skim value from the current iteration
        - Add extra resistance for all trips to the parking zone based on a function
        - Ensure intra-zonal resistance in the study area and external area is set very high
        - Save the modified skim
      END FOR
    END IF
    // IF total outflow > parking ceiling limit THEN
      // The user should adjust car ownership settings in the parking zone based on the new policy
    // END IF
  END FOR
END IF
```

Using this method, zones that exceed the parking limit become more expensive to travel to by car than other zones. As a natural consequence, in the next iteration, some travellers will either choose a different zone to travel to by car or opt for a different mode of transport. If equilibrium is not reached after three full model iterations, the amount of iterations currently used by the model, the original method using redistribution within the zone can still be applied to redistribute the excess car users based on the lowest generalized cost to that zone for other modes, to strictly adhere to the maximum parking limit.

By incorporating this modified method, the model ensures that destination choice is also considered when the demand exceeds the parking limit. This improvement better reflects real-world behaviour, where a reduction in parking availability influences not only mode choice but also destination selection.

5.1.2 Incompatibility with park and ride.

Another limitation of the current model is its incompatibility with the park and ride (P&R) module of the model. When the amount of parking spaces in the city centre decreases significantly one would expect that some drivers going to the city park their car outside of the city at a P&R facility and continue their journey by public transportation. The P&R- and the parking limit modules are currently both incorporated in the model, as separate modules, and they do not interact with each other.

The implication of this approach is that the amount P&R journeys between scenarios stays the same, potentially underestimating the amount of P&R journeys to the city centre. The impact on the performed research is however considered to be limited since most P&R facilities where already near capacity in 2016 as shown in Figure 25 (Gemeente Rotterdam, 2016). This is consistent with the BAU scenario where the same or higher occupancy rates were found, suggesting that even with increased demand due to reduced city centre parking, the potential for additional P&R journeys was inherently limited. However it is recommended that when removing parking spaces in the city these facilities are extended to accommodate for this growth to keep the city centre accessible for former drivers.

Further studies are needed that extend the capacity of the P&R facilities to see the effect of removed parking spaces in the centre on the P&R use, however this is not possible with the current model. But with the suggested modification to the model in paragraph 5.1.1 where parking limits become an integral part of the model, the generalized cost function would automatically account for parking shortages, indirectly influencing the attractiveness of park and ride options. Making these kinds of studies a possibility, and overall improving the realism of the model.

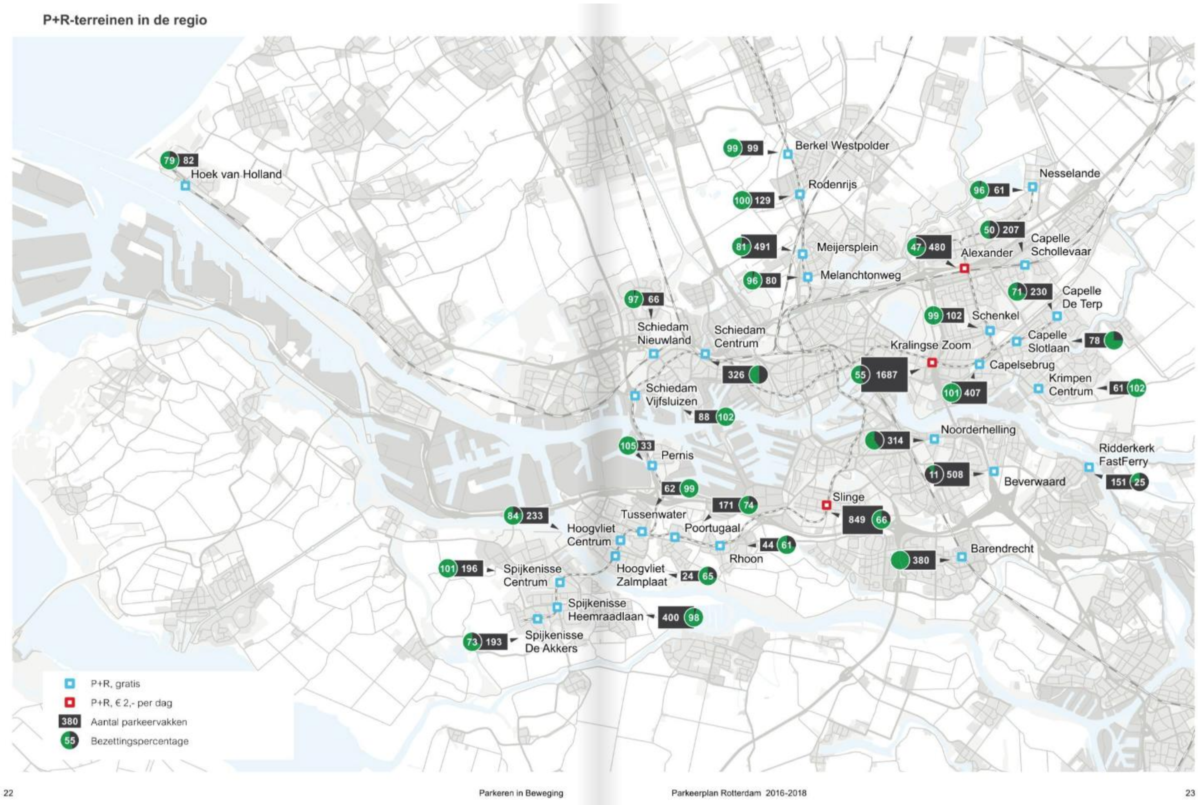


Figure 25: Occupancy rates park and ride facilities Rotterdam (Gemeente Rotterdam, 2016)

5.2 Interpretation of Modal Shift Magnitudes

Although the observed increases in cycling and public transportation usage following parking space reductions may appear relatively modest at first glance, with a maximum upper bound of a 8.3% public transportation increase following a 60% parking capacity reduction, it is important to consider these findings within the context of the business-as-usual (BAU) scenario. In this baseline, the 2030 urban reference scenario is used. In this scenario travel behaviour already reflects a shift toward sustainable mobility, influenced by existing (plans for) urban policies that actively discourage car use—such as a reduction of the speed limit from 50km/h to 30km/h, the redevelopment of streets to give more space to bicyclists and pedestrians—and simultaneously encourage active and public transportation through better connectivity and relative higher speeds. (Gemeente Rotterdam, 2020; Goudappel 2023)

As such, the BAU scenario represents a city in transition, where a portion of the potential modal shift has already occurred prior to any additional intervention. The effect of further policy measures, such as large-scale parking reductions, is therefore superimposed on an environment where sustainable travel choices are already partially embedded in behaviour. This partially explains why the modelled increases in alternative modes are incremental rather than dramatic.

Moreover, it is important to recognize that the reported modal shift percentages refer specifically to trips *departing* from the study area, rather than to all car trips occurring *within* the study area. Since the study area encompasses mostly the city centre—where car use is already relatively low due to high parking fees and better access to alternative modes—the proportion of car users in this group is smaller to begin with. This means that even a 60% reduction in car trips to the study area represents only 4233 trips in the evening rush hour. Through-traffic on arterial roads that pass through the study area without ending there are not directly affected by the parking space reduction scenarios. As such, the car trips that are impacted most strongly are those targeting the central residential and mixed-use streets—areas where parking availability directly influences travel behaviour. The reduction scenarios apply most significantly to local access traffic, not to car flows that merely traverse the area.

5.3 Generalizability of the research

This study introduced a method to find the city wide effects on the alternative modes and presented findings based on a Case Study, but their applicability to different contexts depends on various factors. This section discusses the extent to which the method and results can be generalized beyond the Rotterdam as starting point for further research.

5.3.1 Generalizability of the methodology

The generalizability of the results depends on the assumptions underlying the research methodology. The selection of Rotterdam as a case study assumes that its characteristics, such as relatively high car usage, its current parking policy, and a political willingness to reduce car use, are representative of other cities facing similar urban mobility challenges. However, differences in urban form, public transport availability, and local policy frameworks may limit the direct applicability of the findings to other contexts.

Study area Boundaries

From the literature review, it became clear that a mixed, dense urban environment is a precondition to support other car free initiatives, such as parking policy interventions. The method to define the boundaries of the study area assumes that given a certain amount of density, the selected area will be mixed use as a consequence. While this is the case in many (northern) European cities, this is not necessarily always true, and must be checked beforehand. The quantification of density is based on a urbanisation score that relies on population and workspaces data, that is not necessarily always available for cities outside of the Netherlands.

Secondly the urbanization score based on inhabitants and working spaces within cycling distance—relies on assumptions that may not fully capture the complexity of urban forms in different contexts. For instance, local variations in land use and accessibility might affect the score's accuracy, limiting the generalizability of the findings.

Despite these limitations, the significance of the results lies in their potential to inform urban planning and policy-making. By quantifying urban density and linking it to car-lite measures, this study offers a practical framework for identifying areas where parking space reductions can be most effectively implemented.

While this method was based on existing literature (e.g. Jorritsma et al., 2023), it advances the discussion by combining this literature with a quantifiable metric to identify areas suitable for the introduction of new car-lite measures such as the removal of parking spaces. Which offers a more objective basis for higher-level decision making.

Further research could focus on making this method more comprehensive, by including the level of function mixing, and robustness of the areas active mode network, to make the method suitable for identifying area's in cities that do not have these in all parts of the city.

In conclusion, the area selection can be used for other similar sized cities in the Netherlands, such as Amsterdam, The Hague or Utrecht, and can be used in an international context, given that the city is mixed use, has an existing active mode network, and the necessary data is available.

Use of simulation models

The selection of a simulation model to answer the research question was not location dependent and therefor it is expected that in all other cases, a simulation model will be the most suitable choice to answer the research question in a other context. However, there must be a multi-modal static macroscopic demand model that can simulate route choice and limit parking spaces, with the network of the city available.

Scenario definition

The definition of the scenarios can be generalized to other contexts, where the exact percentage of reduction will be dependent on the current amount of parking spaces available and the expected growth in parking spaces.

In conclusion, the methodology provides a structured approach that can be applied to cities with similar characteristics, the extent to which the specific results of this study hold in other contexts depends on variations in urban structure, mobility behaviour, and policy environments. The following section discusses how these factors influence the generalizability of the findings

5.3.2 Generalizability of the results

As mentioned in the previous paragraph the generalizability of the results depends on the assumptions underlying the research methodology. Where the case study selection, study area boundaries, and the use of simulation models all influenced the results.

Redistribution of former car users

One key finding, that former car users split their mode of transport in the city centre as 45% biking and 55% public transport, or 60% biking and 40% public transport in surrounding neighbourhoods (as shown in Figure 14), is highly location-specific. And therefore must even be specified differently for different parts of the study area. From equation [*3.2*], it can be concluded that this distribution is primarily determined by the relative ease of traveling by public transport versus by bike, with travel time and cost being the main factors. These components are influenced by a variety of elements, such as the frequency and density of the public transport network, and for bicycles, the availability and quality of separate bike infrastructure, as well as its connectivity. In most cities outside the Netherlands it is expected that the split of would be more skewed towards public transportation, since the bicycle infrastructure is less developed. For research outside the context of Rotterdam this distribution must be estimated for the specific context.

Estimation based on parking data

Although the calculations based on the parking data are highly specific to the context of Rotterdam, some valuable insights can be applied to other settings. Section 4.2.3 established an upper and lower bound for the number of car users who are expected to switch to alternative modes of transport when parking availability decreases. The lower bound was defined as one-fifth of the upper bound. The two primary factors influencing where the actual outcome falls within this range are the size of the area where parking spaces are removed and the percentage decrease in parking spaces.

Larger areas where parking is reduced tend to lead to a lower likelihood of users parking in nearby zones, thereby affecting the number of people who switch to other modes. Similarly, a greater reduction in parking spaces in the same area is likely to lead to a higher proportion of people shifting to alternative modes of transport, as the capacity to park in adjacent zones becomes a limiting factor. This means that the scale and extent of parking restrictions play a role in determining the outcome, even if the exact figures are context-dependent. Where large zones with large reductions are more likely to fall at the higher end of the calculated range and small zones where only a few parking spaces are removed fall at the lower end of the range.

5.4 The Impact of space reallocation.

To address the research question, the previous chapter primarily focused on the removal of parking spaces. However, as emphasized in both the introduction and the literature review, in car-lite cities, reducing the number of cars through parking space removal is not the ultimate goal but rather a means to achieving a more liveable urban environment. This section takes a broader perspective and briefly discusses the wider impact of this measure on the city.

To begin with, the term "removal of parking spaces" may not be entirely accurate. These spaces are not simply lost but rather repurposed for alternative uses. Therefore in further research and stakeholder communication, "parking space reallocation" is a more suitable term for this policy.

In the realistic scenario, a total of 17,819 parking spaces will be reallocated for other purposes. Given that the average size of a parking space in the Netherlands is 12 square meters (Zijlstra et al., 2022), this policy would free up approximately 213,828 square meters in Rotterdam. To put this into perspective, this equates to an area of 29 soccer fields, all of which can be repurposed to create a more liveable city.

The On-street parking especially in the densest most mixed parts of the city can be reused for bicycle parking, areas for loading and unloading, and terraces. In more residential areas these areas can be reused for bicycle parking, more greenery, and even playgrounds (See Figure 26 for examples). Surface parking lots can be reused for new housing developments. In combination with an abandonment of the minimum parking norms, as is done in the car-lite areas of for example in for example Amsterdam (Gemeente Amsterdam, 2020) or even with a maximum parking norm of zero as is done in the car-lite plus area of Delft (Gemeente Delft, 2024), these developments can be built affordably and can include more dwellings per area. Without the need for underground parking areas.

Figure 26a: Examples of reallocated parking spaces

Figure 26b: Examples of reallocated parking spaces

5.4.1 The negative impact on (new) residents

The reallocation of parking spaces in combination with lower parking norms can also lead to unintended consequences. With fewer parking spaces available fair distribution becomes an issue, and parking experts say that in many cases, available parking is assigned primarily to larger or more expensive homes, leaving residents of smaller or more affordable units without a parking option. (Van de Reijt, 2024)

This imbalance can result in increased parking pressure in surrounding areas, as residents without an allocated space seek alternatives (Antonson et al., 2017). If municipalities enforce parking regulations that exclude these residents from obtaining permits, they may be left without any viable parking options. This can disproportionately impact lower-income households, limiting their mobility choices and potentially forcing them to give up car ownership altogether. Although this can be also seen as the desired outcome, depending on the distribution of income groups in the area, where this is a lesser problem in more homogeneous areas.

To address this issue, a strategy package needs to be developed to ensure a long term solution. This controversial problem can require controversial solutions to ensure equity between income groups. These solutions can include car-Lite neighbourhoods with only shared cars, parking permits that scale with income, or a parking lottery for residential permits. However, further research is needed to explore optimal strategies for parking space allocation in car-lite developments.

5.4.2 The negative impact on visitors

The reduction of parking spaces can have several negative consequences for visitors, affecting accessibility, convenience, and overall experience. Studies have shown that fewer parking spaces lead to longer search times for available spots, increased walking distances, and greater frustration among visitors. Traditional studies such as the one form Meyer and McShane (1983) found that restricted parking access in downtown areas often limits accessibility, particularly for those who rely on private vehicles, such as individuals with mobility impairments. Similarly, Banerjee et al. (2003) highlighted that the frustration caused by inadequate parking can discourage repeat visits, and hurt local businesses, however this is later disproven by Mingardo en Van Meerkerk (2012), that claim that there is, at least for the case of the Netherlands, no statistical significant relationship between the amount of parking spaces and the attractiveness of a shopping area. Lastly, Antonson et al. (2017) noted that reduced parking supply can create spillover effects, pushing visitors to park in nearby residential areas, leading to conflicts with local residents and increased congestion.

However, other research challenges these concerns by emphasizing the potential long-term benefits of reducing parking availability. Traditionally, Shoup (1997) suggested that excessive parking, rather than its reduction, contributes to traffic congestion and economic inefficiencies. Chester et al. (2015) similarly found that cities that replaced parking spaces with pedestrian-friendly infrastructure ultimately experienced improved accessibility and higher visitor satisfaction. Additionally, Marsden (2006) argued that parking reductions can improve urban accessibility by decreasing congestion and encouraging the use of public transportation and active mobility options, such as walking and cycling.

Other studies suggest that reducing parking does not necessarily decrease accessibility or economic activity in the long run. Kirschner and Lanzendorf (2019) found that initial visitor dissatisfaction tends to diminish as improved pedestrian infrastructure and efficient transit options become available. Furthermore, Antonson et al. (2017) suggested that when parking reductions are paired with strategic public transportation investments, accessibility concerns are minimized.

Ultimately, while the removal of parking spaces may create short-term difficulties for visitors, research suggests that a well-planned transition toward sustainable mobility solutions can mitigate these issues and ultimately improve urban accessibility and visitor experience. Combining this with the outcome of this thesis, which suggest that in the short term, there are no significant capacity concerns for biking or public transportation when parking spaces are removed in Rotterdam, it can be concluded that this issue should be addressed at a strategic level rather than through operational or tactical measures.

