Planning for the Transition to Clean Shared Mobility

Leveraging System Dynamics as a Tool for Urban Policy Development

Matthew Bearden

Cover Figure. Carsharing vehicles
at Kadijksplein in Amsterdam

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Leveraging System Dynamics as a Tool for Urban Policy Development

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Preface

Developing a master's thesis can be represented as a complex system with many interactions, stocks, and feedback loops that each play a crucial role in making the system function. The purpose of this 'system' is to create new knowledge and deeper understanding for addressing a part of the sustainability challenge related to urban mobility.

Through this study, there have been many people supporting, guiding, and challenging me that I would like to recognize and thank. Without their influence and contributions, I would not have been able to complete and make the most of this study.

First and foremost, I cannot express enough gratitude to my loving wife with whom I have spent countless hours discussing, sparring, and deliberating about this topic. She has provided me support, wisdom, and advice through not only this endeavor but also throughout our lives together. From discussing how the model's mathematical relationship should function to discussing the motivations for people to buy a car to lending her extensive vocabulary, she has truly been an indispensable partner throughout this journey. She continues to inspire, and the success of the study must be shared with her.

Throughout this study, my advisors Bart van Arem and Dominic Stead have provided exceptional guidance for this challenging venture. Their recommendations on system dynamics and guidance on policy development exposed me to new realms of knowledge and ways of thinking about complex, challenging issues. They also knew when to encourage and challenge me through the process to maintain the motivation needed to complete the study. For their supervision, I am exceedingly grateful.

At the beginning of the thesis process, I was introduced to APPM Management Consultants by Micha Sijtsma, which provided the foundation for me to work and collaborate with APPM for the study. This collaboration led to the development of a practical, focused thesis that serves an immediate issue in the market. At APPM, I have had the pleasure of collaborating with Bob Brandjes and Harm-Jan Idema, amongst others, throughout the thesis process. Their contributions and assistance were crucial to the development of the topic, analyzing how the system functions, and validating the results. I would like to thank everyone at APPM for their help, collaboration, and resources throughout this process.

Last, but certainly not least, I would like to thank my family, friends, colleagues, and classmates for their continued and unabating support. While listing everyone whose support has contributed to my success would create a list longer than this paper, they all have played a critical role in my personal and professional development.

Sincerely,

Matthew Bearden

Abstract

This research aims to evaluate the policies and strategies that cities can deploy to facilitate the transition to clean shared mobility. The literature review supports the research through providing insights into the direction of the shared mobility market, charging infrastructure, electric vehicle development, charging behavior, as well as existing government and policy instruments and spatial considerations for charging infrastructure. Using metrics, such as uptake in electric vehicles and deployment rate of shared mobility services, a baseline analysis is conducted to establish recent trends in this field for the case study of Amsterdam. Next, the development of the system dynamics model provides insights into the interactions between the various aspects of the personal and shared mobility system that can be used to evaluate potential policy scenarios. Amsterdam's (2019a) Clean Air Action Plan and similar goalsetting plans provide targets to which policies must be steered; therefore, the policies or policy packages to achieve the goals set can be developed via backcasting. Leveraging the four scenarios from the Netherlands Environmental Assessment Agency (PBL), four potential policy packages are developed in accordance with the governance, sustainability, and technological directions prescribed (PBL, 2019). These policy packages are then used in the system dynamics model, which accounts for stakeholder behavior, to evaluate the packages' effects on the carsharing market, electric vehicle market share, parking and spatial considerations, and charging infrastructure demands. Based on the case study considered for the City of Amsterdam, the resulting trends show that the policy packages evaluated facilitate carsharing as a conduit to drastically reduce the market share of personal vehicles and are critical to the shift towards electric vehicle market dominance. The results can then be compared to inform the relative effectiveness of the policy packages considered. While there are limitations to the study, the model provides a beneficial tool for governments to evaluate effectiveness, side-effects, and constraints of transitioning the personal vehicle market towards a more sustainable future.

Executive Summary

Introduction

Around the world, governments, citizens, institutions, and companies are working to address the complex challenges of climate change, livability, and accessibility. In many cities and urban regions, the mobility system is seen as being ripe for sustainable transformation. Within urban mobility, the transition to shared electric mobility through ride-hailing and carsharing presents opportunities to reduce vehicle dependence and repurpose space for parking while improving air quality and maintaining access to vehicles. This paper uses system dynamics to model the personal and shared mobility sector at the city level and estimate the effects of policy scenarios on the future of urban mobility. Using Amsterdam as a case study, the results indicate how policy scenarios affect the uptake of shared and personal electric vehicles (EV). Additional insights are gained regarding the demand for EV charging infrastructure and impacts on air quality in the city. While this study focuses on Amsterdam as a case study, the results show the enormous potential of shared mobility and that modeling transportation systems using system dynamics provides valuable insights for guiding policy development. The implications, therefore, can be applied to other urban regions across the world.

Literature Review

Shared mobility, through carsharing and ride-hailing, has gained significant traction in recent years due to the convenience of accessing a vehicle or ride through smartphone apps (Machado, Hue, Berssaneti, & Quintanilha, 2018). Shared mobility, and carsharing in particular, has shown a positive effect on residents shedding personal vehicles (Machado et al., 2018). For shared mobility and personal vehicles, transitioning to zero emission vehicles provides additional benefits to urban areas. Over the past several years, the uptake of EVs has far exceeded that of other zero emission vehicle platforms in development allowing EVs to gain considerable market share (Jung et al., 2018). While today's attributes of EVs are not yet equal to their internal combustion engine (ICE) vehicle counterparts, significant progress is underway regarding battery range and scope of vehicles offered.

To further improve the attractiveness of EVs and alleviate challenges of battery range, a comprehensive network of charging infrastructure is critical. Charging infrastructure is categorized across three levels, with Level 1 charging predominately used for private charging and Levels 2 and 3 used for public charging (Habib, Khan, Abbas, & Tang, 2018). Level 2 chargers use AC power and can provide a full charge in six hours while Level 3 chargers use DC power and can provide a full charge in less than one hour (Habib et al., 2018). Innovation in Level 2 charging technology includes flexible chargers where the charging power is reduced during peak energy grid demands and vehicle to grid (V2G) chargers where vehicles can sell energy from their batteries back to the energy grid during peak grid demand (Habib et al., 2018). Innovation in Level 3 chargers consists of ultra-high-power chargers which can provide full charges to vehicles in less than ten minutes (Ronanki et al., 2019). Based on charging usage, it is found that Level 2 chargers close to residents' homes or workplaces are the most preferred and Level 3 chargers are used when Level 2 chargers are not available or on longer distance trips (Gnann et al., 2018). For governments to influence the mobility system, a number of policy options are available. Policy options can be categorized as authoritative, treasure, nodal, or organizational allowing for different aspects of the system to be addressed (Howlett, 2000). Overall, these factors are important to consider when planning for shared mobility and influencing the transition to sustainable mobility.