6 Conclusion

This thesis investigated the effect that the reduction of parking spaces has on the alternative modes in the city. By combining the outcome of simulation models with existing literature these effects could be estimated for the case study city of Rotterdam. The effect on the use of the alternative modes was found by comparing the outcome of three intervention scenarios to the 2030 Business as usual (BAU) scenario. The three intervention scenarios, realistic, intermediate, and ambitious, where defined from a scenario were the municipality stops building parking spaces right now, to one where the study area becomes car-lite by common definition. This chapter concludes this research by first answering the research questions, followed by recommendations for future research.

6.1 Answers to the research questions

To answer the main research question of this thesis the four sub-questions are answered first.

a. Which specific areas in a city are most suitable to reduce parking spaces?

The literature review revealed that before car-lite measures, such as the reduction of parking spaces, can be implemented, three key preconditions must be met.

First, the area must be *dense, and mixed-use*. When shops and amenities are located close to residential areas, trips become shorter. Shorter trips increase the feasibility of active modes such as walking and cycling as alternatives to driving. Additionally, a dense urban environment results in higher passenger flows, making public transport operations more viable and cost-effective. Moreover, in a dense environment the positive effects of less cars are shared by the most people.

Second, *a strong active mobility network* must be in place. If safe and convenient infrastructure for walking and cycling is lacking, people remain dependent on cars, even for short trips.

These preconditions were integrated into the case study selection process. A city was chosen that already features a well-developed active mobility network and mixed-use developments. To further quantify urban density, an urbanization score was introduced. This score calculates density based on the number of inhabitants and workplaces within cycling distance. If the score exceeds a certain threshold, the area is classified as highly urbanized, making it a suitable area for parking space reduction.

Further research could focus on making this method more comprehensive, by including the level of function mixing, and robustness of the areas active mode network, to make the method suitable for identifying area's in cities that do not have these in all parts of the city.

b. What is the effect of the reduction in parking spaces on the demand for cycling?

Depending on the level of intervention and the underlying assumptions, this thesis found an increase in bike trips ranging from 0.4-6.6% compared to the BAU scenario. Although these numbers seem conservative, they are compared to the BAU scenario in which people are already more inclined, to use public transportation and biking. This is in line with the current plans of the municipality of Rotterdam for a city that focuses on more active mobility and public transportation (Gemeente Rotterdam, 2020). In the ambitious scenario, the absolute increase in bike trips was 3465, but since parking spaces where removed all across the study area there was limited bundling of cyclists, meaning that only a handful of routes saw an absolute increase of more than 15 cyclists per hour. Routes that saw percentage increase higher than the average 6.6% where almost entirely located within the study area, indicating that it were mostly trips with their destination within the municipality of Rotterdam that switched modes. This was supported by the origin destination matrixes where >90% of former drivers that switched to cycling had their destination within the municipality of Rotterdam. This indicates that this car-lite policy shifts mainly short distance car trips towards cycling. Another broader implication is that because in the ambitious scenario 60% less car tips have the study area as their destination, cycling becomes more pleasant and safer overall.

c. What is the effect of the reduction in parking spaces on the demand for public transportation?

Depending on the level of intervention and the underlying assumptions, this thesis found an increase in public transportation trips ranging from 0.6% to 8.3% compared to the BAU scenario. These numbers seem again conservative but must be again put in the perspective of the BAU scenario. In the intermediate scenario, that saw a 40% decrease in car trips, the maximum increase in public transportation trips was 5.5%. Even if public transportation were already operating at full capacity in the BAU scenario, the analysis showed that the additional demand—across buses, trams, and metro services on the busiest sections— is 3% of the total section capacity and could easily be accommodated by adding just one extra vehicle per line. However, this thesis also found that adding this vehicle is not required for metro and tram since even with the maximum increase in the intermediate scenario, the spare capacity could accommodate the increase in demand, without exceeding 85% threshold in the peak hour. The busiest bus-line (44) had a peak hour intensity of 89% and thus exceeded the threshold, but this was already the case in the BAU scenario, nevertheless research into a potential capacity increase for bus line 44 is recommended.

From a passenger perspective, passengers that switched from car to public transportation, mostly originated inside of the MRDH (70%), and that for the network of Rotterdam a majority (55%) of switched users chose for public transportation.

The effect that the influx of former drivers has, as a result of a reduction in parking spaces, is for the case of Rotterdam not disruptive, even when assuming high conversion rates towards public transportation. It is expected that continuing with normal operational- and tactical planning, will suffice, especially when these parking spaces are removed over a larger timeframe. For the strategic level it is however advisable to focus on expending infrastructure, to ensure the general accessibility of the city when this measure is implemented as part of a car-lite policy package.

d. How does the public transportation supply need to react to the change in demand?

The analysis demonstrated that the maximum expected modal shift from private car to public transport—triggered by a 40 % reduction in parking supply in the study area—can be accommodated without fundamentally overhauling Rotterdam's network. At the operational level, the key pressure point is not the full two-hour peak period, but the 15-minute peak-of-peak window between 17:00 and 17:14, during which over 30% of the additional demand is concentrated. During this interval, metro lines A, B, and C between Oostplein and Gerdesiaweg see an average of 33 additional passengers per train, equating to about 7.5% of total capacity per vehicle. This pushes line B's occupancy to 86.5%. For the tram corridor between Tiendplein and 1e Middellandstraat, occupancy rises to 98% of available capacity during the same 15-minute period, while BRT line 44 surpasses 100% of its capacity.

These findings imply that the issue is not the average hourly volume, but rather the extreme concentration of demand during a short, intense peak-of-peak period. To address this, public transport supply could be strategically increased only during this quarter-hour—by deploying an additional vehicle or reallocating capacity from slightly less busy intervals, if extra vehicles are not available. By fine-tuning service to this critical window, the network can absorb the demand shock without requiring broad, permanent increases in frequency or major investments.

Over the tactical horizon, the induced demand equates to roughly a 1.1 % per-year increase over a five year period—or about 50% of RET's historic 2.4 % annual growth rate (2010–2019). By incorporating this incremental rise into existing vehicle procurement and schedule-expansion plans, RET can maintain rolling stock availability, without necessitating extraordinary capital projects beyond business-as-usual.

Finally, at the strategic level, specific car-lite strategies such as parking-space removal must be incorporated within broader car-lite strategic planning. For public transportation this means, network densification in high-demand areas, extension of Park & Ride facilities, and expansion of the network to its peripheral areas. Only by coupling demand-management measures (parking reductions) with supply-side enhancements (service quality, coverage, and connectivity) can Rotterdam secure a lasting modal shift, reduce private-car dependency, and achieve its long-term sustainability objectives.

Main research question: How does the large scale reduction of parking spaces affect the demand of alternative modes?

This thesis investigated how a large-scale reduction of parking spaces affects the demand for alternative modes of transport. By analysing three intervention scenarios, ranging from a realistic reduction to an ambitious car-lite strategy, this research quantified the modal shift towards cycling and public transport in the city of Rotterdam.

The findings indicate that reducing parking spaces leads to a measurable increase in the use of alternative modes, with cycling trips increasing by up to 6.6% and public transport trips by up to 8.3%. The shift towards cycling predominantly affected short-distance trips within the municipality of Rotterdam, whereas the increase in public transport demand remained manageable within existing capacity limits during most of the rush hour, but showed potential overcrowding during the peak-of-peak period. Therefor this thesis recommends analysing the impact on this critical time window during the planning of car-lite strategies.

Furthermore, the results suggest that the overall impact of a parking space reduction as a single standalone measure in an already ambitious baseline scenario, is non-disruptive for the transport system, especially when implemented over a longer time frame. The policy primarily encourages local trips to transition to cycling and ensures that public transport remains a viable alternative without requiring immediate large-scale capacity expansions. In the long term it is however available to invest in the expansion of the public transportation infrastructure, to ensure general accessibility, especially when the reduction of parking spaces is part of a car-lite measures package.

In conclusion, the large-scale reduction of parking spaces effectively promotes the use of alternative modes, particularly for shorter trips, contributing to a shift towards a more sustainable urban mobility system. However, careful planning is necessary to ensure that areas with high public transport demand remain well-served and that cycling infrastructure supports the increased usage.

6.2 Recommendations

The findings of this thesis highlight the potential of parking space reductions to encourage a shift towards alternative modes of transport. While the results indicate that both cycling and public transport usage increase following such interventions, several aspects need further exploration.

At the beginning of the research, traffic simulation with the V-MRDH model was deemed sufficient to answer the main research question, however when analysing the outcomes of the model it was found that these did not match with the general expectations and the existing literature. Therefor it is for further research not recommended to use this version of the model to simulate the outcomes of a reduction in parking spaces. This thesis further recommended a change in the model structure to better reflect real world interactions and choices.

Secondly although this thesis introduces a method for defining the optimal zone for the implementation of car-lite measures, it is currently limited to cities that are known to have a great active modes network and plenty of function mixing. Further research could focus on incorporating these two indicators in the quantification method, to make the method encompassing for all cities. Besides identifying the best parts of the city this method could then also be used to identify parts of the city that are lacking behind, and need to be improved in terms of function mixing or infrastructure before car-lite measures become feasible.

Besides providing health benefits, reducing environmental pollution, and improving the general quality of live, reducing the available amount of parking spaces can have negative consequences for (new) residents of the intervention area. With traditional solutions the remaining available parking spaces are often assigned to people who can afford them most, widening mobility poverty between income groups. To address this further research is needed to explore optimal strategies for parking space allocation in car-lite developments.

Lastly, as demonstrated in this thesis, the removal of parking spaces in Rotterdam does pose short-term challenges for the peak-of-peak public transportation demand. Besides, other short-term challenges, such as increased search times for residents and visitor frustration may arise, but evidence suggests that in the long-term improved pedestrian infrastructure and public transportation can mitigate these effects. Therefor it is recommended that before and after the reduction of parking spaces, the public transportation planning should be approached on the strategical level, focusing on long-term mobility solutions.

7 Bibliography

Abbasi, M., Mamdoohi, A. R., & Arndt, W. (2023). Modal shift behavior of car users to light rail transit, some evidence from the field. Transactions On Transport Sciences, 14(1), 24–29. https://doi.org/10.5507/tots.2022.021

Albalate, D., & Gragera, A. (2020). The impact of curbside parking regulations on car ownership. Regional Science And Urban Economics, 81, 103518. https://doi.org/10.1016/j.regsciurbeco.2020.103518

Antonson, H., Hrelja, R., & Henriksson, P. (2017). People and parking requirements: Residential attitudes and day-to-day consequences of a land use policy shift towards sustainable mobility. Land Use Policy, 62, 213–222. https://doi.org/10.1016/j.landusepol.2016.12.022

Bakker, N. (2017). Verkeer in beeld #03 - jun 2017. In *Verkeer in Beeld*. https://www.mobiliteitsplatform.nl/sites/default/files/LukthetopdeCoolsingel%2Cdanlukthetoveral.pdf

Banerjee & Associates. (2003). *An Overview of Common Parking Issues, Parking Management Options, and Creative Solutions*. https://ccdcboise.com/wp-content/uploads/2016/02/Parking-Problems-and-Creative-Solutions.pdf

Boogaard, H., Patton, A., Atkinson, R., Brook, J., Chang, H., Crouse, D., Fussell, J., Hoek, G., Hoffmann, B., Kappeler, R., Joss, M. K., Ondras, M., Sagiv, S., Samoli, E., Shaikh, R., Smargiassi, A., Szpiro, A., Van Vliet, E., Vienneau, D., . . . Forastiere, F. (2022). Long-term exposure to traffic-related air pollution and selected health outcomes: A systematic review and meta-analysis. *Environment International*, *164*, 107262. https://doi.org/10.1016/j.envint.2022.107262

Calvert, S., Minderhoud, M., Taale, H., Wilmink, I., Knoop, V. L., & TrafficQuest. (2015). *Traffic assignment and simulation models: State-of-the-Art Background Document* (pp. 2–40) [Report; PDF]. TrafficQuest. https://traffic-quest.nl/wp-content/uploads/2015/12/2.3_traffic_assignment_simulation_models_background_report_v1.0.pdf

Caulfield, B. (2011). An examination of the factors that impact upon multiple vehicle ownership: The case of Dublin, Ireland. *Transport Policy*, *19*(1), 132–138. https://doi.org/10.1016/j.tranpol.2011.08.003

CBS StatLine. (2016). Motorvoertuigen van particulieren; wijken en buurten [Dataset]. https://opendata.cbs.nl/#/CBS/nl/dataset/83603NED/table

Centraal bureau voor de statistiek. (2019). *Personenmobiliteit; reiskenmerken en vervoerwijzen, regio's, 2010-2017* [Dataset; Digitaal]. https://opendata.cbs.nl/#/CBS/nl/dataset/83498NED/table?dl=9A01

Centraal Bureau voor de Statistiek. (2022, September 15). Meer fietsdoden na eenzijdige ongevallen. *Centraal Bureau Voor De Statistiek*. https://www.cbs.nl/nl-nl/nieuws/2022/37/meer-fietsdoden-na-eenzijdige-ongevallen

Centraal Bureau voor de Statistiek [CBS]. (2024). *Kerncijfers Wijken en buurten 2024* [Dataset]. https://opendata.cbs.nl/#/CBS/nl/dataset/85984NED/table

Centraal Planbureau voor de Leefomgeving. (2015). *Welvaart en Leefomgeving 2015*. Geraadpleegd op 26 november 2024, van https://www.wlo2015.nl/

Chaniotakis, E., & Pel, A. J. (2015). Drivers' parking location choice under uncertain parking availability and search times: A stated preference experiment. *Transportation Research Part A Policy And Practice*, *82*, 228–239. https://doi.org/10.1016/j.tra.2015.10.004

Chester, M., Fraser, A., Matute, J., Flower, C., & Pendyala, R. (2015). Parking Infrastructure: A Constraint on or Opportunity for Urban Redevelopment? A Study of Los Angeles County Parking Supply and Growth. *Journal Of The American Planning Association*, *81*(4), 268–286. https://doi.org/10.1080/01944363.2015.1092879

Christiansen, P., Fearnley, N., Hanssen, J. U., & Skollerud, K. (2017). Household parking facilities: relationship to travel behaviour and car ownership. *Transportation Research Procedia*, *25*, 4185–4195. https://doi.org/10.1016/j.trpro.2017.05.366

CROW. (2017). *Parkeren en gedrag: Een totaaloverzicht van alle relevante kennis op het gebied van parkeren en gedrag*. https://www.retailinsiders.nl/docs/eac281ea-36ba-4658-8d38-66257e46ee91.pdf

CROW. (2024, 27 maart). *Amsterdam schrapt in 4 jaar ruim 7000 parkeerplekken*. Parkeren. https://www.kennisnetwerkparkeren.nl/nieuws/915-amsterdam-schrapt-in-4-jaar-ruim-7000-parkeerplekken

De Jong, A., Te Riele, S., Huisman, C., Van Duin, C., Husby, T., & Stoeldraijer, L. (2022). Regionale bevolkings- en huishoudensprognose 2022–2050: Steden en randgemeenten groeien verder. In *PBL/CBS*. Centraal Bureau voor de Statistiek. https://www.pbl.nl/sites/default/files/downloads/pbl-cbs-2022-regionale-bevolkingsprognose-2022-2050-4977.pdf

De Las Heras-Rosas, C., & Herrera, J. (2019). Towards Sustainable Mobility through a Change in Values. Evidence in 12 European Countries. Sustainability (Basel), 11(16), 4274. https://doi.org/10.3390/su11164274

De Romph, E., & Cellissen, R. (2022). Verkeersmodellen vergeleken. In *Bijdrage Aan Het Colloquium Vervoersplanologisch Speurwerk*. https://www.cvs-congres.nl/e2/site/cvs/custom/site/upload/file/paper_search/2022/cvs_103_verkeersmodellen_vergeleken_1_2022.pdf

Dembski, S., Sykes, O., Couch, C., Desjardins, X., Evers, D., Osterhage, F., Siedentop, S., & Zimmermann, K. (2019). Reurbanisation and suburbia in Northwest Europe: A comparative perspective on spatial trends and policy approaches. *Progress in Planning*, *150*, 100462. https://doi.org/10.1016/j.progress.2019.100462

Evans, R. J., Burke, M. I., & Dodson, J. (2007). Clothing the Emperor?: Transport modelling and decision-making in Australian cities. ResearchGate. https://www.researchgate.net/publication/29465763_Clothing_the_Emperor_Transport_modelling_and_decision-making_in_Australian_cities

Farber, S., & Páez, A. (2011). Running to stay in place: the time-use implications of automobile oriented land-use and travel. Journal Of Transport Geography, 19(4), 782–793. https://doi.org/10.1016/j.jtrangeo.2010.09.008

Fosgerau, M., Łukawska, M., Paulsen, M., & Rasmussen, T. K. (2023). Bikeability and the induced demand for cycling. *Proceedings Of The National Academy Of Sciences*, *120*(16). https://doi.org/10.1073/pnas.2220515120

Gemeente Amsterdam. (2019). *Agenda Amsterdam Autoluw*. https://openresearch.amsterdam/image/2019/11/28/amsterdam_autoluw_agenda.pdf

Gemeente Amsterdam. (2020). Nota parkeernormen auto. In *Nota Parkeernormen Auto*. https://openresearch.amsterdam/image/2020/6/3/nota_parkeernormen_auto.pdf

Gemeente Amsterdam. (2023). *Verplaatsingen per persoon van/naar/binnen Amsterdam naar vervoerswijze per weekdag, 2013-2023* [Dataset]. https://onderzoek.amsterdam.nl/dataset/mobiliteit-in-amsterdam

Gemeente Amsterdam. (2024, February 12). *Onderzoeksrapport - Pilot knip Weesperstraat*. Openresearch.Amsterdam. https://openresearch.amsterdam/nl/page/105378/onderzoeksrapport---pilot-knip-weesperstraat

Gemeente Delft. (2024, 26 januari). *Beleidsregels parkeernormen Delft 2023*. Lokale Wet- en Regelgeving. https://lokaleregelgeving.overheid.nl/CVDR714401/1

Gemeente Den Haag. (2021). *Nota Parkeernormen Den Haag 2021*. https://denhaag.raadsinformatie.nl/document/10512188/3?connection_type=17&connection_id=7608287

Gemeente Rotterdam. (2016). *Parkeerplan Rotterdam 2016-2018*.