Baseline Analysis

The city of Amsterdam is selected as the case study for this research due to its aggressive pursuit towards the transition to EVs, the availability of open data, and proximity to additional resources. The baseline data includes trends in shared mobility, personal vehicle ownership, parking, and a spatial analysis investigating the distribution of charging points and their corresponding utilization at a postcode level. Within shared mobility, carsharing has experienced a significant increase in the availability of vehicles increasing from 2,700 in 2015 to 9,000 in 2019 (CROW, 2020). While the growth in ride-hailing across the various services is not available, eight million rides annually gives insights into the scale of this market (Amsterdam, 2019). Additionally, a significant increase in ride-hailing through digital platforms has been observed with 85% of all taxi trips in 2018 hailed in this manner (Amsterdam, 2019d). There are 250,000 personal vehicles in Amsterdam accounting for a modal share of 19% (Amsterdam, 2019). The share of personal EVs is unknown for Amsterdam; however, EVs represent 2.3% of the stock for the Netherlands (CROW, 2019). As residents shed their ICE vehicles for carsharing services or purchase an EV, charging infrastructure will be necessary to accommodate the increase in EVs. As of 2019, there were 1,800 Level 2 charging points and 22 Level 3 charging points in Amsterdam with the Level 2 chargers distributed throughout residential neighborhoods in the city and Level 3 located along arterial roadways (Confidential source, 2020 & EVdata, 2020). In Amsterdam, approximately 70% of all parking is publicly owned accounting for 225,000 parking spaces (Ostermeijer, Koster, & van Ommeren, 2019). With these baselines established, the methodology is developed for exploring the future of this system.

Methods

Planning for the future of shared and electric mobility is a complex task due to the many components and uncertainties in this field. System dynamics is proposed to model the relationships between various components of the system and forecast future trends based on scenarios. The model uses available data and estimates uncertainties to mathematically represent how the system operates (Bala, Arshad, & Noh, 2017). The model is adapted from the Struben and Sterman's (2008) study on the potential of alternative fuel vehicles. The model uses social exposure to various mobility platforms to build a willingness to consider stock and attributes to calculate the utility of each platform. The combination of willingness to consider and utility provide the market share for vehicle sales. The sales increase the vehicle stocks which in turn increases social exposure. Vehicles are also discarded at rate determined by their average lifespan, which can reduce the overall vehicle stock if sales decrease. As the base model is completed and validated, it is used to test the various scenarios by applying policy packages. The results can then be used to compare future outcomes to guide policy makers towards a desired future.

Backcasting methodology is used to set sustainability goals, apply future scenarios, and develop policy packages to test in the model (Banister et al., 2000). Sustainable mobility goals or targets are first established so that future scenarios can be applied providing different pathways towards this desired future (Banister et al., 2000). Using indicators, such as influence of local government, the market, and society, policy packages are developed. These policy packages combine authoritative, treasure, nodal, and organizational policies in accordance with the scenario with policies that can be implemented at the local city level. These policies aim to address various deficiencies hindering the complete uptake in shared cars and EVs.

Application to Case Study and Development of Policy Packages

To apply the system dynamics model to the case study of Amsterdam, parameters from the baseline analysis, assumptions, and platform utility estimates are developed. The baseline parameters include the quantities of vehicles of each platform, parking, and charging points. Assumptions are made regarding willingness to consider as a result of social exposure, EV stocks, and users for shared mobility platforms based on national trends and through calibration of the model. For comparing the utility of the platforms, financial factors, accessibility, ownership sensitivity, and platform attributes are estimated based on existing research and vehicle attributes. These parameters are then used to calibrate the model and run sensitivity analyses for initial validation of the model before applying policy package scenarios.

Using backcasting methodology, the future vision, application of scenarios, and development of policy packages are applied to Amsterdam. The vision for the future includes emission-free travel and reducing the dependence on personal vehicle ownership in accordance with Amsterdam's Clean Air Action Plan and Autoluw Agenda (Amsterdam, 2019a & Amsterdam, 2019c). Future scenarios developed by the Netherlands Environment Assessment Agency (PBL) are evaluated on their proposed governance structures, their focus on sustainability, and the importance of technology (PBL, 2019). The four scenarios by PBL, Bubble City, State of Green, Market Place, and Our Neighborhood, describe four alternative visions of cities and urban regions. Using these scenarios, four policy packages are developed with policies targeting parking quantities, vehicle access limits, subsidies, parking costs, and marketing. These scenarios are then applied to the system dynamics model to evaluate their effects on the future of the mobility system.

Results

Results from the model provide trends of carsharing usage, vehicle stocks, parking pressure, and charging infrastructure pressure for the four scenarios through the year 2040. Carsharing usage is shown to increase to between 95,000 and 141,000 users and 26,000 to 35,000 vehicles based on eight new users per new carsharing vehicle set in the model. As a result of carsharing usage, the total vehicle stock shows an overall reduction of 7% to 22% by 2040. The vehicle stocks of ICE vehicles are reduced by 50% to 78% and EVs overtake ICE vehicles for the State of Green scenario in 2035. This reduces CO2 emissions from ICE vehicles by 78% in 2040. While parking stocks are modified through the policy packages, the most extreme scenario in State of Green removes 115,000 spaces while reducing the parking spaces per vehicle ratio from 1.0 to 0.7. This reduction in parking repurposes 717 million square meters of space for other uses, including green space, terraces, playgrounds, and other amenities. Charging infrastructure is installed in the model at a constant rate of 50 new charging points per month and informs the total number of EVs per charging point. The model shows the ratio increasing from 9 EVs per charging point to peaks of 11 to 12 vehicles per charging point between 2023 and 2025 then decreasing to 8 to 9.5 in 2040 due to the diminishing growth rate of EVs. For all of the scenarios, the effects of the policy packages are observed with marketing having a significant early effect for shared cars and EV adoption and the vehicle access limits and corresponding contra-marketing drastically reducing the sales for ICE vehicles.

Discussion

Careful planning of charging infrastructure plays a critical role in the acceptance and adoption of EVs and shared electric mobility. Cities can combine charging infrastructure installations with policy packages to further expedite the transition. The effects of the various policies can be seen in the trends of subsidies, having positive effects early and vehicle access limits reducing the demand for ICE vehicles. While this study does not provide an exact ratio of EVs to charging points, through monitoring of EV uptake across all platforms, the number of charging points installed can be correlated with the type of charging technology to further enable access and contribute to the power grid. Through this transition, public street space can be repurposed, and overall urban quality can be improved.

The validity of any model can be questioned as accuracy in forecasting is only as good as their inputs, assumptions, and modeling techniques. A degree of validity, however, can be gained though stakeholder and expert outreach and evaluated on the usefulness of the model's development and output. For this study, working sessions have been held to review the model structure, policy development, and model results. The results have been accepted as reasonable based on the level of uncertainty surrounding the technological development of EVs, charging infrastructure, and acceptance of shared mobility.

There are several limitations in the development of this study and model. While Amsterdam provides an extensive range of open data, additional sources of data could have made the study and model more robust. Key desired data includes charging behaviors, EVs registered per postcode, and shared mobility usage. There are limitations with the development of the system dynamics model, the exclusion of other transport modes, simplification of vehicle stocks, and modeling the city as a whole instead of on a postcode level. With many research projects and rapid development of vehicle charging technology underway, there are many unknowns for how these will develop over time. Finally, there is limited research and information regarding the factors and their importance for how consumers choose between purchasing a vehicle and using shared mobility. Future studies should build upon these shortcomings and allow for the development of more robust studies.

Reflecting on this research provides an opportunity to assess the study and the overall knowledge gained. Developing the system dynamics model required studying many facets in the field of personal mobility and understanding its context in Amsterdam. As there are many aspects of the transport system, understanding the tools available to cities to influence change and transitions provides key insights to how sustainability can be gained. Additionally, the methods for developing this model can be applied to other cities so that policymakers can use system dynamics as a tool to evaluate future policy development.

Conclusion

During this study, many factors of the mobility system are examined. Using system dynamics, future scenarios are explored to forecast the effects of various policies on transitioning cities to clean shared mobility. Through the analysis and development of the model, a number of recommendations are proposed for future research. These proposals include further studies into consumer choice between vehicle purchases and shared mobility usage, further development of the urban mobility systems with system dynamics, and research into the effects of local policy development on national and international policies. The results of the study show significant opportunities of shared mobility to reduce vehicle ownership in cities. furthermore, as EVs become more widespread and ranges increase, they will provide a viable alternative to ICE vehicles. Cities have the ability to influence these transitions through effective policies and investments in charging infrastructure. Using system dynamics as a tool for modeling the mobility system and testing various policy initiatives can assist in developing more effective strategies for this transition. Overall, the investments in infrastructure, modeling, and policy development have the ability to result in a more equitable, clean, and effective transportation system and improve the quality of life for citizens.

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Abreviations

AC	Alternating Current
BEV	Battery Electric Vehicle
CBS	Central Bureau of Statistics
CCS	Combined Charging System
CID	Community Improvement District
CO2	Carbon Dioxide
DC	Direct Current
ELV	Electric L-Category Vehicles
EU	European Union
EU-27	European Union excluding the United Kingdom
EU-28	European Union including the United Kingdom
EV	Electric vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal combustion engine
MaaS	Mobility as a Service
MRA	Metropolitan Region of Amsterdam
MRDH	Metropolitan Region of Rotterdam and The Hague
NHTS	National Household Travel Survey
P2P	Person to person
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
PHEV	Plug-in Hybrid Electric Vehicle
PT	Public Transport
RDW	Rijksdienst voor het Wegverkeer (Netherlands Vehicle Authority)
V2G	Vehicle to Grid

Equation Variables

a	affinity for platform j
β	Utility factor weight
d	Discards
g	Growth rate (population)
i	Initial
j	Vehicle type
σ	market share
U	Utility
μ	Utility factor
V	Vehicle stock
WtC	Willingness to consider

1 Introduction

Policymakers around the world are under pressure to improve quality of life, expand accessibility to economic prosperity, and address the numerous challenges with climate change. The urgency surrounding these issues has come to the forefront of many governments and organizations with the increased frequency of extreme weather events, protests over inequality, and the growing concern over the future of our planet. As a result, the United Nations (UN) developed 17 Sustainable Development Goals aimed at providing resources to governments and organizations to address these issues (United Nations, 2020). Within these goals, seven are focused on issues related to health, equality, mobility, and sustainable development. This paper aims to focus on the mobility sector and its role in addressing these challenges.

Many countries are experiencing profound challenges resulting from carbon emissions, congestion, and land pressures as a result of their mobility and transportation systems. Private automobiles, while offering opportunities for accessibility and freedom, are choking government resources due to the population's overreliance on them. In the European Union (EU), 27% of greenhouse gas emission result from the transport sector with 44% of this being the direct result of passenger vehicles (European Environment Agency, 2020). Decarbonizing this sector could reduce 469.3 kg of CO2 from the EU-27 according to 2018 EEA data. The EU estimates that across the EU-28 countries 206 billion euros are lost annually on passenger cars due to the delay costs associated with congestion (European Commission, 2019). While overreliance on personal automobiles and resulting air quality and congestion are significant challenges, there is momentous opportunity in addressing them through sustainable initiatives.

In particular, cities and urban regions experience significant effects from the overreliance on personal automobiles. While climate change is generally considered on a national scale, cities experience issues on a local level with extreme rain or heat. Other pressing urban issues, including the negative health impacts resulting from local air and noise pollution, are rising to the forefront of city council agendas. Additionally, cities are continually under pressure from population growth and the need of keeping the city mobile while maintaining its livability.

This research focuses on the opportunities of clean shared mobility systems in the urban context. Clean shared mobility systems, through electric ride-hailing and carsharing services, present the possibility to reduce vehicle ownership, decrease vehicle emissions, and reallocate public space currently reserved for parking (Shaheen, 2018). Local governments, however, need to be aware of the policy tools available and understand the impacts of these different policy options. This study seeks to link local policy options with the different components of shared mobility, personal vehicles, and infrastructure through the development of a system dynamics model to project the effects of various policy packages on this system.

1.1 Statement of the Problem

The current personal vehicle regime constantly burdens cities, their resources, and citizens. While personal vehicles are associated as a gateway to freedom and representation of economic prosperity, they have become a strain on urban infrastructures, air quality, and personal finances. Electric and other zero emission vehicles partly address issues with regard to air pollution; however, they still contribute to congestion and require significant amounts of public space. Additionally, the adoption of electric vehicles by consumers is inhibited by higher costs, vehicle range, scope of vehicles offered on the market, and access to charging infrastructure. In order to promote widespread electric vehicle use, a reliable network of charging infrastructure is required. This section will further discuss these challenges that policy makers must address to achieve feasible reliance on electric vehicles.