Gemeente Rotterdam. (2020). *Rotterdamse mobiliteits aanpak*. Geraadpleegd op 25 maart 2024, van https://www.rotterdam.nl/mobiliteitsaanpak

Gemeente Rotterdam. (2022, 1 januari). *Beleidsregeling Parkeernormen auto en fiets gemeente Rotterdam 2022*. Lokale Wet- en Regelgeving. https://lokaleregelgeving.overheid.nl/CVDR671029/1

Golias, J., Yannis, G., & Harvatis, M. (2002). Off-Street parking choice sensitivity. *Transportation Planning And Technology*, *25*(4), 333–348. https://doi.org/10.1080/0308106022000019620

Goudappel B.V., Schoorlemmer, S., De Vries, F., Witte, L., & Van Der Toorn, J. (2023). Verkeersmodel V-MRDH 3.0: Technische Rapportage.

Goudappel, Ipsos I&O, Stemerding, M., Van Essen, M., Litjens, T., Groenhuis, S., & Wolf, B. (2025). Landelijk Reizigersonderzoek 2024. In *Ministerie van Infrastructuur en Waterstaat*. https://open.overheid.nl/documenten/2bab9bb1-5a00-4182-93da-7c1e76a737e2/file

Guo, Z. (2012). Does residential parking supply affect household car ownership? The case of New York City. *Journal Of Transport Geography*, *26*, 18–28. https://doi.org/10.1016/j.jtrangeo.2012.08.006

Hammadou, H., & Papaix, C. (2015). Policy packages for modal shift and CO2 reduction in Lille, France. *Transportation Research Part D Transport And Environment*, *38*, 105–116. https://doi.org/10.1016/j.trd.2015.04.008

Harbers, A., Van Amsterdam, H., Spoon, M., & PBL Planbureau voor de Leefomgeving. (2024). Ruimtelijke dichtheden en functiemenging in Nederland [Book]. In *PBL* (Vol. 2). PBL Planbureau voor de Leefomgeving. https://www.pbl.nl/system/files/document/2024-09/pbl-2024-rudifun-5305.pdf (Oorspronkelijk gepubliceerd 2024)

Harrison, R. M., Allan, J., Carruthers, D., Heal, M. R., Lewis, A. C., Marner, B., Murrells, T., & Williams, A. (2021). Non-exhaust vehicle emissions of particulate matter and VOC from road traffic: A review. *Atmospheric Environment*, *262*, 118592. https://doi.org/10.1016/j.atmosenv.2021.118592

Hegewald, J., Schubert, M., Freiberg, A., Starke, K. R., Augustin, F., Riedel-Heller, S. G., Zeeb, H., & Seidler, A. (2020). Traffic Noise and Mental Health: A Systematic Review and Meta-Analysis. *International Journal Of Environmental Research And Public Health*, *17*(17), 6175. https://doi.org/10.3390/ijerph17176175

HEI . (2010). *Traffic-Related Air Pollution: A Critical Review of the Literature on*. https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health

Higgins, T. J. (1992). Parking taxes: Effectiveness, legality and implementation, some general considerations. *Transportation*, *19*(3), 221–230. https://doi.org/10.1007/bf01099978

Hymel, K. (2019). If you build it, they will drive: Measuring induced demand for vehicle travel in urban areas. *Transport Policy*, *76*, 57–66. https://doi.org/10.1016/j.tranpol.2018.12.006

Høynes, Rebecca & Kolltveit, Lars & Rydningen, Ulf. (2022). Oslo 2019 A car free city centre. WIT Transactions on Ecology and the Environment. 226. 3-16.

Iseki, H. (2016). Equity in Regional Public Transit Finance: Tradeoffs between Social and Geographic Equity. *Journal Of Urban Planning And Development*, *142*(4). https://doi.org/10.1061/(asce)up.1943-5444.0000328

Jonson, J. E., Borken-Kleefeld, J., Simpson, D., Nyíri, A., Posch, M., & Heyes, C. (2017). Impact of excess NO x emissions from diesel cars on air quality, public health and eutrophication in Europe. *Environmental Research Letters*, *12*(9), 094017. https://doi.org/10.1088/1748-9326/aa8850

Jorritsma, P., Witte, J., Alonso-Gonzáles, M. & Hamersma, M. (2021). Deelauto- en deelfietsmobiliteit in Nederland; Ontwikkelingen, effecten en potentie. Den Haag: Kennisinstituut voor Mobiliteitsbeleid.

Jorritsma, P., Arendsen, K., & Faber, R. (2023). Autoluw beleid gemeenten: Doelen, effecten en rollen. In Kennisinstituut Voor Mobiliteitsbeleid.

Kennisinstituut voor Mobiliteitsbeleid, Kansen, M., Van Der Waard, J., & Savelberg, F. (2018). Sturen in parkeren. In *Kennisinstituut voor Mobiliteitsbeleid*. https://sv10.acquire.nl/static/files/tinymce/uploads/Sturen+in+parkeren.pdf

Kirschner, F., & Lanzendorf, M. (2019). Parking management for promoting sustainable transport in urban neighbourhoods. A review of existing policies and challenges from a German perspective. *Transport Reviews*, *40*(1), 54–75. https://doi.org/10.1080/01441647.2019.1666929

Kirschner, F., & Lanzendorf, M. (2020). Support for innovative on-street parking policies: empirical evidence from an urban neighborhood. *Journal of Transport Geography*, *85*, 102726. https://doi.org/10.1016/j.jtrangeo.2020.102726

Lambe, B., Murphy, N., & Bauman, A. (2017). Smarter Travel, car restriction and reticence: Understanding the process in Ireland's active travel towns. *Case Studies on Transport Policy*, *5*(2), 208–214. https://doi.org/10.1016/j.cstp.2017.02.003

Li, Z., & Hensher, D. (2013). Crowding in Public Transport: A Review of Objective and Subjective Measures. *Journal Of Public Transportation*, *16*(2), 107–134. https://doi.org/10.5038/2375-0901.16.2.6

Mackett, RL; Brown, B; (2011) Transport, Physical Activity and Health: Present knowledge and the way ahead. Centre for Transport Studies, University College London: London, UK. https://discovery.ucl.ac.uk/id/eprint/1333502/

Marchant, N. (2020, 7 december). Paris halves street parking and asks residents what they want to do with the space. *World Economic Forum*. https://www.weforum.org/stories/2020/12/paris-parking-spaces-greenery-cities/

Marsden, G. (2006). The evidence base for parking policies—a review. *Transport Policy*, *13*(6), 447–457. https://doi.org/10.1016/j.tranpol.2006.05.009

McAslan, D., & Sprei, F. (2023). Minimum parking requirements and car ownership: An analysis of Swedish municipalities. *Transport Policy*, *135*, 45–58. https://doi.org/10.1016/j.tranpol.2023.03.003

McAskie, L. (2021, 18 januari). *How Oslo Hit Reverse On Its City Street Parking and Revived City Life – and How Your City Can Too*. CityChangers.org – Home Base For Urban Shapers. Geraadpleegd op 11 november 2024, van https://citychangers.org/how-oslo-hit-reverse-on-its-city-street-parking/

Melia, S., Parkhurst, G., & Barton, H. (2011). Carfree, low-car - what's the difference. *World Transport Policy & Transport*, *16*, 24–28. Retrieved from https://uwe-repository.worktribe.com/output/970345

Melia, S. (2014). Carfree and Low-Car Development. In *Transport and sustainability* (pp. 213–233). https://doi.org/10.1108/s2044-994120140000005012

Metropoolregio Rotterdam Den Haag. (2024). *V-MRDH 3.0.2*. MRDH. Geraadpleegd op 26 november 2024, van https://mrdh.nl/verkeersmodel

Mingardo, G., & Van Meerkerk, J. (2012). Is parking supply related to turnover of shopping areas? The case of the Netherlands. *Journal Of Retailing And Consumer Services*, *19*(2), 195–201. https://doi.org/10.1016/j.jretconser.2011.12.001

Mingardo, G., Vermeulen, S., & Bornioli, A. (2022). Parking pricing strategies and behaviour: Evidence from the Netherlands. *Transportation Research Part A Policy And Practice*, *157*, 185–197. https://doi.org/10.1016/j.tra.2022.01.005

Ministerie van Infrastructuur en Waterstaat. (2025, January 2). *Factsheet: Parkeerbeleid*. https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/werkwijzen/werkwijze-in-gww/communicatie-bij-werkzaamheden/werkwijzer-hinderaanpak/toolbox-slim-reizen/factsheet-parkeerbeleid#vuistregels

Mohri, S. S., Mortazavi, S., & Nassir, N. (2021). A clustering method for measuring accessibility and equity in public transportation service: Case study of Melbourne. *Sustainable Cities And Society*, *74*, 103241. https://doi.org/10.1016/j.scs.2021.103241

Nieuwenhuijsen, M., Bastiaanssen, J., Sersli, S., Waygood, E. O. D., & Khreis, H. (2018). Implementing Car-Free Cities: Rationale, Requirements, Barriers and Facilitators. In *Springer eBooks* (pp. 199–219). https://doi.org/10.1007/978-3-319-74983-9_11

Nieuwenhuijsen, M. J., Khreis, H., Verlinghieri, E., & Rojas-Rueda, D. (2016). Transport and health: a marriage of convenience or an absolute necessity. *Environment International*, *88*, 150–152. https://doi.org/10.1016/j.envint.2015.12.030

Not Just Bikes. (2020, 24 augustus). *Rotterdam: the City Rebuilt for Cars* [Video]. YouTube. https://www.youtube.com/watch?v=22ovt1EMULY

Papadimitriou, E. (2024). *Thematic Report Main factors causing fatal crashes*. European commission.

Peters, A. (2020, 30 januari). Here are 11 more cities that have joined the car-free revolution: From Amsterdam to Tempe, Arizona, more and more cities are finding that eliminating cars from their streets makes people happier and healthier. fastcompany.com. Geraadpleegd op 3 april 2024, van https://www.fastcompany.com/90456075/here-are-11-more-neighborhoods-that-have-joined-the-car-free-revolution

Pont, M. B., & Haupt, P. (2023). *Spacematrix: Space, Density and Urban Form*. https://doi.org/10.59490/mg.38

RET. (z.d.). *RET - materiaal informatie*. https://corporate.ret.nl/over-ret/materieel/

Rye, T., Burns, J., Whitefield, A., Oxley-Glenister, K., & Pinkard, J. (2023, 1 oktober). *Reducing car use through parking policies: an evidence review*. https://era.ed.ac.uk/handle/1842/41037

Rye, T., Tully, S., Godin, G., Schmalholz, N. and Hertel, M., 2022. Parking and SUMP. Using parking management to achieve SUMP objectives effectively and sustainably. European Platform on Sustainable Urban Mobility Plans.

Seriani, S., Fernandez, R., & Hermosilla, E. (2015). Experimental Study for Estimating Capacity of Cycle Lanes. *Transportation Research Procedia*, *8*, 192–203. https://doi.org/10.1016/j.trpro.2015.06.054

Shoup, D. C. (1997). *The High Cost of Free Parking*. https://escholarship.org/content/qt4vz087cc/qt4vz087cc.pdf?t=lpmcp0

Snelder, M., & Vonk Noordegraaf, D. (2022). Review LMS/NRM. In *TNO-rapport* (Report TNO 2022 R10341; pp. 3–40). TNO. https://open.rijkswaterstaat.nl/publish/pages/139330/review_lms_nrm.pdf

Sprei, F., Hult, C., Hult, Å., & Roth, A. (2020). Review of the Effects of Developments with Low Parking Requirements. *Sustainability*, *12*(5), 1744. https://doi.org/10.3390/su12051744

Stansfeld, S., Clark, C., Smuk, M., Gallacher, J., & Babisch, W. (2021). Road traffic noise, noise sensitivity, noise annoyance, psychological and physical health and mortality. *Environmental Health*, *20*(1). https://doi.org/10.1186/s12940-021-00720-3

The Brussels Times. (2019, 19 augustus). Geraadpleegd op 7 november 2024, van https://www.brusselstimes.com/63432/brussels-to-scrap-65000-on-street-parking-spots

Turnheim, B. (2023). The historical dismantling of tramways as a case of destabilisation and phase-out of established system. Proceedings Of The National Academy Of Sciences Of The United States Of America, 120(47). https://doi.org/10.1073/pnas.2206227120

United Nations. (2013). *Review of developments in transport in Asia and the Pacific*. https://unescap.org/publications/review-developments-transport-asia-and-pacific-2013

Van Dijken, K., IOO bv, Berdowski, Z., Desczka, S., Dykstra, M., Mosselman, M., Van Der Valk, P., & Willemsen, S. (2002). *Parkeren in Nederland* (Door Adviesdienst Verkeer en Vervoer; S. J. Zwartjes, C. Harteveld, J. H. T. Kramer, A. Van Luipen, C. J. Brouwer, B. Sönmez, & T. De Wit, Reds.) [Report]. IOO bv. https://vexpan.nl/wp-content/uploads/2023/07/adoc.pub_parkeren-in-nederland.pdf

Van de Reijt, A. (2024, 3 mei). *Passende parkeernormen leiden tot een nieuwe uitdaging*. Vexpan. Geraadpleegd op 4 maart 2025, van https://vexpan.nl/artikelen/passende-parkeernormen-leiden-tot-een-nieuwe-uitdaging/

Van der Loo, J. B. (2024). *The influence of parking on car ownership* [Master thesis, TU Delft]. https://resolver.tudelft.nl/uuid:1d813f68-6d28-4446-8a39-c1b5f44fee9d

Van der Tuin, M., De Romph, E., & Pieters, M. (2021). *Grip op parkeercapaciteiten – modelaanpak en data-analyse*.

Van Der Waerden, P., Timmermans, H., & De Bruin-Verhoeven, M. (2015). Car drivers' characteristics and the maximum walking distance between parking facility and final destination. *Journal Of Transport And Land Use*, *10*(1). https://doi.org/10.5198/jtlu.2017.568

Van Leeuwen, N., & Venema, J. (2022, 5 april). *Statistische gegevens per vierkant 2021-2020-2019*. Centraal Bureau Voor de Statistiek. Geraadpleegd op 17 september 2024, van https://www.cbs.nl/nl-nl/longread/diversen/2022/statistische-gegevens-per-vierkant-2021-2020-2019?onepage=true

Vervoerregio Amsterdam. (2023). Concessieverlening Amsterdam 2025: Concessieverleningsstrategie. In *amsterdam.raadsinformatie.nl* (INT/2023/12515). Geraadpleegd op 3 maart 2024, van https://amsterdam.raadsinformatie.nl/document/12887215/1/Bijlage_-_Concept_Concessieverleningsstrategie_Amsterdam_2025

Wegener, Michael & Fuerst, Franz. (2004). Land-Use Transport Interaction: State of the Art. SSRN Electronic Journal. 10.2139/ssrn.1434678.

Wener, R. E., & Evans, G. W. (2006). A morning stroll. *Environment And Behavior*, *39*(1), 62–74. https://doi.org/10.1177/0013916506295571

Welch, D., Shepherd, D., McBride, D., Dirks, K., & Marsh, S. (2013). Road traffic noise and health-related quality of life: A cross-sectional study. *Noise And Health*, *15*(65), 224. https://doi.org/10.4103/1463-1741.113513

World Health Organization: WHO. (2023, 13 december). *Road traffic injuries*. https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries#:~:text=Overview,with%20many%20incurring%20a%20disability.