Personal vehicles are often a requirement to access jobs, food, and leisure when public transport is inadequate; however, due to this reliance, households and cities are burdened both financially and spatially. While public transport and active transport, such a bicycles or walking, are preferred alternatives to vehicle ownership, access to these services or their corresponding infrastructure is lacking in many places or does not fully address the mobility needs of citizens. As a result, there is still the inherent need to transform the personal vehicle regime through other methods.

Electric vehicles (EV)s offer opportunity with regard to addressing air pollution; however, there are significant challenges in gaining their widespread adoption. EVs on the market today are more expensive than their respective internal combustion engine (ICE) vehicle. For the Volkswagen e-Golf, the purchase price is approximately 34% higher than for the comparable Volkswagen Golf ICE models (Electric Vehicle Database, 2020). The vehicle range is another challenge for consumer acceptance and can result in range anxiety. A Volkswagen e-Golf has 35% of the range of its ICE counterpart on a full tank. Options are another inhibiting factor, as the EV market is still scaling and there are still limited options for vehicles in comparison with ICE vehicles in similar classes. Furthermore, with the relative infancy of the electric vehicle market compared to the ICE market, there is a very limited secondhand market for EVs, limiting this financially attractive option almost entirely on ICEs and making the entry cost higher for the EV market. While significant progress is being made in the EV market, these challenges continue to impede full consumer acceptance and adoption.

Charging infrastructure with its technological, spatial, and temporal considerations for deployment presents another challenge to the adoption of electric vehicles. Various charging infrastructure technologies, ranging from flexible power slow chargers to high power fast chargers which must be considered based on their application, are under development (Habib et al., 2018). These various charging infrastructure types must be planned spatially to provide adequate access to users. The timing for the installation of charging infrastructure is important as cities and investors want to ensure they will meet a minimum utilization and not install infrastructure that will be soon rendered obsolete. On the other hand, consumers will be deterred from purchasing EVs if adequate charging infrastructure is not available. Cities must account for and balance these challenges when planning the deployment of charging infrastructure for EVs.

As cities seek to address the various issues with personal ICE vehicles, there are a number of challenges that need to be considered and addressed. The need for access to a vehicle for many citizens cannot be ignored. While electric vehicles address air pollution issues, they are not yet competitive with ICE vehicles on price, range, and platform scope. There are also many challenges with planning charging infrastructure for EVs, including installing the right technology in the right place to ensure viability. To address these issues, policy makers need to understand the entire scope of issues as well as options for addressing them.

1.2 Background and Need

There are a number of opportunities to address the challenges with personal mobility and transition to zero emission vehicles. Shared mobility systems have emerged in recent years as an alternative to vehicle ownership. Policies can be used to address shortcomings of EVs, while technological gains over the next decade are expected to bring EV attributes closer to consumers expectations for their vehicles with regards to cost, range, and options available. Charging infrastructure can be leveraged to address range issues and as the technologies improve, create added benefits not available with ICE vehicles. This section provides an overview of the opportunities within personal and shared mobility.

Shared mobility has gained recent popularity due to the ease of access, pay-as-you-go schemes, and range of vehicle options. Shared mobility, either through ride-hailing or carsharing, can be accessed through smart phone apps, making services readily attainable (Machado et al., 2018). As payment strategies are usage-based for the services, large capital costs are avoided in accessing these services. Depending on the nature of the trip and number of passengers, different vehicle options are available meaning the vehicle you utilize can conform to the individual, momentary need. Shared mobility offers the flexibility of personal vehicles without many of the negative aspects discussed.

While EVs are not yet comparable to their ICE counterparts, there are a number of tools available to policy makers to lessen the effects of their shortcomings. Subsidies and tax incentives can be leveraged to make EVs more financially attractive. An established and accessible charging network can reduce the anxieties with the vehicle range. Marketing can be used to broaden the awareness of the new vehicle models and attributes as they arrive to market. Cities will need to develop a range of policies to maximize the awareness and impact of these vehicles.

Planning for the deployment of charging infrastructure requires understanding the technologies, determining the number of each type of chargers, determining locations to install the chargers, and planning the phasing of these installations. As new charging infrastructure is developed, including flexible charging, vehicle to grid, and high-power fast chargers, each charging type will have a different impact on the energy grid and should be accounted for in their distribution (Habib et al., 2018). A spatial analysis can provide insights into the accessibility to charging infrastructure in areas across a city. Developing a deployment strategy based on the spatial analysis can then determine the sequence for areas to prioritize. To ensure EVs are attractive for citizens across a city, a charging infrastructure strategy needs to account for the location and timing for each charging infrastructure type.

Shared mobility is an alternative to personal vehicle ownership through either ride-hailing or shared car services. When shared mobility deploys EVs, benefits to air quality can be gained as well. To overcome the challenges with EVs, both shared and personal, cities need to evaluate the policy tools available to address financial challenges with subsidies or to ensure a coherent network of charging infrastructure is available. For the deployment of charging infrastructure, a strategy including the technological, spatial, and temporal considerations should be developed. Overall, these measures have the opportunity to address many of the negative aspects of traditional personal vehicles.

1.3 Purpose of the Study

As cities are under pressure from abundance of personal car use, shared electric vehicles are proposed as a way to reduce the reliance on personal vehicles. Policy tools need to be evaluated to determine their impacts on the personal vehicle system. Additionally, a strategy is needed for implementing charging infrastructure over time to aid in this transition. The purpose of this study is to use a system dynamics model as a tool to evaluate policy packages for cities to incentivize the transition to clean shared mobility.

1.4 Research Questions

The following research questions guide the research and investigation into planning for clean shared mobility.

What type, how many, where, and when should cities plan charging infrastructure for shared mobility fleets?

What policies and regulations can cities use to facilitate shared electric vehicles?

How many charging points per (shared) electric vehicle are required to service demand?

What are the effects on public street space as a result of shared mobility?

1.5 Research Methods

To explore the transition to clean shared mobility, several research methods are used to gain an in-depth understanding of the current sector, develop a system dynamics model, and develop policy packages to test future scenarios. Using the City of Amsterdam as a case study, a baseline analysis is performed to determine the current state of vehicle ownership, shared mobility usage, spatial distribution of charging infrastructure, and utilization of charging infrastructure. Next, a system dynamics model is developed to study the interactions, links, and feedback loops between various segments of this system. Using backcasting, policy packages are developed from Amsterdam's goals for zero emission mobility and Netherlands Environmental Agency (PBL) scenarios with a focus on city-led policies. These policies are then implemented in the model to project the impacts of the different policy combinations on the personal vehicle ownership, carsharing, and electric mobility systems.