Yan, X., Levine, J., & Marans, R. (2018). The effectiveness of parking policies to reduce parking demand pressure and car use. *Transport Policy*, *73*, 41–50. https://doi.org/10.1016/j.tranpol.2018.10.009

Yin, C., Shao, C., & Wang, X. (2018). Built Environment and Parking Availability: Impacts on Car Ownership and Use. *Sustainability*, *10*(7), 2285. https://doi.org/10.3390/su10072285

Zijlstra, T., Witte, J., & Bakker, S. (2022). De maatschappelijke effecten van het wijdverbreide autobezit in Nederland. In KiM. Geraadpleegd op 28 oktober 2024, van https://www.kimnet.nl/publicaties/publicaties/2022/02/22/het-wijdverbreide-autobezit-in-nederland

Appendix A: New parking ceilings for each scenario

Scenario 1	Centrum	Delfshaven	Noord	Kralingen Oost	Feyenoord
Moring rush hour	0	4486	2154	1628	5095
Rest Day	0	30714	14894	10909	30026
Evening rush hour	0	4961	2514	1784	4675

Scenario 0.8	Centrum	Delfshaven	Noord	Kralingen Oost	Feyenoord
Moring rush hour	1398	4777	2585	1900	5786
Rest Day	7865	32709	17873	12728	34097
Evening rush hour	1271	5283	3017	2082	5308

Scenario 0.6	Centrum	Delfshaven	Noord	Kralingen oost	Feyenoord
Moring rush hour	2795	5010	3016	2172	6477
Rest Day	15730	34305	20852	14546	38168
Evening rush hour	2542	5541	3520	2379	5942

Scenario 0.4	Centrum	Delfshaven	Noord	Kralingen oost	Feyenoord
Moring rush hour	4193	5302	3447	2473	7254
Rest Day	23596	36299	23831	16566	42748
Evening rush hour	3813	5863	4023	2709	6655

Scenario 0.2	Centrum	Delfshaven	Noord	Kralingen oost	Feyenoord
Moring rush hour	5590	5535	3878	2745	7945
Rest Day	31461	37895	26810	18385	46820
Evening rush hour	5084	6121	4526	3007	7289

Appendix B: Other methods for determining the urbanisation level

Besides the method by Studio bereikbaar given in section 3.3, there were other methods considered for determining the urbanisation level. Ultimately these where not used in this thesis, but could be used for other research.

Method by CBS

This method by the CBS, obtains an urbanisation code for each region using the average address density of that region. The CBS defines the address density as the number of addresses within a circle with a radius of one kilometre around that point divided by the area of the circle. These address densities are then divided in five categories where each category has approximately the same number of inhabitants. These categories are defined in Table 10.

Table 10: Urbanization classification by CBS

Urbanization code	Urbanization class	Addresses per sq. km
CBS-5	Very Highly Urban	>2500
CBS-4	Highly Urban	1500-2500
CBS-3	Moderately Urban	1000-1500
CBS-2	Little Urban	500-1000
CBS-1	Not Urban	<500

Using this classification method it is expected that suburbs of big cities are classified the same as the inner core of the cities because the method uses the same number of inhabitants in each class for the whole of the Netherlands, and since less than 20% of the population of the Netherlands is living in the dense city centres they do not deserve their own category. A visual representation of this method for the city of Rotterdam is found in Figure 27.

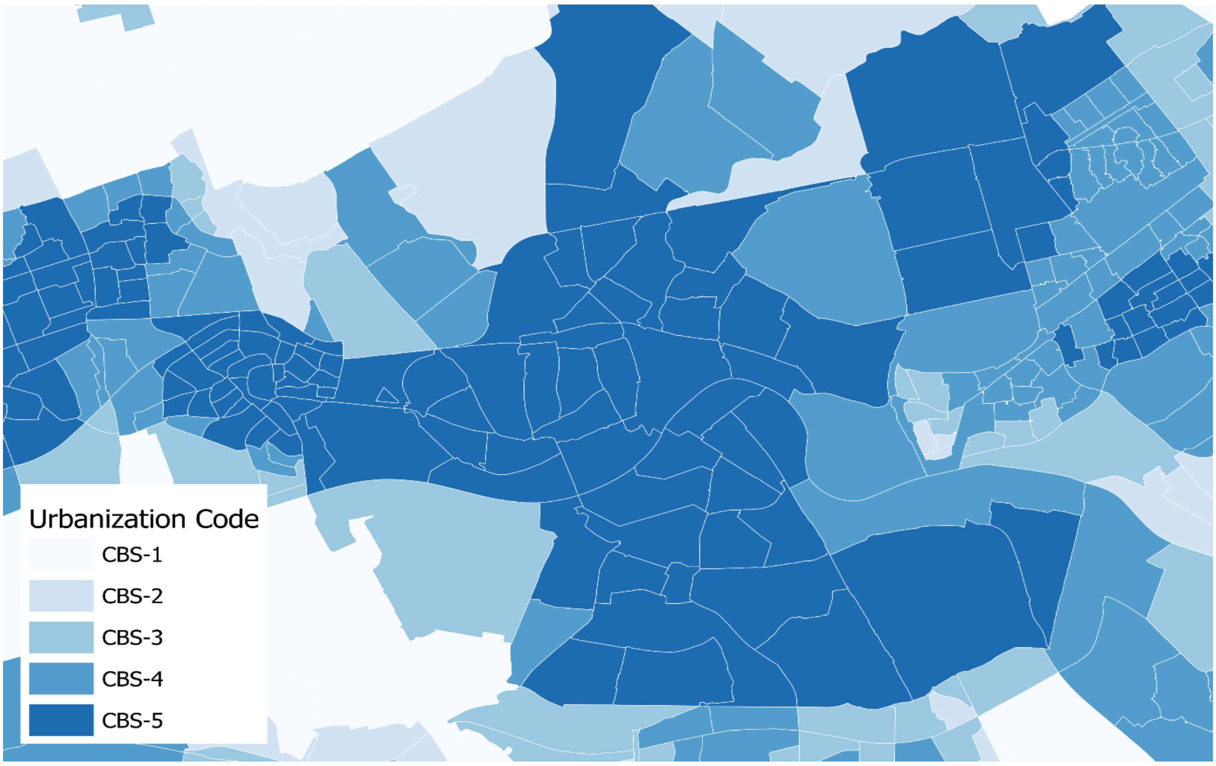


Figure 27: Visualisation for Rotterdam with method by CBS

To account for this issue a new higher class can be introduced with at least 5000 addresses per sq. kilometre, as can be found in Figure 28. Now the city centre has its own category but this method is still not ideal to accurately reflect the space demand of the area. Areas around parks or bodies of water that have limited space don't get the highest urbanisation class, and big shopping malls, which have a lot of addresses, but is not the target area for car-low policies do get the highest class. Therefore, in combination with the existence of a better method, there was chosen to not use this method in this thesis.

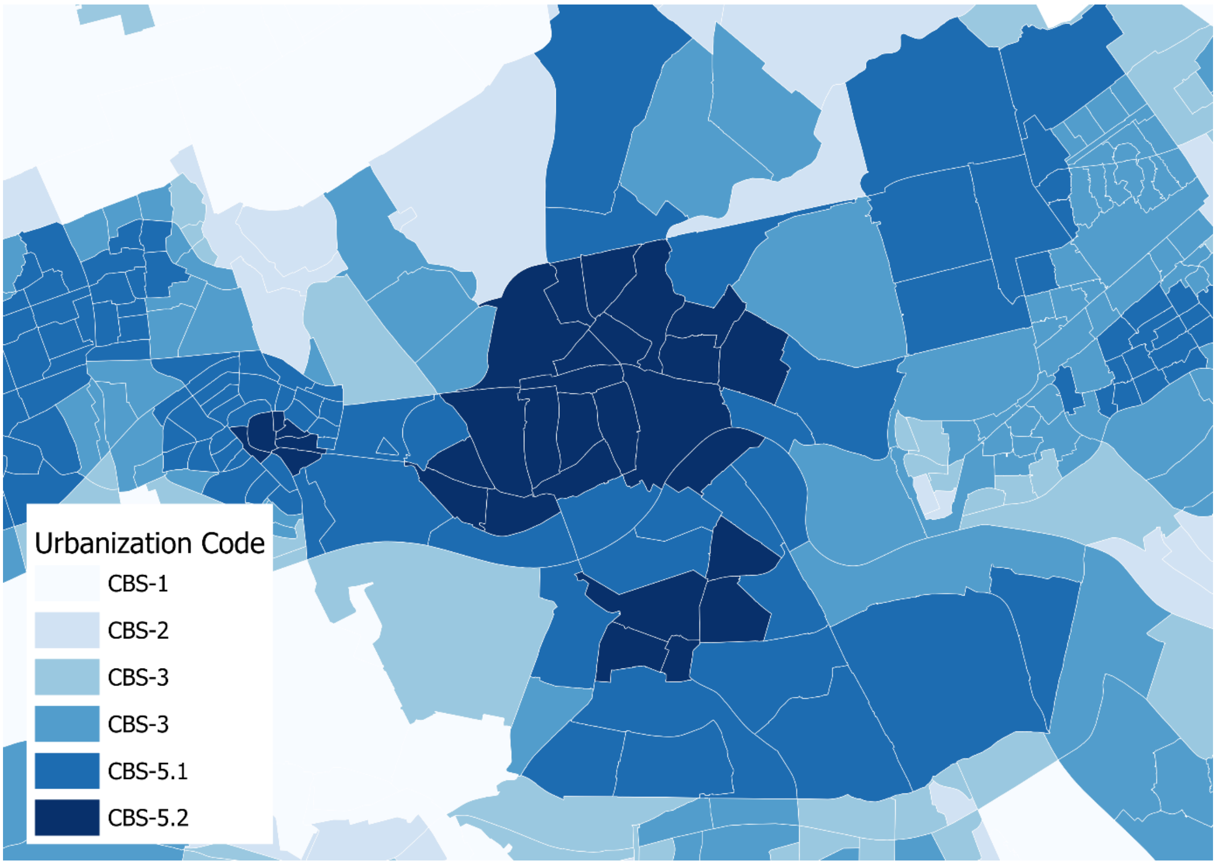


Figure 28: Urbanization classification on the basis of modified CBS. with threshold value for 5.2 > 5000 addresses per sq. km.

Method by PVL

Recognizing the problem that with the address density method the size of an address can vary widely and thus gives skewed results in some regions, the Planbureau voor de Leefomgeving (PVL) created the RUDIFUN dataset with several spatial density indicators to classify and assess urbanized areas in the Netherlands. Key among these indicators is the Floor Space Index (FSI), which is calculated by dividing the total floor area of buildings by the land area they occupy. This measure reflects the built density of an area, with higher FSI values indicating denser, often more urbanized, regions. (Harbers et al., 2024).

The PVL approach, is valuable in studies focused on high-density urban areas, where walkability and accessibility are critical factors. This makes it applicable for urban planning assessments, as it offers a structured, measurable way to assess and compare density levels. And is calculated using formula B.1.

$$FSI = \frac{gross\ floorarea}{site\ area} \quad [B.1]$$

When using the threshold values found in Table 11, Appling it to the Rotterdam region the Figure 29 is obtained. The Threshold values were chosen based on the work by Pont en Haupt (2023, p. 124, fig. 13) where all mid and high rise is clustered into one category. And a category with (almost) no buildings was added.

Table 11: Urbanisation classification using FSI and threshold values by Pont en Haupt (2023)

Urbanization code	Urbanization class	Floor Space Index
PLV-6	High/mid-rise strip/block type	>1.20
PLV-5	Low-rise block type	0.90-1.20
PVL-4	Hybrid low-rise strip/block type	0.60-0.90
PLV-3	Low-rise strip type	0.40-0.60
PLV-2	Low-rise point type	0.05-0.40
PLV-1	Field / Forest / Park	<0.05

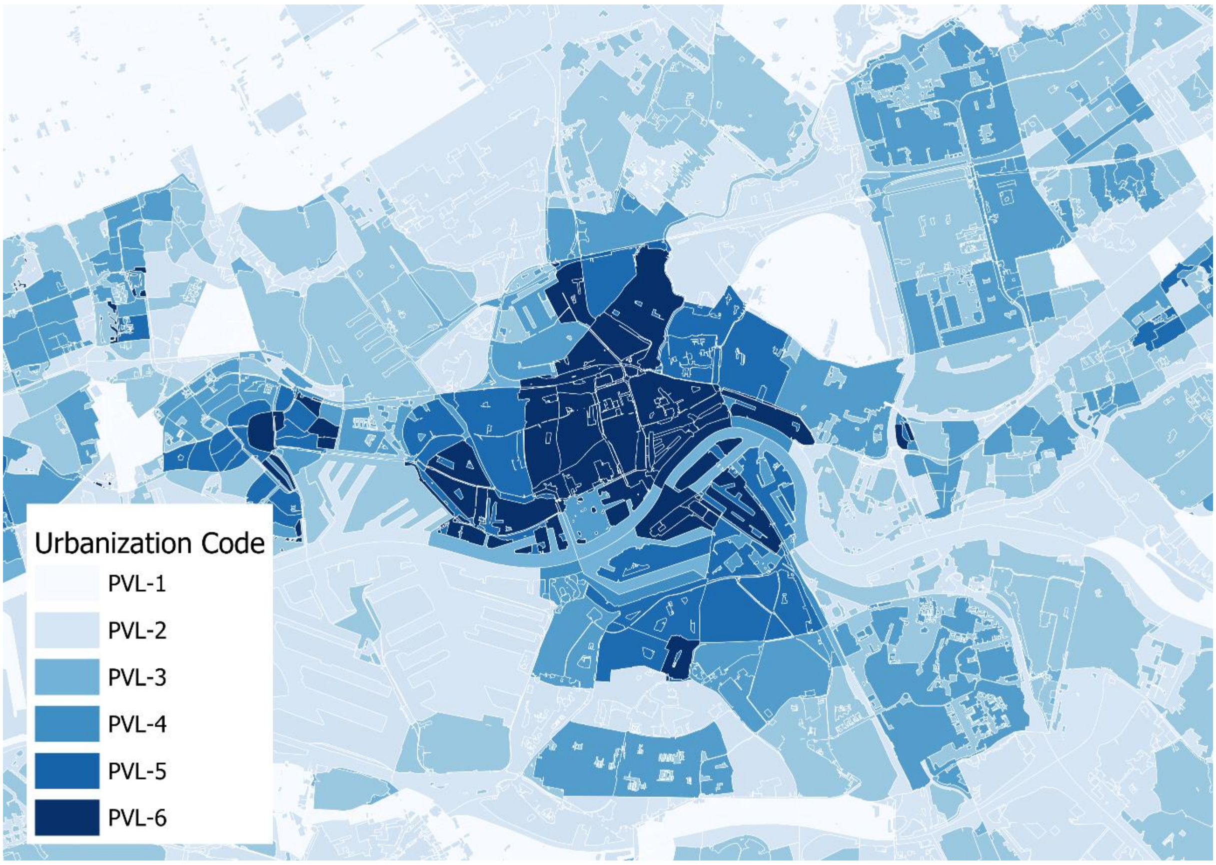
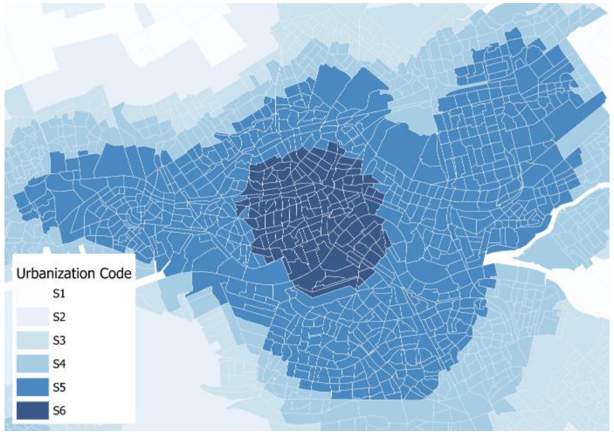


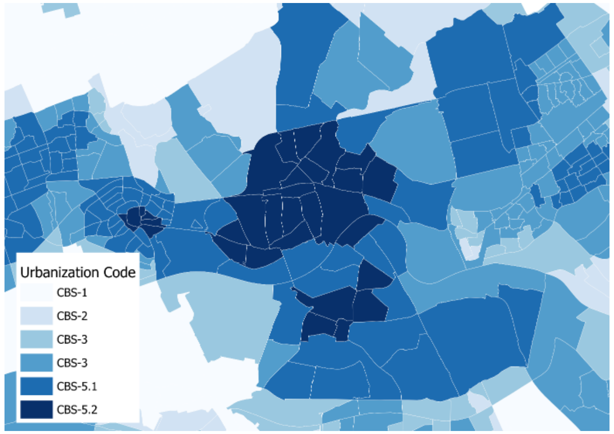
Figure 29: Visualisation Urbanization classification using FSI

However, despite its strengths, this method is not used in this thesis. While it gives a better indication of the urban density then the method by the CBS, the PVL classification does not fully capture the intensity of use of the area. Instead, the population and workspaces approach using Studio Bereikbaar's methodology provides the necessary focus relevant to this research.