1.6 Thesis Outline

The thesis begins with a literature review of relevant topics within the shared mobility and personal mobility realm with additional insights into consumer behavior and charging technology. Next, a baseline analysis is conducted for the Netherlands and Amsterdam to build an understanding of the current context of shared mobility usage, personal vehicle ownership, spatial aspects for charging infrastructure for the case study. The methods section then describes the system dynamics and backcasting methodology. From the methodologies, the parameters for the model including the baseline data, assumptions, and utility estimates are discussed along with the development of the policy packages. The results section presents the outcomes of the model with respect to the overall vehicle stocks, parking pressures, charging pressures, and air quality gains. The discussion section responds to the research questions while giving further insight into the validity of the model and limitations of the study. Finally, recommendations for future research are presented as well as the overall conclusions.

2 Literature Review

The emergence of shared mobility, especially when coupled with the shift to EVs over traditional ICEs, creates an opportunity to greatly shift the urban mobility landscape (Jittrapirom et al., 2019). To achieve this shift, the components of the urban mobility landscape need to be understood by policy makers, industry players, and the public to make informed decisions regarding policy, investments, use, and impact. In the literature review, a review of existing research in shared mobility, zero-emission vehicle technology, charging infrastructure technology, spatial considerations for planning charging infrastructure based on consumer behavior, and policy tools for influencing the mobility system at the urban level is included. This section assesses the opportunities, challenges, and trends of the shared mobility services, charging infrastructure, and EVs as discussed in existing literature. Through these topics, the technological and spatial aspects of the research questions are analyzed. This review provides a baseline for the existing research and trends at the core of the research objective.

2.1 Shared Mobility

Shared mobility is not a new phenomenon but has re-emerged as a priority of the shared economy to provide mobility options for people without the need for personal vehicle ownership (Machado et al., 2018). These mobility options range from carsharing and ride-hailing to shared bikes and scooters with either personal vehicles or vehicle fleets to provide mobility options. For the purpose of this research, carsharing and ride-hailing will be the primary focus as these services are experiencing significant investments and scrutiny and, if their potential is realized, significantly affect personal vehicle ownership in the urban mobility landscape.

The idea of ride-hailing and shared mobility is not a new concept and has been in use as taxis, personal carsharing, carpooling, and vanpooling (Shaheen, Chan, & Micheaux, 2015). What has changed, however, is the ability to connect to these services on demand through the use of a smartphone and systems that connect mobility providers with users to initiate rides or unlock vehicles digitally (Machado et al., 2018). With the convenience of mobility on demand or mobility as a service (MaaS), the industry has experienced significant growth over the past few years (Jittapirom et al., 2019). From Uber's entrance into the market in San Francisco in 2010, the industry has expanded to cities around the world and continues to account for a growing number of trips each year (Shaheen, 2018 & Conway et al. 2018).

Shared mobility with respect to automobiles can be divided into two major categories, carsharing and on-demand mobility or ride-hailing (Cohen & Shaheen, 2018). Their study defines carsharing ss a service in which the users lease a vehicle for a short period and operates it themselves. To utilize a carsharing service, a user must possess a valid driving permit within the jurisdiction of the vehicle service area and be registered with the carsharing service so that insurance is provided, and a payment mechanism is available. The period can range from less than an hour to several days and is priced either by time or distance traveled. Ride-hailing can be defined as a mobility service which is used for a single trip and requested and processed typically through a smartphone app (Cohen & Shaheen, 2018). These services are dynamically priced depending on the service provider's supply of vehicles and demand for rides with the cost generally established before the ride begins. Today, these services are provided by people driving a vehicle, similar to a taxi; however, in the future it is assumed that trips will be provided by autonomous vehicles (Jittapirom et al., 2019). Figure 1 shows the categories for shared mobility types and examples of each service.

Within the carsharing category, sub-categories are defined based on the possible location of the vehicle at the end of the lease period or trip (Machado et al., 2018). These subcategories are station-based and free-floating, where station-based requires the user to return to specific locations and free-floating allows the user to leave the vehicle in any parking within a defined area or region,

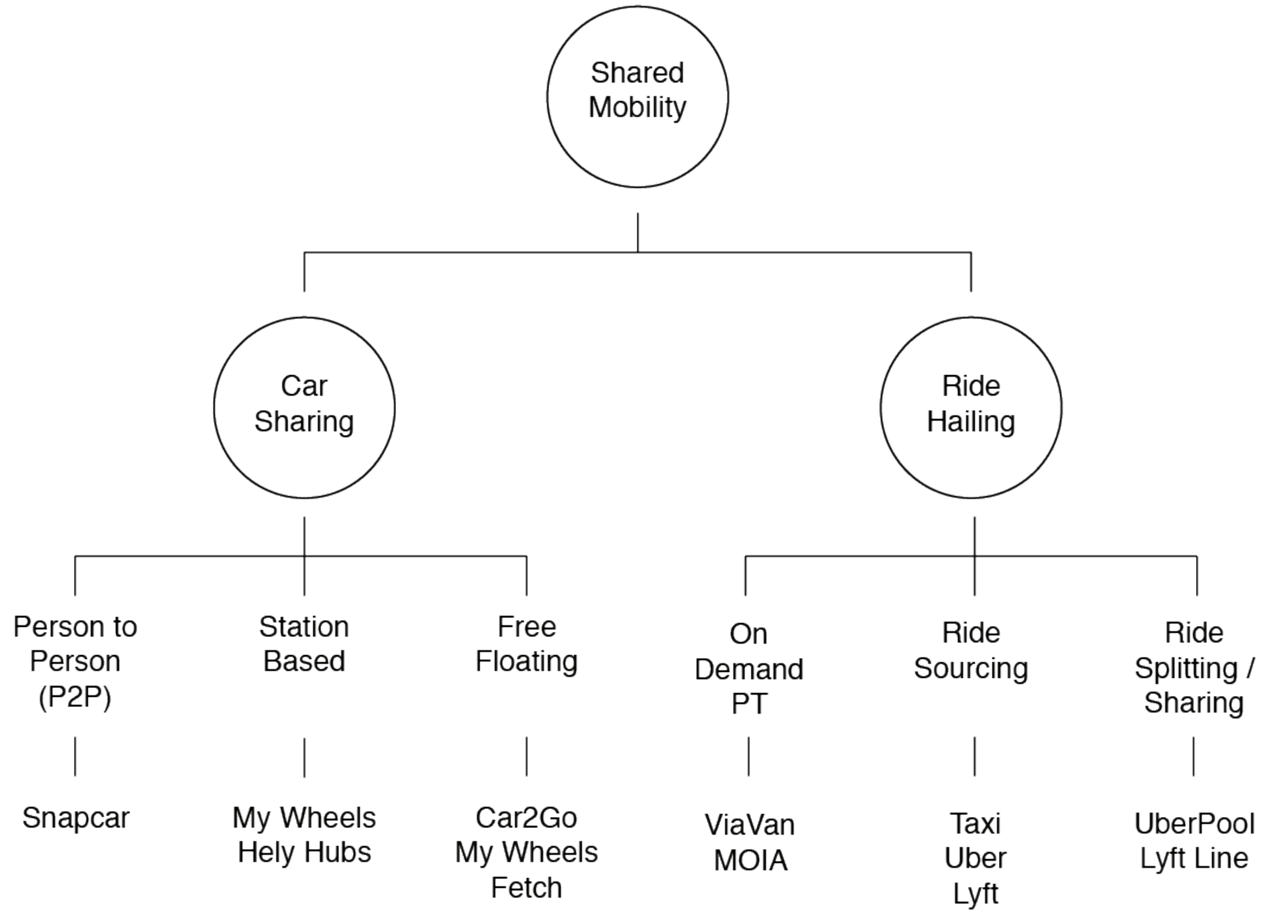

Figure 1. Categories of shared mobility adapted from Machado et al., (2018)

usually a neighborhood or city (Shaheen et al., 2015). The vehicles may be owned by individuals who allow the vehicles to be shared in return for a fee which is called person to person (P2P) or by a company operating and maintaining a vehicle fleet (Shaheen et al., 2015).

Within the ride-hailing category, sub-categories are defined based on characteristics of the ride service, including where the pick-up and drop-off points are located and whether the ride is shared with other passengers (Cohen & Shaheen, 2018). The subcategories are on-demand public transport (On-Demand PT), ride-sourcing, and ride-splitting (Machado et al., 2018). On-demand public transport can either be a lone ride or a shared ride with the pick-up and drop-off point optimized for the route of the vehicle as opposed to the exact location or destination of the user (Machado et al., 2018 & Pettersson, 2019). Ride-sourcing offers an individual ride from a requested pick- up location to the destination where the vehicle is not shared with other passengers (Cohen & Shaheen, 2018). Ride-splitting offers an individual ride from a requested pick-up location to the destination; however, the ride is shared with other passengers and may include stops to pick-up or drop-off other passengers along the route (Cohen & Shaheen, 2018).

The rise of shared mobility services and MaaS has inspired several studies to determine their impact on other modes, including public transport and personal vehicle ownership. Conway et al. (2018) studies the National Household Travel Survey (NHTS) in the United States and finds a growing number of households are shedding their personal vehicles for shared modes. In the NHTS study, ten percent of Americans were found to have use ride-hailing services in the past month, signifying a significant market penetration for a technology that was less than ten years old at the time of the survey. Additionally, the analysis found that households with higher vehicle ownership used ride-hailing services less signaling an inverse relationship between ride-hailing usage vehicle ownership. The relationship with public transportation, however, has produced mixed results with some areas seeing a complementary effect and others a substitutive effect. The study also found that higher income and younger households have a higher usage of ride-hailing services (Conway et al., 2018).

2.2 Electric Vehicles

Electric vehicles have seen significant technological improvements over the past decade with hybrid electric vehicles (HEV) first entering the commercial market in 2007 with the Toyota Prius (Ajanovic, 2015). As these vehicles use regenerative braking and the electrical systems are combined with an ICE, they do not contain plug in chargers and have no implications for public charging infrastructure or the grid (Ajanovic, 2015). Plug-in hybrid vehicles (PHEV) emerged as the next generation of electric vehicles with a charging connection. Due to the limited range of 30 to 60 km of the battery technology, an ICE is also provided in these vehicles. With PHEVs, the internal charging equipment does not provide the ability to connect to fast charging systems and Level 2 charging is the highest power method possible (Wolbertus & van den Hoed, 2019). Battery electric vehicles (BEV) are becoming the primary electric vehicle type as technology has improved the range limitations rendering an ICE backup unnecessary (Spöttle et al., 2018).

As development continues with BEVs, battery range is expected to further improve. Car manufacturers are supplying BEVs with Lithium Ion batteries which account for approximately half the cost for manufacturing the vehicle (Jung, Silva, & Han, 2018). Enhanced battery technology also currently shows a correlation with the weight of the vehicle as longer range batteries are heavier, resulting in heavier and less efficient vehicles (Jung et al., 2018). Figure 2 shows a linear trend between the vehicle range and weight for the main BEVs on the market (Electric Vehicle Database, 2020). From a review of the Electric Vehicle Database (2020), Tesla vehicles are shown to have both a higher vehicle weight and longer ranges.

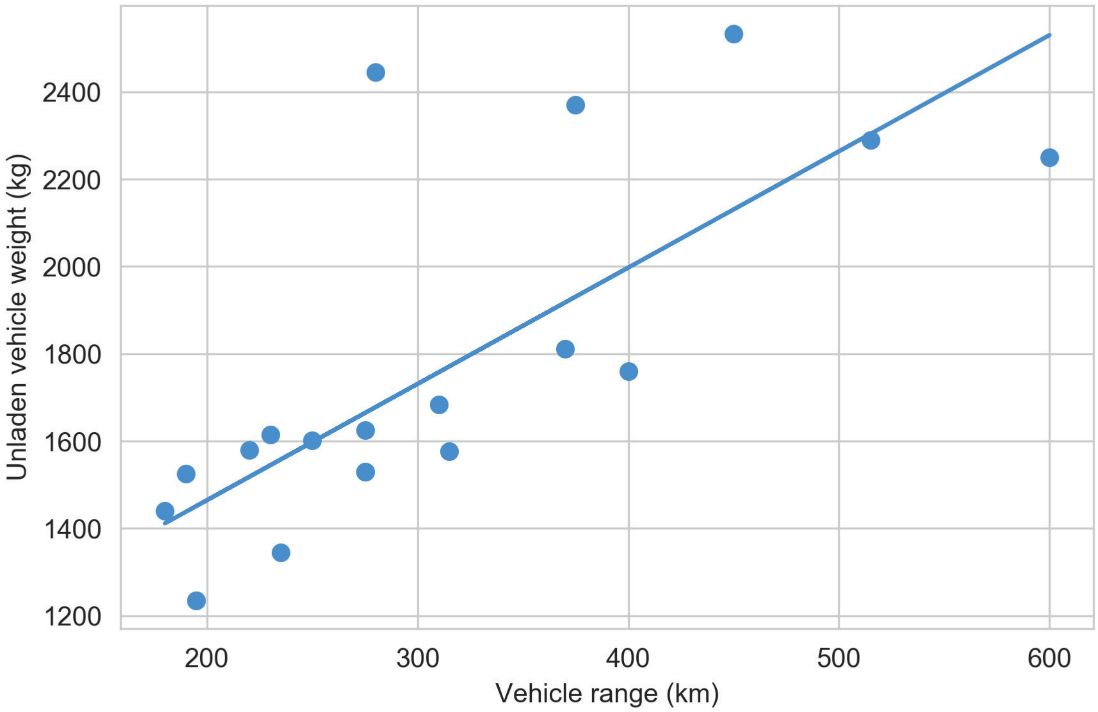

Figure 2. Vehicle weight to vehicle range and trend line for electric vehicles. (Electric Vehicle Database, 2020)