Overview of results for Rotterdam with the different methods



Studio Bereikbaar



Centraal bureau voor de statastiek

Plan bureau voor de leefomgeving

Appendix C: Matrix compression zones

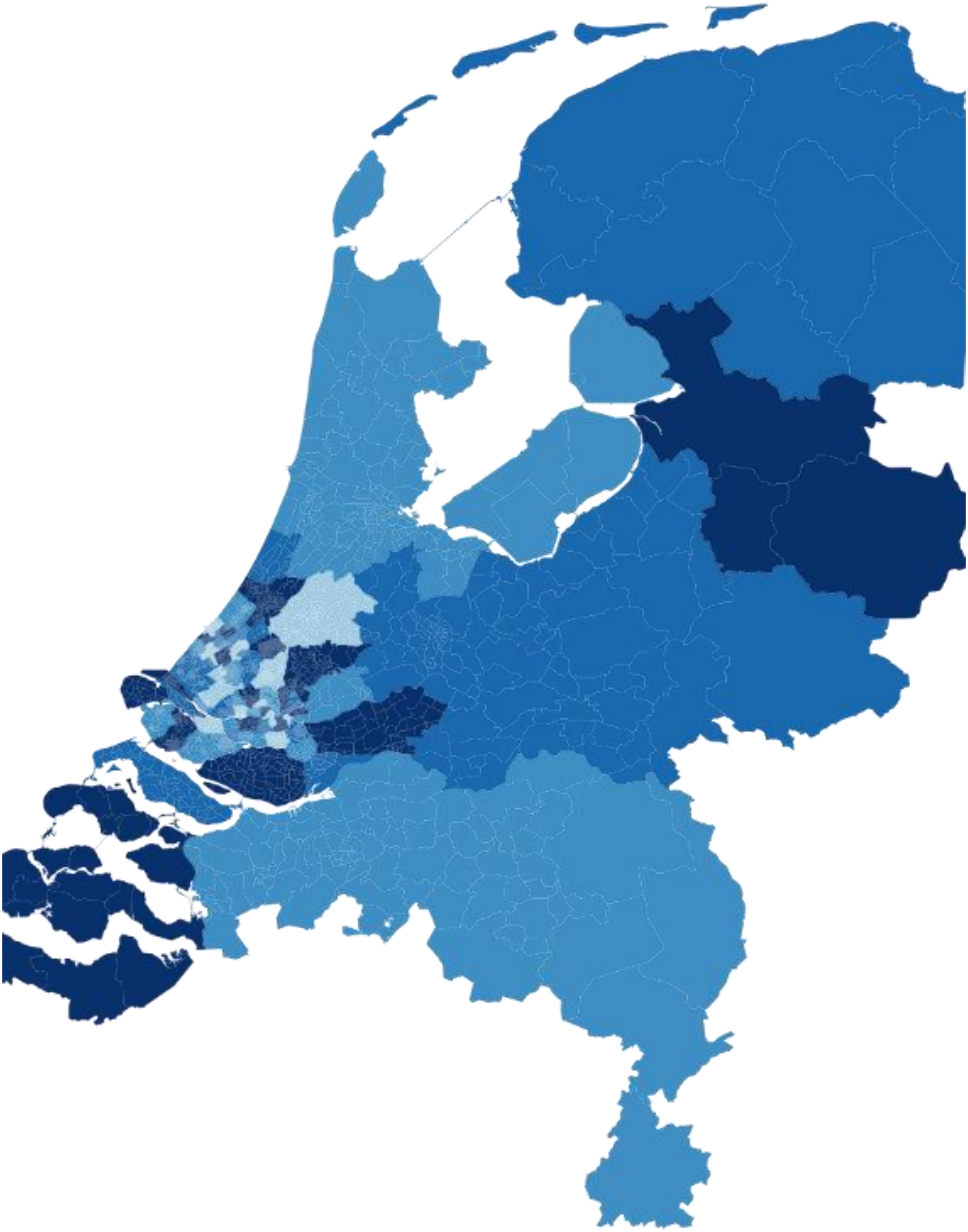


Figure 30: Matrix compression zones

Appendix D: Detailed description of the model application

To ensure the reproducibility of the results, this appendix provides a detailed description of how the model is used to analyse the effects of parking space removal on alternative transport modes. The model methodology including technical information is given in section 3.4.

Defining the study area in the simulation model

During the study it became clear that current aggregated model zones do not overlap with the defined study area. Therefore it is necessary to reaggregate these zones to exactly overlap with the with the defined study area. In the reaggregation process, zones that are included in the study area are removed from their original aggregation zone.

A visualisation of the new situation can be found in Figure 31, The study area is composed of the following model zones:

[5297 … 5367, 5372, 5373, 5378, 5381, 5382, 5383, 5384, 5385, 5386, 5387, 5388, 5389, 5390, 5391, 5398, 5403, 5404, 5405, 5406, 5407, 5408, 5409, 5410, 5430, 5432, 5433, 5456, 5457, 5458, 5460, 5462, 5463, 5464, 5466, 5467, 5469, 5470, 5471, 5472, 5473, 5474, 5475, 5476, 5477, 5478, 5479, 5480, 5726, 5727, 5728, 5729, 5730, 5731, 5745, 5746, 5748, 5754, 5757, 5758, 5760, 5808, 5811, 6126, 6127, 6128, 6132, 6174, 6175, 6176, 6177, 6178, 6179, 6180, 6181, 6185, 6186, 6187, 6192, 6193, 6194, 6195, 6196, 6197, 6571]

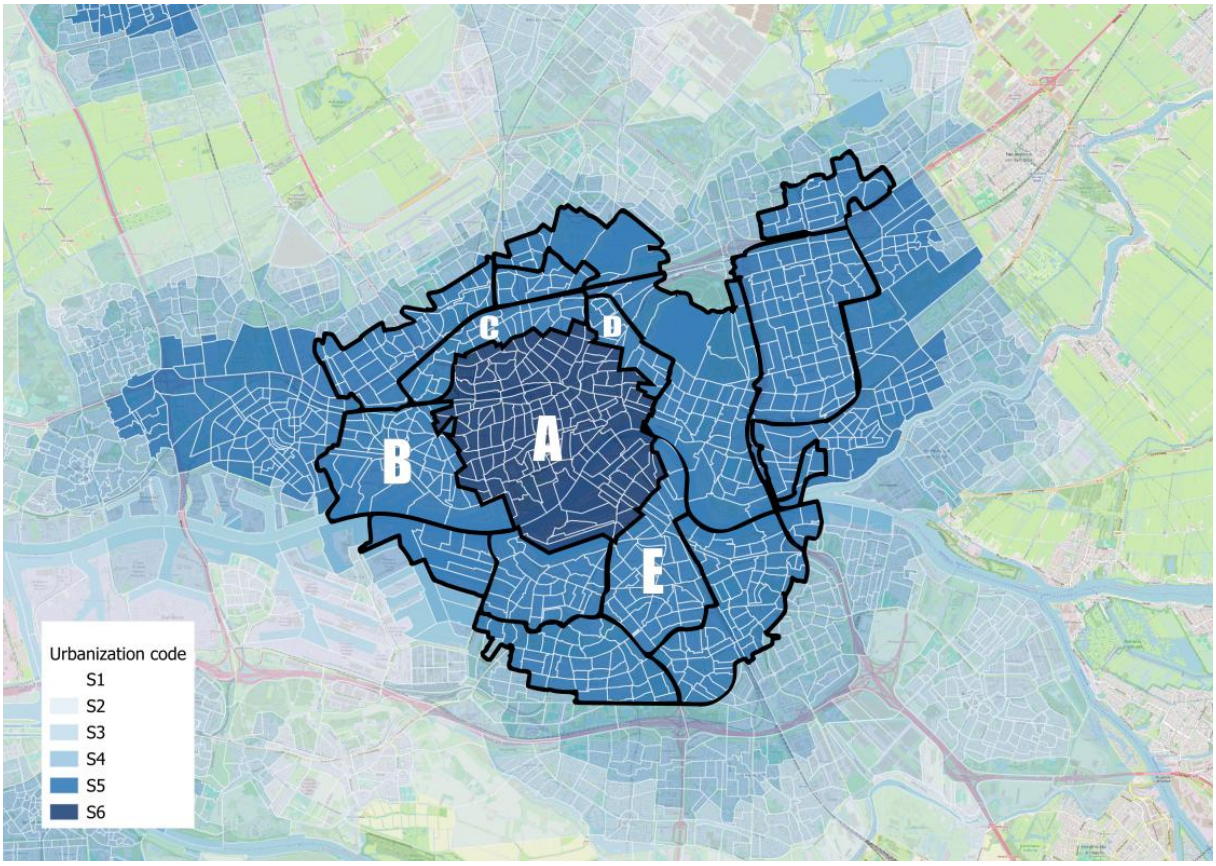


Figure 31: Reaggregated model zones

Calculating the parking limits

First the original parking data selected in 3.4.4 is reaggregated to match the new aggregated zones as defined in the previous paragraph. After reaggregation the parking limits are calculated using the method described in 3.4.5. obtaining the parking limits for the modified aggregated zones in the BAU scenario as shown in Table 12. Since Rotterdam centre is entirely within the study area all of the parking spaces are reaggregated to the study area.

Table 12: Parking limits in the BAU scenario after reaggregation

	Morning rush hour	Rest of the day	Evening rush hour
Rotterdam centre	0	0	0
Delfshaven	4039	27661	4468
Noord	2035	14034	2365
Kralingen Oost	1406	9389	1534
Feyenoord	5141	30359	4723
Study area	17026	98227	15716

Simulation set-up

In Omnitrans version 8.1.0 a new instance of the V-MRDH model version 3.0.2 is opened that includes the 2030_StedRef forecast year that will serve as the BAU scenario. For each intervention scenario a separate subvariant of the 2030_StedRef scenario is created for both the road network, as well as the bicycle and public transport network (FOV). For each subvariant a new empty matrix cube is created where the results after assignment will be stored. As well as a matrix cube that will store the synthetic simulation results and contains the 2030_StedRef social economic data.

For each intervention scenario, the project setup should look like as shown in Figure 32. For each intervention scenario the script “SimRun 2030StedRef” is modified to save the data to these newly created matrixcubes. This script should also point to the file containing the reagregated zones and parking limits as defined in the previous paragraphs.

After everything is set-up the “SimRun 2030StedRef” is run on the 2030_StedRef_3.0.2_Min40Procent_SIM variant. This is the most time consuming part and took 52 hours with the resources available for the project.

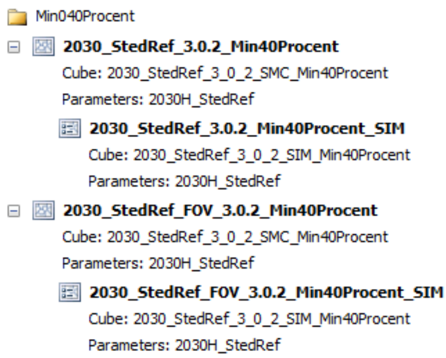


Figure 32: Project setup

Network assignment and export

When the simulation is finished the results are assigned to the network by running the FOV and motor vehicle assignment scrips on their respective variants. After assigning the results can be exported, using the modified export scripts that include the reaggregated zones.

Appendix E: Visualisations outcome V-MRDH model

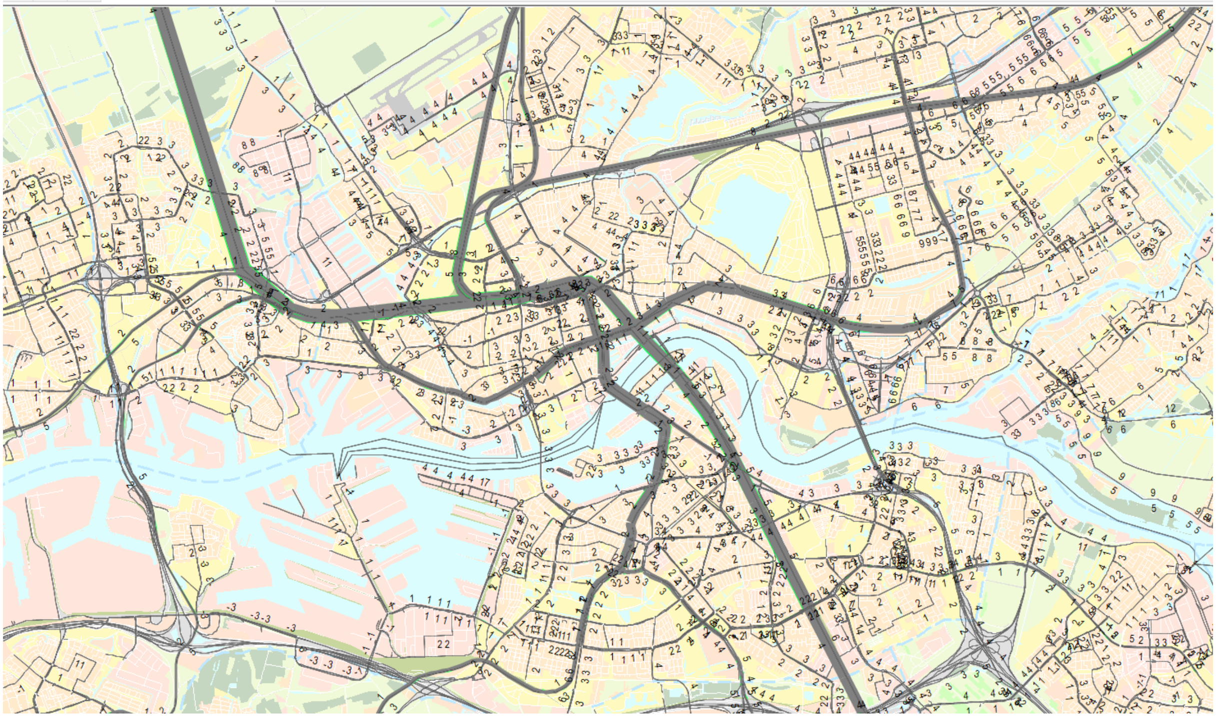


Figure 33: Difference in OV trips in the evening rush hour between the BAU and intermediate scenario.