BEVs are categorized in two main groups, short range (less than 150 mi or 240 km) and long range (Jung et al., 2018). New long range BEVs, including the Ford Mustang Mach e reach driving distances of 600 km on a single charge (EV Database, 2020). The miles per gallon electric equivalent (MPGe) was also studied and showed the lighter vehicle models are more efficient (Jung et al., 2018). As new waves of electric vehicles arrive to the market, the impact of reducing the weight of the battery has the potential to drastically increase MPGe and ranges.

Light-duty electric vehicles including Electric L-Category Vehicles (ELV)s, electric scooters, electric cargo bikes, and electric bikes are additional mobility options that need to be charged through the electric grid (Santucci et al., 2016). These vehicles are popular in Europe and provide practical transport options for shorter travel distances, low speeds, and low amounts of cargo. Mobility hubs are emerging as an opportunity to provide a range of these services along with BEVs at strategic locations throughout the city with a concentration in proximity to transit stations (Bell, D., 2019). As hubs are implemented, they require public infrastructure and space for charging and parking. A major benefit with ELVs, however, is the smaller footprint where more mobility options can be parked in the space for a single car. Mobility hubs with multiple mobility options offer the benefit of combining charging infrastructure at a single location.

2.3 Charging Infrastructure Technology

Charging technology for EVs is a rapidly growing field with a range of types and power levels resulting in various considerations for deployment. Charging infrastructure is categorized by three power levels with Level 1 being appropriate for personal residential use and Level 2 and Level 3 for public and commercial use (Habib et al., 2018). For public charging in urban areas, Level 2 and Level 3 power levels and smart charging, including flexible charging and vehicle to grid (V2G), are the primary focus (Habib et al., 2018). These charging technologies have different impacts on the energy grid and require different energy infrastructures which results in variations in installation needs and costs for each type (Habib et al., 2018).

Level 2 is characterized by Habib et al. (2018) as providing a power output between 5kW and 50kW, with the majority of charges occurring at either 11 or 22 kW, and can provide a full charge in two to six hours. Level 3 charging is higher power, ranging from 22 kW to 60 kW with new higher power up to 350 kW entering the market (High Power Charging, n.d.). These chargers are considered ‘fast chargers’ or ‘ultra-fast chargers’ and can provide a full vehicle charge in less than an hour (Spöttle et al., 2018). Spöttle et al. discuss that charging points provide vehicles with either AC or DC current, with AC providing slower charging speeds for Level 2 chargers and DC providing faster charging speeds for Level 3. With AC charging as the standard for Level 2, vehicles contain an onboard converter to transition the power to DC to charge the batteries (Spöttle et al., 2018). Spöttle et al. explain Level 3 DC chargers convert the AC power of the grid at the charging point outside the vehicle which requires additional equipment and space for the charging infrastructure. Additionally, for ultra-fast charging, cooled cables are required (Spöttle et al., 2018). The cost of equipment and installation increases with the charging station power due to the additional equipment, substation connections, and upgrades for Level 3 charging (Nie, Y. & Ghamami, M., 2013).

In addition to the different levels of charging infrastructure, there are also different types of plugs used to connect a vehicle to the charging station. The European Union (EU) has standardized Type 2 plugs for Level 2 charging points throughout the block resulting with all EVs having the ability to connect (Spöttle et al., 2018). There are competing standards for Level 3 charging with the Combined Charging System (CCS) and CHAdeMO plug types based on manufacturer preference and not yet standardized by the EU (Ronanki et al., 2019). Their study explains that CCS connectors are compatible with both AC and DC charging with the capability to handle up to 350 kW. Additionally, CCS connectors are the standard being developed by the Charging Interface Initiative founded by several major European car manufacturers. CHAdeMO connectors, developed by several major Japanese manufacturers, are capable of accommodating power up to 400 kW. Additionally, Tesla

Table 1. EV Charging Point Specifications for Allego and EV Box (Allego, 2020 & EV Box, 2020)

Level	Manufacturer	Model	Type	Max Power (kW)	Connector Type	Vehicle Connections
2	EVBOX	Public Charging Point	AC	22 / 11	Type 2	2
2	EVBOX	Business Line	AC	22 / 11 / 7.4 / 3.7	Type 2	1 or 2
2	Allego	ICU Twin	AC	22 / 11	Type 2	2
2	Allego	DC Wallbox	DC	24	CCS2 / CHAdeMO	1
3	EVBOX	Troniq 50	DC / AC	50 / 22	CCS2 / CHAdeMO / Type 2	1
3	EVBOX	Ultroniq 200A	DC	175	CCS2 / CHAdeMO	1
3	EVBOX	Ultroniq 500A	DC	350	CCS2 / CHAdeMO	1
3	Allego	Efacec QC 45	DC / AC	50 / 43	CCS2 / CHAdeMO / Type 2	1
3	Allego	High Power	DC	350	CCS2 / CHAdeMO	1

Superchargers have a special type of plug that only allows Tesla vehicles to connect (Ronanki et al., 2019). Table 1 provides a summary of Allego and EVBOX, two common charging station manufacturers, Level 2 and 3 charging solutions.