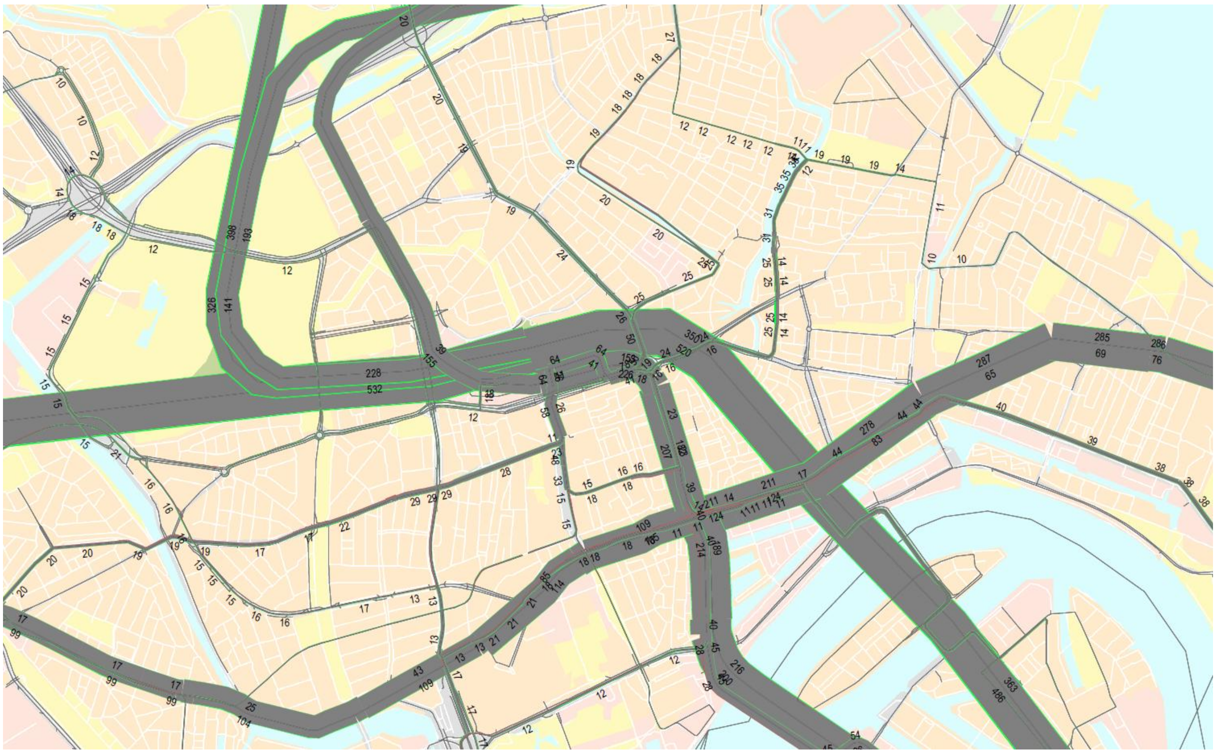


Figure 34: Figure 33, zoomed in

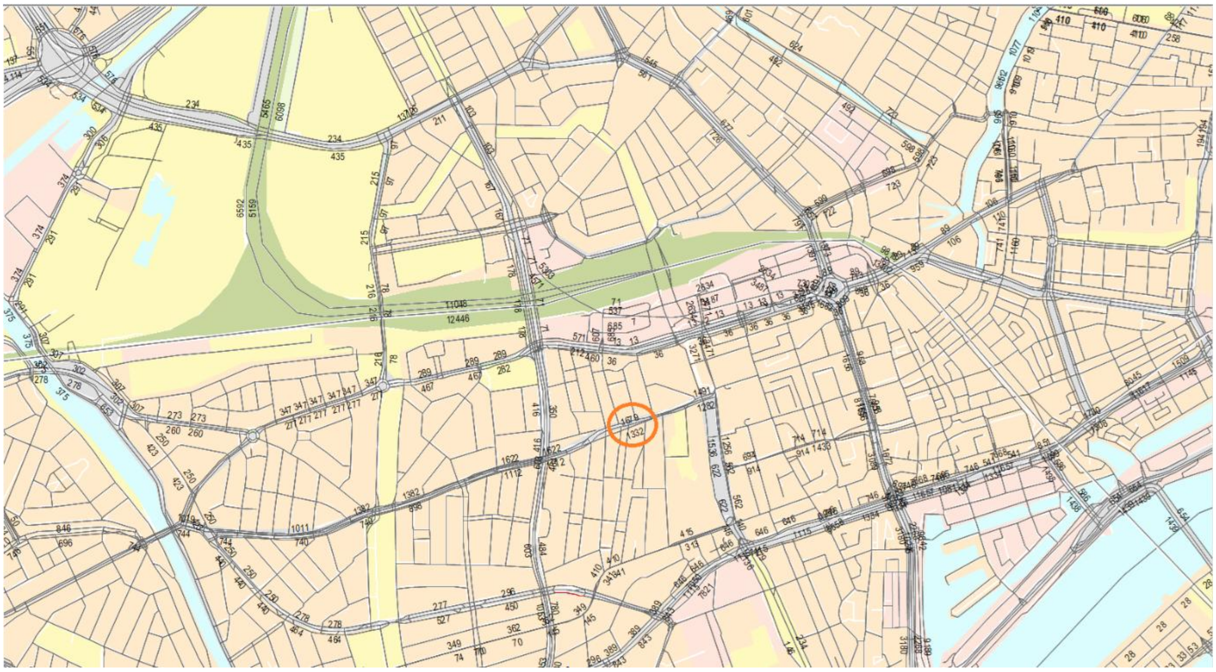


Figure 35: Link loads in the intermediate scenario, relevant link circled with orange circle.

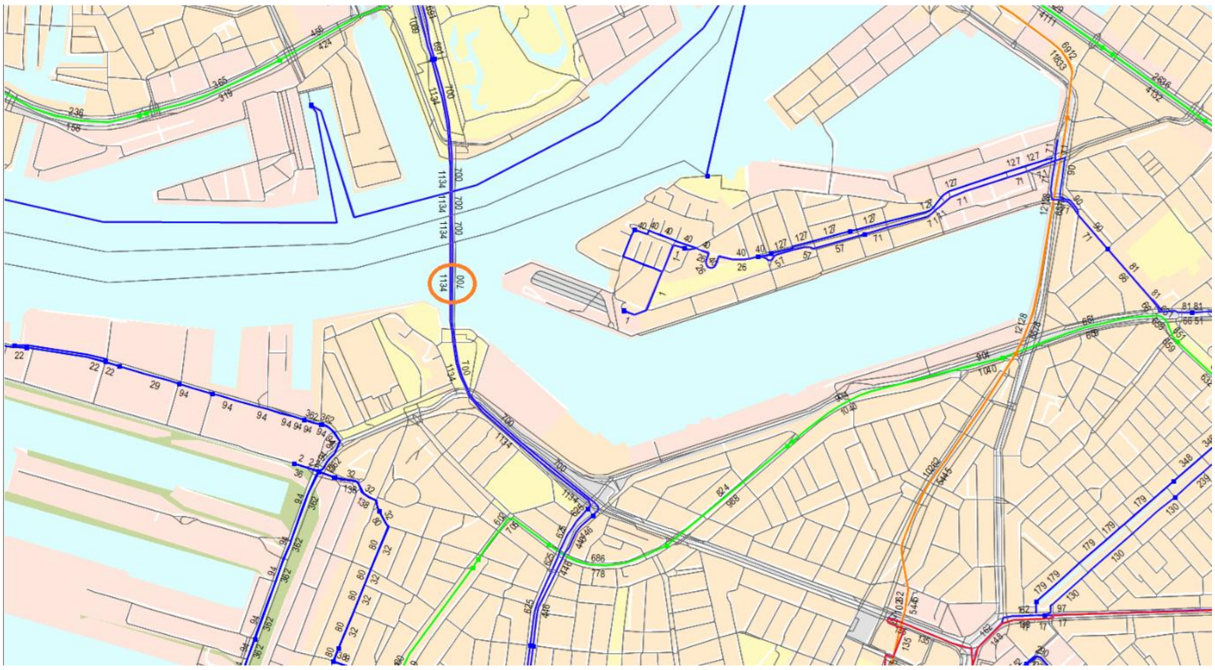


Figure 36: Link loads in the intermediate scenario, relevant link circeled with orange circle

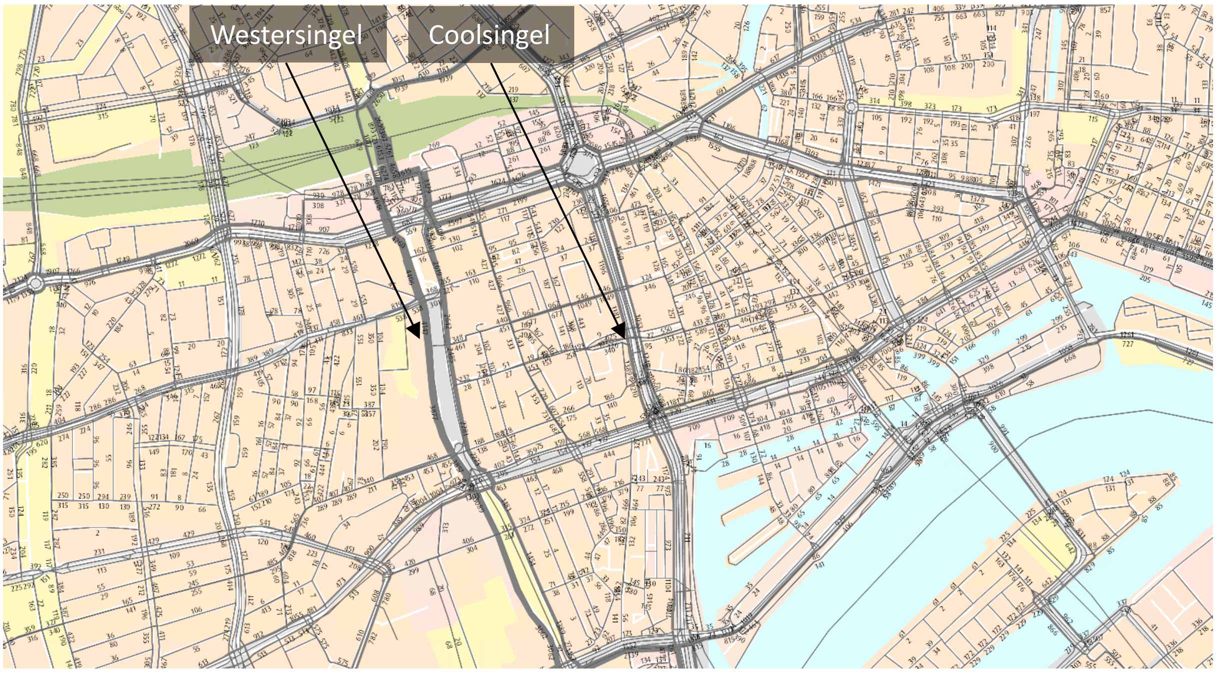


Figure 37: Bicycle intensities in ambitious scenario

Figure 38: Streets that see an increase of more than 15 bicyicles per hour in the ambitous scenario compeared to the BAU scenario. (increase for 2 hour evening rush)

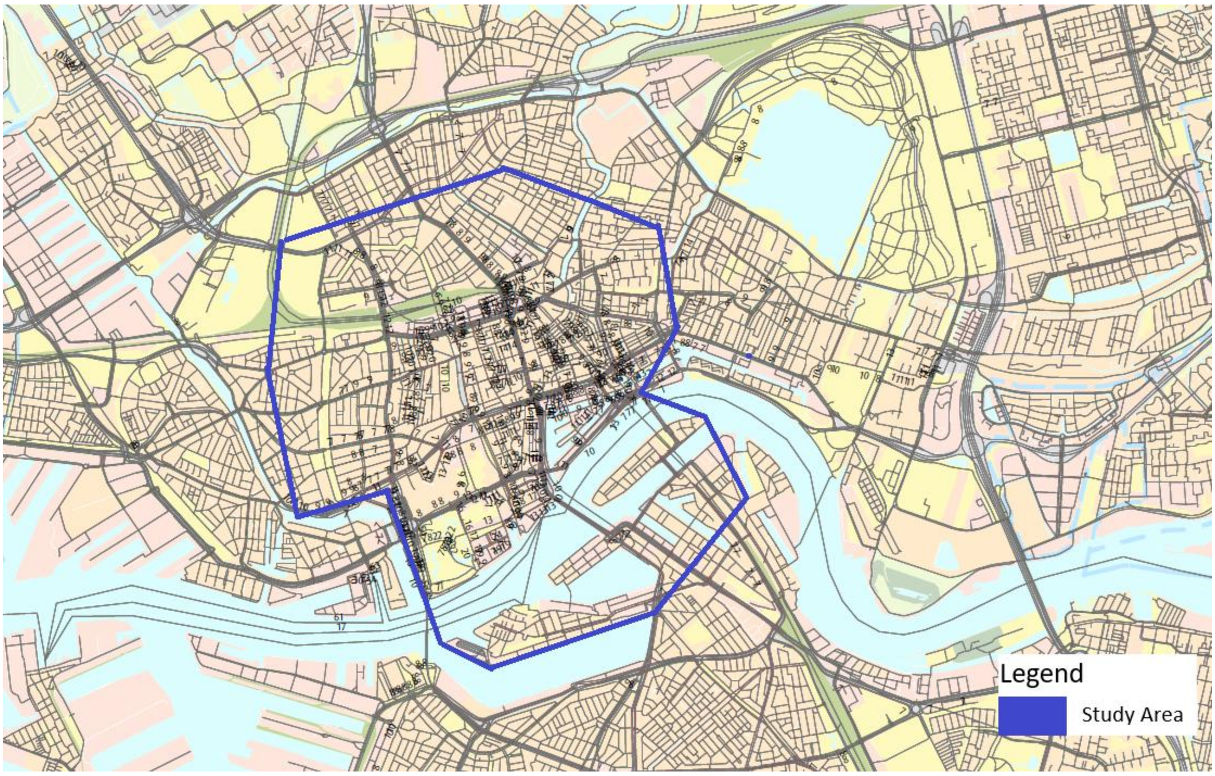
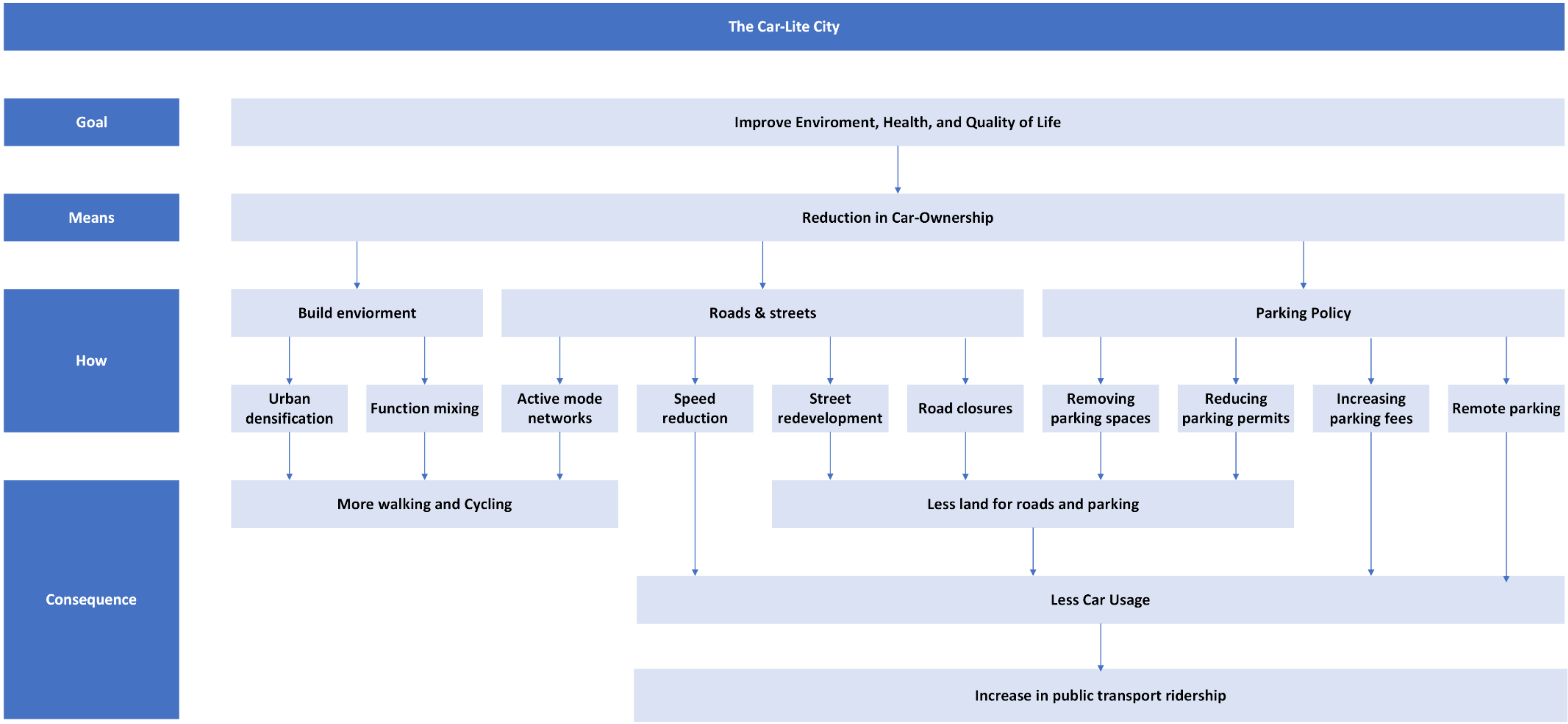


Figure 39: Streets that see an increase more than the 6.6% avarage increase in bike trips in the ambitious scenario compared to the BAU scenario.

Appendix F: The car-lite city from goal to consequence



Appendix G: Effect parking ceiling

Below Table 13 - Table 16 present in stylised tables the effect on the mode distribution when the parking limit is introduced as outputted by the V-MRDH model.

Table 13: Effect distribution parking limit - 2030_WLO_HOOG – BAU scenario

			Trips without parking limit						Trips with Parking limit						Difference in trips					
			Departures			Arrivels			Depatures			Arrivels			Depatures			Arrivels		
Area	Zones	Plafond	Autopersonen	Openbaarvervoer	Fiets	Autopersonen2	Openbaarvervoer2	Fiets2	Autopersonen3	Openbaarvervoer3	Fiets3	Autopersonen4	Openbaarvervoer4	Fiets4	Autopersonen5	Openbaarvervoer5	Fiets5	Autopersonen6	Openbaarvervoer6	Fiets6
Study Area	[5297,5298,52	8262	11447	22935	30010	4626	8428	23726	8261	24661	31471	4324	8311	24145	-3186	1726	1461	-302	-117	419
Delfshaven	[5420,5421,54	8376	6797	7400	18712	7479	8794	20682	6818	7405	18687	7247	8854	20854	21	5	-25	-232	60	172
Noord	[5360,5361,53	6538	4804	4551	14477	5489	4758	15762	4823	4559	14451	5328	4773	15907	19	8	-26	-161	15	145
Kralingen Oost	[5726,5727,57	4295	3032	2220	8632	3253	2815	9561	3044	2224	8615	3137	2823	9668	12	4	-17	-116	8	107
Kralingen West	[5733,5734,57	5946	5599	8609	8893	3221	2920	7041	5600	8613	8888	3149	2947	7087	1	4	-5	-72	27	46
IJsselmonde (bi)	[6086,6089,60	8163	5113	3454	6897	4619	3512	6801	5119	3449	6895	4575	3543	6813	6	-5	-2	-44	31	12
Feyenoord	[5356,5357,53	10300	9930	10978	22899	9208	10391	23169	9914	10984	22909	9016	10489	23262	-16	6	10	-192	98	93
Charlois Noord	[6198,6199,62	5288	3502	4193	9951	4021	4957	10549	3507	4189	9951	3942	5008	10576	5	-4	0	-79	51	27
Charlois Zuid	[6240,6302,62	4298	1972	1416	4219	2447	2174	4782	1974	1414	4219	2421	2193	4789	2	-2	0	-26	19	7
Overschie	[5500,5563,55	5857	5898	1350	3279	3573	1084	2652	5856	1365	3312	3538	1097	2674	-42	15	33	-35	13	22
Hillegersberg Zuid	[5653,5654,56	2491	1826	843	2339	1433	806	2261	1831	841	2335	1410	817	2274	5	-2	-4	-23	11	13
HillegersbergRest Schiebroek	[5644,5647,56	1175	951	508	774	858	511	751	953	507	773	848	517	755	2	-1	-1	-10	6	4
Prins Alexander Noord	[5896,5897,58	6495	4726	901	3796	4760	1468	4162	4729	899	3795	4738	1484	4168	3	-2	-1	-22	16	6
Prins Alexander Zuid	[5818,5819,58	14841	13884	4360	9947	11158	3319	9197	13896	4353	9942	11100	3357	9216	12	-7	-5	-58	38	19
IJsselmonde (bui)	[5997,5999,60	607	367	77	200	460	160	260	367	77	200	457	162	261	0	0	0	-3	2	1
Eemhaven Waalhaven	[6304,6305,63	1031	613	164	376	109	28	145	615	164	375	108	28	145	2	0	-1	-1	0	0
Den Haag Centrum	[79,80,81,82,8	13462	11082	18024	40063	7430	12069	37079	11042	18045	40082	7384	12093	37103	-40	21	19	-46	24	24
Laak	[218,214,215,:	7639	6802	8349	20944	6040	6221	20724	6692	8386	21017	5987	6235	20763	-110	37	73	-53	14	39
Escamp	[418,309,310,:	21771	12890	7220	27464	15787	11388	30881	12895	7217	27463	15734	11421	30901	5	-3	-1	-53	33	20
Loosduinen	[733,749,808,4	11330	6123	3489	13614	5485	3728	12442	6126	3487	13613	5472	3738	12446	3	-2	-1	-13	10	4
Segbroek	[611,612,613,(	7688	4971	3717	15123	5866	5656	16043	4973	3716	15122	5846	5670	16050	2	-1	-1	-20	14	7
Scheveningen	[23,25,26,27,2	8678	6304	5793	19212	6231	6739	17973	6309	5791	19210	6206	6757	17980	5	-2	-2	-25	18	7
Haagse Hout	[113,10,12,13,	12515	10196	10137	16896	6303	5582	14898	10206	10134	16889	6267	5597	14919	10	-3	-7	-36	15	21
Leidschenveen	[978,986,1000	2349	3107	1067	1868	959	195	755	2349	1338	2358	944	194	771	-758	271	490	-15	-1	16
Capelle aan den IJssel	[4359,4361,43	18266	17326	3883	9623	14785	3945	9514	17341	3875	9617	14715	3994	9534	15	-8	-6	-70	49	20
Delft Centrum	[2277,2279,22	5047	4571	3555	12836	4285	3181	12806	4475	3583	12906	4239	3202	12831	-96	28	70	-46	21	25
Delft Rest	[2330,2352,24	16101	13587	7305	20250	11317	3824	17908	13599	7299	20243	11253	3855	17942	12	-6	-7	-64	31	34
Leidschendam	[1380,1382,13	12779	10844	3073	10455	11091	3629	10856	10852	3071	10449	11007	3639	10929	8	-2	-6	-84	10	73
Midden Delfland	[2652,2655,26	3377	1816	177	1267	1237	165	1114	1816	177	1267	1233	167	1117	0	0	0	-4	2	3
Rijswijk	[2577,2579,25	16192	15133	5289	13883	14428	5088	14392	15143	5284	13878	14343	5119	14444	10	-5	-5	-85	31	52
Schiedam binnen	[3411,3360,33	9785	7932	3960	11938	9720	5659	13758	7939	3956	11935	9626	5722	13788	7	-4	-3	-94	63	30
Schiedam buiten	[3458,3372,33	5057	4630	1504	4429	2857	730	3182	4635	1504	4424	2846	734	3190	5	0	-5	-11	4	8
Vlaardingen	[4957,4968,49	6858	3685	708	2540	4267	1028	2781	3686	707	2540	4252	1039	2785	1	-1	0	-15	11	4
Wassenaar	[1242]	438	473	229	331	208	76	225	438	244	352	207	76	226	-35	15	21	-1	0	1
Westland	[3128,3260,28	4055	1571	160	1269	2289	365	1668	1571	160	1269	2286	367	1670	0	0	0	-3	2	2
Zoetermeer	[1641,1655,16	13894	13434	4029	16158	11778	3591	14958	13430	4026	16165	11752	3608	14967	-4	-3	7	-26	17	9
Totaal			236938	165627	405564	209077	138984	395458	232824	167704	407617	206937	139630	396950	-4114	2077	2053	-2140	646	1492

Table 14: Effect distribution Parking limits - 2030_WLO_HOOG – Realistic scenario

			Trips without parking limit						Trips with Parking limit						Difference in trips					
			Departures			Arrivels			Depatures			Arrivels			Depatures			Arrivels		
Area	Zones	Plafond	Autopersonen	Openbaarvervoer	Fiets	Autopersonen2	Openbaarvervoer2	Fiets2	Autopersonen3	Openbaarvervoer3	Fiets3	Autopersonen4	Openbaarvervoer4	Fiets4	Autopersonen5	Openbaarvervoer5	Fiets5	Autopersonen6	Openbaarvervoer6	Fiets6
Study Area	[5297,5298,52	6609	11405	22969	30017	4594	8455	23732	6609	25584	32199	4134	8286	24359	-4796	2615	2182	-460	-169	627
Delfshaven	[5420,5421,54	7957	6771	7415	18723	7446	8816	20694	6803	7420	18686	7090	8912	20952	32	5	-37	-356	96	258
Noord	[5360,5361,53	5884	4782	4561	14490	5460	4773	15776	4809	4572	14452	5215	4797	15994	27	11	-38	-245	24	218
Kralingen Oost	[5726,5727,57	3909	3018	2225	8641	3235	2822	9571	3036	2231	8616	3058	2836	9734	18	6	-25	-177	14	163
Kralingen West	[5733,5734,57	5946	5591	8613	8897	3215	2925	7043	5601	8616	8885	3102	2967	7114	10	3	-12	-113	42	71
IJsselmonde (bi)	[6086,6089,60	8163	5105	3459	6899	4610	3518	6803	5117	3452	6894	4525	3569	6836	12	-7	-5	-85	51	33
Feyenoord	[5356,5357,53	9476	9895	10997	22914	9165	10418	23185	9476	11161	23173	8771	10546	23448	-419	164	259	-394	128	263
Charlois Noord	[6198,6199,62	5288	3495	4199	9952	4012	4965	10550	3504	4194	9948	3870	5042	10614	9	-5	-4	-142	77	64
Charlois Zuid	[6240,6302,62	4298	1968	1418	4220	2442	2177	4784	1972	1415	4220	2393	2207	4802	4	-3	0	-49	30	18
Overschie	[5500,5563,55	5857	5890	1353	3284	3566	1086	2656	5857	1365	3312	3516	1106	2687	-33	12	28	-50	20	31
Hillegersberg Zuid	[5653,5654,56	2491	1824	844	2340	1431	808	2262	1831	842	2335	1395	824	2281	7	-2	-5	-36	16	19
HillegersbergRest Schiebroek	[5644,5647,56	1175	950	509	774	856	512	752	952	507	773	841	521	757	2	-2	-1	-15	9	5
Prins Alexander Noord	[5896,5897,58	6495	4720	902	3800	4753	1471	4166	4724	899	3799	4719	1495	4176	4	-3	-1	-34	24	10
Prins Alexander Zuid	[5818,5819,58	14841	13870	4366	9956	11143	3325	9206	13889	4355	9948	11053	3385	9235	19	-11	-8	-90	60	29
IJsselmonde (bui)	[5997,5999,60	607	366	78	200	459	161	261	366	77	200	454	163	263	0	-1	0	-5	2	2
Eemhaven Waalhaven	[6304,6305,63	1031	613	164	376	109	28	145	615	164	375	107	28	146	2	0	-1	-2	0	1
Den Haag Centrum	[79,80,81,82,8	13462	10958	18106	40105	7306	12145	37128	10287	18394	40487	7172	12154	37252	-671	288	382	-134	9	124
Laak	[218,214,215,2	7639	6590	8409	21097	5833	6277	20874	6574	8418	21104	5753	6308	20924	-16	9	7	-80	31	50
Escamp	[418,309,310,3	21771	11914	7402	28260	14752	11594	31708	11923	7396	28256	14640	11657	31757	9	-6	-4	-112	63	49
Loosduinen	[733,749,808,4	11330	5576	3582	14068	4994	3810	12851	5581	3579	14066	4962	3831	12862	5	-3	-2	-32	21	11
Segbroek	[611,612,613,6	7688	4795	3761	15255	5686	5705	16173	4800	3760	15251	5627	5735	16204	5	-1	-4	-59	30	31
Scheveningen	[23,25,26,27,2	8678	6197	5830	19282	6119	6777	18046	6208	5826	19275	6052	6818	18073	11	-4	-7	-67	41	27
Haagse Hout	[113,10,12,13,	12515	9933	10210	17086	6060	5642	15079	9953	10205	17072	5991	5669	15122	20	-5	-14	-69	27	43
Leidschenveen	[978,986,1000	2349	3093	1070	1879	950	197	762	2349	1337	2360	934	196	778	-744	267	481	-16	-1	16
Capelle aan den IJssel	[4359,4361,43	18266	17306	3890	9637	14760	3954	9529	17328	3876	9629	14649	4033	9562	22	-14	-8	-111	79	33
Delft Centrum	[2277,2279,22	5047	4460	3592	12911	4207	3202	12862	4404	3605	12954	4156	3238	12878	-56	13	43	-51	36	16
Delft Rest	[2330,2352,24	16101	12030	7440	21671	9687	3951	19410	12044	7431	21667	9612	3996	19440	14	-9	-4	-75	45	30
Leidschendam	[1380,1382,13	12779	10772	3088	10512	11013	3647	10917	10782	3085	10505	10912	3666	10997	10	-3	-7	-101	19	80
Midden Delfland	[2652,2655,26	3377	1763	178	1318	1195	166	1155	1764	178	1318	1190	168	1158	1	0	0	-5	2	3
Rijswijk	[2577,2579,25	16192	14987	5321	13998	14288	5116	14503	15001	5313	13991	14181	5163	14563	14	-8	-7	-107	47	60
Schiedam binnen	[3411,3360,33	9785	7914	3967	11949	9696	5670	13771	7925	3960	11945	9553	5769	13814	11	-7	-4	-143	99	43
Schiedam buiten	[3458,3372,33	5057	4623	1507	4433	2853	732	3185	4631	1507	4426	2835	738	3196	8	0	-7	-18	6	11
Vlaardingen	[4957,4968,49	6858	3680	709	2544	4260	1030	2786	3682	707	2544	4237	1047	2792	2	-2	0	-23	17	6
Wassenaar	[1242]	438	470	230	333	206	77	226	438	244	352	204	77	228	-32	14	19	-2	0	2
Westland	[3128,3260,28	4055	1548	162	1290	2264	368	1690	1548	162	1290	2258	371	1693	0	0	0	-6	3	3
Zoetermeer	[1641,1655,16	13894	13410	4036	16174	11751	3601	14976	13329	4050	16242	11688	3624	15015	-81	14	68	-63	23	39
Totaal			232282	166562	409285	204376	139921	399217	225712	169887	412549	200849	140942	401706	-6570	3325	3264	-3527	1021	2489

Table 15: Effect distribution parking limits - 2030_Stedref – Intermediate scenario

			Trips without parking limit						Trips with Parking limit						Difference in trips					
			Departures			Arrivels			Depatures			Arrivels			Depatures			Arrivels		
Area	Zones	Plafond	Autopersonen	Openbaarvervoer	Fiets	Autopersonen2	Openbaarvervoer2	Fiets2	Autopersonen3	Openbaarvervoer3	Fiets3	Autopersonen4	Openbaarvervoer4	Fiets4	Autopersonen5	Openbaarvervoer5	Fiets5	Autopersonen6	Openbaarvervoer6	Fiets6
Study Area	[5297,5298,52	4957	10617	23624	30149	4273	8700	23805	4957	26742	32693	3757	8506	24513	-5660	3118	2544	-516	-194	708
Delfshaven	[5420,5421,54	7622	6342	7661	18906	6964	9099	20889	6377	7667	18865	6558	9207	21186	35	6	-41	-406	108	297
Noord	[5360,5361,53	5230	4467	4748	14618	5111	4967	15928	4497	4760	14576	4833	4992	16179	30	12	-42	-278	25	251
Kralingen Oost	[5726,5727,57	3522	2818	2323	8742	3026	2927	9674	2838	2330	8715	2822	2942	9863	20	7	-27	-204	15	189
Kralingen West	[5733,5734,57	5946	5255	8836	9010	3022	3017	7142	5279	8833	8989	2892	3065	7224	24	-3	-21	-130	48	82
IJsselmonde (bi)	[6086,6089,60	8163	4839	3587	7037	4363	3625	6942	4853	3580	7030	4257	3685	6987	14	-7	-7	-106	60	45
Feyenoord	[5356,5357,53	8652	9273	11384	23150	8600	10734	23431	8652	11629	23528	8116	10870	23776	-621	245	378	-484	136	345
Charlois Noord	[6198,6199,62	5288	3292	4303	10052	3779	5082	10664	3303	4299	10045	3608	5169	10747	11	-4	-7	-171	87	83
Charlois Zuid	[6240,6302,62	4298	1860	1464	4283	2308	2234	4859	1864	1460	4282	2249	2269	4884	4	-4	-1	-59	35	25
Overschie	[5500,5563,55	5857	5623	1431	3473	3391	1130	2787	5638	1427	3461	3339	1154	2815	15	-4	-12	-52	24	28
Hillegersberg Zuid	[5653,5654,56	2491	1733	881	2394	1356	838	2307	1742	878	2388	1315	857	2328	9	-3	-6	-41	19	21
HillegersbergRest Schiebroek	[5644,5647,56	1175	902	529	801	814	527	778	905	527	800	797	538	785	3	-2	-1	-17	11	7
Prins Alexander Noord	[5896,5897,58	6495	4514	950	3958	4532	1534	4322	4519	947	3957	4493	1563	4333	5	-3	-1	-39	29	11
Prins Alexander Zuid	[5818,5819,58	14841	13259	4575	10357	10633	3478	9558	13281	4562	10348	10527	3548	9594	22	-13	-9	-106	70	36
IJsselmonde (bui)	[5997,5999,60	607	351	82	211	438	168	274	351	82	211	432	170	277	0	0	0	-6	2	3
Eemhaven Waalhaven	[6304,6305,63	1031	587	174	392	103	29	149	590	174	390	101	30	151	3	0	-2	-2	1	2
Den Haag Centrum	[79,80,81,82,8	13462	10184	18730	40255	6771	12576	37230	10090	18769	40309	6723	12609	37245	-94	39	54	-48	33	15
Laak	[218,214,215,2	7639	6134	8753	21208	5419	6542	21022	6142	8750	21203	5380	6570	21033	8	-3	-5	-39	28	11
Escamp	[418,309,310,3	21771	11152	7695	28729	13839	11997	32214	11157	7691	28727	13785	12040	32226	5	-4	-2	-54	43	12
Loosduinen	[733,749,808,4	11330	5258	3724	14244	4702	3943	13009	5261	3722	14243	4687	3955	13012	3	-2	-1	-15	12	3
Segbroek	[611,612,613,6	7688	4472	3905	15434	5309	5905	16350	4475	3904	15433	5286	5923	16355	3	-1	-1	-23	18	5
Scheveningen	[23,25,26,27,2	8678	5826	6039	19443	5735	6998	18208	5833	6035	19441	5707	7021	18213	7	-4	-2	-28	23	5
Haagse Hout	[113,10,12,13,	12515	9304	10621	17304	5673	5852	15255	9318	10613	17298	5640	5874	15267	14	-8	-6	-33	22	12
Leidschenveen	[978,986,1000	2349	2940	1129	1973	897	207	804	2349	1341	2356	885	207	816	-591	212	383	-12	0	12
Capelle aan den IJssel	[4359,4361,43	18266	16611	4106	10115	14137	4148	9954	16636	4091	10105	14006	4239	9994	25	-15	-10	-131	91	40
Delft Centrum	[2277,2279,22	5047	4206	3714	13043	3962	3308	13000	4212	3709	13042	3924	3347	12998	6	-5	-1	-38	39	-2
Delft Rest	[2330,2352,24	16101	11359	7740	22042	9158	4121	19764	11371	7731	22040	9097	4169	19778	12	-9	-2	-61	48	14
Leidschendam	[1380,1382,13	12779	10190	3239	10943	10430	3808	11332	10198	3236	10938	10360	3825	11386	8	-3	-5	-70	17	54
Midden Delfland	[2652,2655,26	3377	1690	190	1380	1139	175	1202	1690	190	1380	1135	178	1203	0	0	0	-4	3	1
Rijswijk	[2577,2579,25	16192	14232	5572	14502	13571	5332	14999	14243	5565	14497	13496	5373	15033	11	-7	-5	-75	41	34
Schiedam binnen	[3411,3360,33	9785	7517	4122	12192	9212	5855	14066	7528	4114	12188	9052	5967	14113	11	-8	-4	-160	112	47
Schiedam buiten	[3458,3372,33	5057	4403	1599	4562	2719	769	3280	4411	1599	4554	2700	777	3292	8	0	-8	-19	8	12
Vlaardingen	[4957,4968,49	6858	3536	747	2651	4091	1075	2909	3538	745	2650	4066	1094	2915	2	-2	-1	-25	19	6
Wassenaar	[1242]	438	447	241	346	196	81	233	438	245	351	195	81	233	-9	4	5	-1	0	0
Westland	[3128,3260,28	4055	1474	173	1353	2163	389	1769	1474	173	1352	2159	391	1771	0	0	-1	-4	2	2
Zoetermeer	[1641,1655,16	13894	12800	4208	16613	11195	3754	15372	12651	4238	16731	11116	3771	15434	-149	30	118	-79	17	62
Totaal			219467	172799	415865	193031	144924	405481	212661	176358	419116	189495	145976	407959	-6806	3559	3251	-3536	1052	2478

Table 16: Effect distribution parking limit - 2030_StedRef – Ambitious scenario

			Trips without parking limit						Trips with Parking limit						Difference in trips					
			Departures			Arrivels			Depatures			Arrivels			Depatures			Arrivels		
Area	Zones	Plafond	Autopersonen	Openbaarvervoer	Fiets	Autopersonen2	Openbaarvervoer2	Fiets2	Autopersonen3	Openbaarvervoer3	Fiets3	Autopersonen4	Openbaarvervoer4	Fiets4	Autopersonen5	Openbaarvervoer5	Fiets5	Autopersonen6	Openbaarvervoer6	Fiets6
Study Area	[5297,5298,52	3305	10617	23624	30149	4273	8700	23805	3304	27606	33481	3305	8553	24916	-7313	3982	3332	-968	-147	1111
Delfshaven	[5420,5421,54	7203	6342	7661	18906	6964	9099	20889	6350	7674	18885	6427	9251	21272	8	13	-21	-537	152	383
Noord	[5360,5361,53	4576	4467	4748	14618	5111	4967	15928	4454	4760	14619	4576	5052	16375	-13	12	1	-535	85	447
Kralingen Oost	[5726,5727,57	3093	2818	2323	8742	3026	2927	9674	2747	2353	8784	2748	2948	9930	-71	30	42	-278	21	256
Kralingen West	[5733,5734,57	5946	5255	8836	9010	3022	3017	7142	5273	8836	8992	2845	3082	7254	18	0	-18	-177	65	112
IJsselmonde (bi)	[6086,6089,60	8163	4839	3587	7037	4363	3625	6942	4851	3582	7030	4190	3709	7029	12	-5	-7	-173	84	87
Feyenoord	[5356,5357,53	7725	9273	11384	23150	8600	10734	23431	7724	11983	24102	7725	10900	24132	-1549	599	952	-875	166	701
Charlois Noord	[6198,6199,62	5288	3292	4303	10052	3779	5082	10664	3296	4305	10045	3518	5194	10812	4	2	-7	-261	112	148
Charlois Zuid	[6240,6302,62	4298	1860	1464	4283	2308	2234	4859	1862	1461	4283	2216	2281	4905	2	-3	0	-92	47	46
Overschie	[5500,5563,55	5857	5623	1431	3473	3391	1130	2787	5633	1429	3464	3322	1161	2825	10	-2	-9	-69	31	38
Hillegersberg Zuid	[5653,5654,56	2491	1733	881	2394	1356	838	2307	1736	878	2393	1302	863	2335	3	-3	-1	-54	25	28
HillegersbergRest Schiebroek	[5644,5647,56	1175	902	529	801	814	527	778	904	528	801	791	542	787	2	-1	0	-23	15	9
Prins Alexander Noord	[5896,5897,58	6495	4514	950	3958	4532	1534	4322	4518	947	3958	4479	1572	4337	4	-3	0	-53	38	15
Prins Alexander Zuid	[5818,5819,58	14841	13259	4575	10357	10633	3478	9558	13279	4562	10350	10488	3573	9609	20	-13	-7	-145	95	51
IJsselmonde (bui)	[5997,5999,60	607	351	82	211	438	168	274	351	82	211	429	171	279	0	0	0	-9	3	5
Eemhaven Waalhaven	[6304,6305,63	1031	587	174	392	103	29	149	590	174	390	100	30	152	3	0	-2	-3	1	3
Den Haag Centrum	[79,80,81,82,8	13462	10184	18730	40255	6771	12576	37230	10092	18769	40308	6715	12619	37242	-92	39	53	-56	43	12
Laak	[218,214,215,2	7639	6134	8753	21208	5419	6542	21022	6143	8750	21203	5373	6579	21031	9	-3	-5	-46	37	9
Escamp	[418,309,310,3	21771	11152	7695	28729	13839	11997	32214	11157	7691	28727	13776	12050	32226	5	-4	-2	-63	53	12
Loosduinen	[733,749,808,4	11330	5258	3724	14244	4702	3943	13009	5262	3722	14243	4684	3958	13012	4	-2	-1	-18	15	3
Segbroek	[611,612,613,6	7688	4472	3905	15434	5309	5905	16350	4475	3904	15433	5282	5927	16355	3	-1	-1	-27	22	5
Scheveningen	[23,25,26,27,2	8678	5826	6039	19443	5735	6998	18208	5834	6035	19440	5703	7026	18213	8	-4	-3	-32	28	5
Haagse Hout	[113,10,12,13,	12515	9304	10621	17304	5673	5852	15255	9319	10613	17298	5635	5880	15266	15	-8	-6	-38	28	11
Leidschenveen	[978,986,1000	2349	2940	1129	1973	897	207	804	2349	1341	2356	885	207	816	-591	212	383	-12	0	12
Capelle aan den IJssel	[4359,4361,43	18266	16611	4106	10115	14137	4148	9954	16634	4090	10108	13957	4270	10011	23	-16	-7	-180	122	57
Delft Centrum	[2277,2279,22	5047	4206	3714	13043	3962	3308	13000	4211	3709	13043	3915	3357	12997	5	-5	0	-47	49	-3
Delft Rest	[2330,2352,24	16101	11359	7740	22042	9158	4121	19764	11369	7731	22042	9080	4182	19782	10	-9	0	-78	61	18
Leidschendam	[1380,1382,13	12779	10190	3239	10943	10430	3808	11332	10198	3236	10938	10354	3830	11386	8	-3	-5	-76	22	54
Midden Delfland	[2652,2655,26	3377	1690	190	1380	1139	175	1202	1690	190	1380	1134	179	1204	0	0	0	-5	4	2
Rijswijk	[2577,2579,25	16192	14232	5572	14502	13571	5332	14999	14243	5565	14498	13486	5382	15033	11	-7	-4	-85	50	34
Schiedam binnen	[3411,3360,33	9785	7517	4122	12192	9212	5855	14066	7522	4116	12192	8999	6004	14129	5	-6	0	-213	149	63
Schiedam buiten	[3458,3372,33	5057	4403	1599	4562	2719	769	3280	4411	1600	4553	2693	779	3296	8	1	-9	-26	10	16
Vlaardingen	[4957,4968,49	6858	3536	747	2651	4091	1075	2909	3537	745	2651	4057	1101	2917	1	-2	0	-34	26	8
Wassenaar	[1242]	438	447	241	346	196	81	233	438	245	351	195	81	233	-9	4	5	-1	0	0
Westland	[3128,3260,28	4055	1474	173	1353	2163	389	1769	1474	173	1353	2158	392	1771	0	0	0	-5	3	2
Zoetermeer	[1641,1655,16	13894	12800	4208	16613	11195	3754	15372	12651	4238	16732	11111	3776	15434	-149	30	119	-84	22	62
Totaal			219467	172799	415865	193031	144924	405481	209881	177623	420637	187653	146461	409303	-9586	4824	4772	-5378	1537	3822

Appendix H: Cumulative results per urbanization level

Table 17:Public transportation trips evening rush hour - OD matrix 2030_StedRef - Baseline

OD - public transport	Den Haag - S6	Rotterdam - S6	S5	S4	S3	S2	S1	Outside MRDH	Total Departures
Den Haag - S6	12694	941	13512	2238	1781	849	106	13125	45341
Rotterdam - S6 - (Study area)	1065	7677	18145	4563	4055	1424	246	13810	50994
S5	10001	12008	32396	8481	5828	2020	395	20764	91969
S4	2188	2312	7248	2536	2139	1010	199	4776	22465
S3	783	1516	4058	1822	1674	732	303	2779	13677
S2	387	580	1427	723	658	458	309	1393	5939
S1	63	134	293	161	253	256	231	412	1804
Outside MRDH	6709	5105	16746	3669	2952	1475	541	539637	576863
Total Arrivals	33898	30298	93890	24215	19362	8230	2331	596769	809274

Table 18: Bike trips evening rush hour - OD matrix 2030_StedRef - Baseline

OD - Bike	Den Haag - S6	Rotterdam - S6	S5	S4	S3	S2	S1	Outside MRDH	Total Departures
Den Haag - S6	63829	0	15962	1527	647	727	57	456	83391
Rotterdam - S6 – (Study area)	0	36093	14286	1048	705	304	157	230	52837
S5	15158	11981	192030	21711	7836	3804	946	5026	258681
S4	1285	641	20851	45482	14452	3177	590	2329	88822
S3	345	444	7126	13114	63782	13045	1067	2958	101885
S2	397	160	2957	2575	12489	41590	2922	1717	64810
S1	56	56	690	664	1758	3789	18427	615	26055
Outside MRDH	94	32	1823	1522	2204	1606	375	501746	509402
Total Arrivals	81288	49428	255950	87657	103881	68045	24541	515079	1186315

Appendix I: Cumulative data for neighbourhoods Rotterdam

Table 19:Distribution of number of parking spaces in Rotterdam by study van der Tuin et al. (2021)

Zone name	POP	Free Parking spaces	Paid parking spaces	Total
Rotterdam Centrum	13235	1396	13580	28212
Delfshaven	2549	4032	27958	34538
Noord	1410	9337	17046	27792
Kralingen Oost	871	244	15206	16320
Kralingen West	2369	21037	9688	33094
IJsselmonde (bi)	3150	48383	2078	53611
Feyenoord	5433	15180	21914	42527
Charlois Noord	1053	11878	7780	20711
Charlois Zuid	568	33318	69	33955
Overschie	1610	61395	668	63673
Hillegersberg Zuid	719	6832	415	7966
HillegersbergRest Schiebroek	4040	41167	828	46035
Prins Alexander Noord	3403	57786	0	61189
Prins Alexander Zuid	2955	40183	7742	50879
IJsselmonde (bui)	642	16328	0	16970
Hoek van Holland	923	34680	0	35603
Hoogvliet	2883	43963	0	46846
Rozenburg	971	18916	0	19887
Eemhaven Waalhaven	1098	37674	0	38772
Vondelingenplaat	2	13464	0	13466
Botlek	192	24346	0	24538
Europoort	0	18170	0	18170
Maasvlakte	15	54159	0	54174
Total	50089	613865	124970	788924

Table 20: Cumulative number of parking spaces of neighbourhoods of Rotterdam where urbanisation level >4

Zone naam	PoPP	Free parking spaces	Paid parking spaces	Totaal
Rotterdam Centrum	13235	1396	13580	28212
Delfshaven	2549	4032	27958	34538
Noord	1408	7564	16887	25859
Kralingen Oost	871	244	15206	16320
Kralingen West	2219	10501	7953	20672
IJsselmonde (bi)	93	5893	817	6803
Feyenoord	5433	15180	21914	42527
Charlois Noord	1017	9686	7780	18483
Charlois Zuid	0	6636	69	6705
Overschie	161	1661	668	2490
Hillegersberg Zuid	579	3761	381	4721
HillegersbergRest Schiebroek	0	0	0	0
Prins Alexander Noord	1252	11137	0	12389
Prins Alexander Zuid	1483	16238	7742	25462
IJsselmonde (bui)	0	0	0	0
Hoek van Holland	0	0	0	0
Hoogvliet	0	0	0	0
Rozenburg	0	0	0	0
Eemhaven Waalhaven	7	2745	0	2752
Vondelingenplaat	0	0	0	0
Botlek	0	0	0	0
Europoort	0	0	0	0
Maasvlakte	0	0	0	0
	30306	96671	120953	247930

Appendix J: Origin-Destination Matrices

Figure 40: Difference between OD-Matrices BAU scenario and intermediate scenario for mode=car and purpose=all

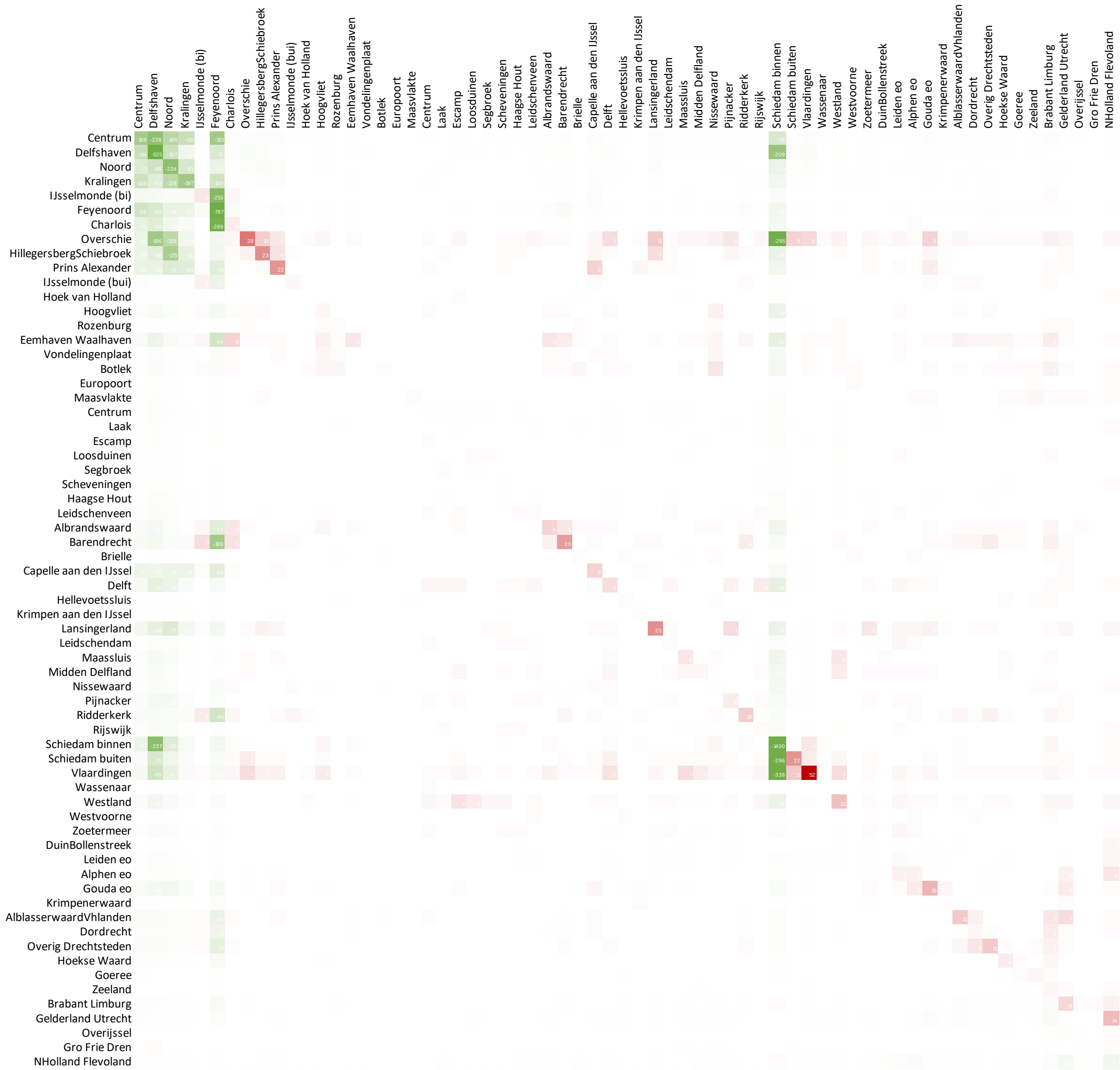


Figure 41: Difference between OD-Matrices BAU and intermediate scenario for mode=car and purpose=all with the modified V-MRDH method.