Other charging methods currently in development include static and dynamic inductive charging, static and dynamic capacitive charging, and dynamic conductive charging (Collin et al., 2019). Inductive charging uses charging coils installed on the bottom of the vehicle and in the road surface which transfer the power through magnetic coupling. Charging can occur either while the vehicle is still (static) or while driving (dynamic) and eliminates the need for various plug types. Additionally, dynamic charging eliminates the need for waiting. Capacitive charging uses plates in the bottom of the car and in the road surface which transfers the power wirelessly at high frequencies (Collin et al., 2019). Dynamic conductive charging transfers power through making a physical connection between the charging surfaces. These can be overhead, similar to the pantograph system on trains, or in the road surface. Both conductive methods encounter challenges due to height of the overhead cabling system or weather issues, construction, and safety within road systems (Collin et al., 2019). Battery swapping technologies have also been developed and tested; however, implementation on a large scale is hindered by the lack of battery standardization and vehicle design (Adegbohun et al, 2019). Battery swapping would also require added space for the swapping infrastructure and time for the battery swap to occur. Plug-less charging technologies present many solutions for reducing the inconvenience of the current charging system; however, these systems also encounter new implementation barriers. Although inductive charging is the most developed, capacitive charging has promising potential as it generates efficiencies greater than 90% during the charging process (Collin et al., 2019). Conductive charging and battery swapping would be more appropriate for special cases such as freight vehicles or other specialized fleets.

Smart charging, also referred to as optimized charging or flexible charging, leverages a dynamic power supply during vehicle charging that is adjusted and optimized due to constraints on the power grid (Abousleiman & Scholer, 2015). Smart charging has been developed in response to the intermittence of renewable energy including wind and solar to match the cyclical nature of power consumption loads. Amsterdam, for instance, began testing a smart charging network for its Level 2 public charging stations using 102 charging stations with 50 stations set to provide a constant 25A (Buatois et al., 2019). The other 52 stations provided 35A except during peak demand hours during the morning and evening when the power reduced to 16A. Overall, the additional 10A in the flex chargers during off-peak periods compensated for the reduced power during peak periods and provided faster average charging speeds than with the constant 25A. Their results indicate that there is limited impact to the user overall of the slower speeds during peak times and that smart charging can help to reduce the costs of added generation and grid distribution investments (Buatois et al., 2019).

Vehicle to grid (V2G) is another emerging technology to reduce the impacts on the grid due to EV charging and help to facilitate decentralized energy storage (Habib et al., 2018). V2G systems provide bidirectional power flow capabilities to utilize the EV battery as storage for the grid that can be utilized during peak grid demand. These systems then provide financial income to the EV owner at peak rates, creating additional revenue streams for the user (Habib et al., 2018). The major challenges with V2G include the additional wear on the vehicle batteries due to the increased loading and unloading, infrastructural costs for bidirectional charging equipment, and customer acceptance due to lower charge status of their battery during peak times (Habib et al., 2018).

Smart management of public charging infrastructure is an important aspect for ensuring charging points availability as greater numbers of EVs enter the market. Smart management of parking locations has been implemented and studied by applying a fee on vehicles if they continue to occupy the charging location after they are fully charged (Wolbertus, R., and Gerzon, B., 2018). Results of the study showed users were likely to move their vehicles when a fee is introduced, resulting in increased efficiency of charging locations. Dynamic allocation of parking at charging points has the ability to increase the efficiency of charging points by allowing users to reserve spaces and navigate them to the reserved space (Cassandras & Geng, 2014). Through the dynamic resource allocation model by Cassandras and Geng, space utilization can increase up to 14%; travel time to charging spaces can be reduced by 9.5%, and travel time looking for a space can decrease by 30%.

2.4 Charging Behavior and Spatial Considerations

Research performed through data analysis, surveys, and modeling found that user groups and motivation for using Level 2 or Level 3 charging vary (Wolbertus, & Van den Hoed, 2019). Studies have shown that Level 2 chargers at trip destinations are preferred to Level 3 fast chargers for daily or inner-city travel (Gnann et al., 2018). A study of charging usage in Norway and Sweden revealed Level 2 as the primary charging mode over Level 3 due to the convenience of home and workplace charging (Gnann et al., 2018). Users in the study are also found to take advantage of opportunity charging, when they connect to Level 2 charging when available at a destination even though battery levels are not low enough to necessitate charging for the remainder of their trip. As a higher concentration of Level 2 chargers are provided, Zang et al. (2018) found the demand on fast charging decreases due to increased travel success ratios where the user is able to complete their trip without needing to charge. It can be interpreted that Level 3 charging is used to complement Level 2 charging when Level 2 charging is not available when the vehicle is not in use. Sun et al. (2016) found in Japan that situations where Level 2 charging is not available at the origin or destination, private users are willing to detour up to 1750 meters on working days and 750 meters on non-working days and commercial users will detour up to 500 meters during either occasion for Level 3 charging. Additionally, the study found that users prefer Level 3 fast-charging stations to be located at refueling stations. Overall, when Level 2 chargers are available when the EV is not in use, the demand of fast Level 3 chargers is reduced, except during longer distance travel (Wolbertus, R., & Van den Hoed, R., 2019).

As many cities have used demand and request-driven policies to install early charging infrastructure, an uneven distribution of charging points exists in cities. To reduce the barrier for new uptakes in EVs, a more even distribution should be planned. The travel success ratio, as used by Zang et al. (2018), can provide a measurement tool for the concentration of chargers throughout a given area by modeling the probability that charging infrastructure is available at the origin or destination of trips.

With existing charging infrastructure networks in place, citizens' willingness to travel for charging locations need to be considered (Mashhoodi et al., 2019). Through a stated-choice experiment, Wolbertus and Van den Hoed, (2019) found that fast Level 3 chargers are preferred to Level 2 chargers when the distance is greater than 200 meters from the charging point to their home or destination. Mashhoodi et al. found that by increasing the walking distance to a five-minute walk or 400 meters, cost savings of 40% for charging infrastructure could be achieved. This distance, however, does not consider users with mobility issues including disabilities. Charging infrastructure for these demographics may need to be prioritized to within 50 meters (Mashhoodi et al., 2019). Depending on the urban density and market share of EVs, smaller distances may become necessary to accommodate the saturation of EVs. With the majority of research focused on private EVs, the spatial distribution of shared mobility vehicles requires further investigation; however, the distances of 200 to 400 meters to charging locations could be used to establish guidelines for spatial distributions of shared mobility vehicles, mobility hubs, or pick-up points. Additionally, these findings present a challenge for leveraging non-mixed-use commercial office space charging infrastructure to meet demands during off or closed hours due to distance from households.

The additional costs and waiting times for Level 3 fast chargers can be prohibitive to wide distribution throughout inner-city areas (Wolbertus & Van den Hoed, 2019). Availability of fast-charging networks improve adoption of EVs for intercity travel over medium and long distances due their mitigation of range anxiety and the ability to serve as a backup when Level 2 charging is not available (Nie, & Ghamami, 2013). Level 3 fast chargers should therefore be planned in proximity of inter-city and longer-distance travel. Wolbertus and Van den Hoed, (2019) found that, in Amsterdam, taxis are the principle users of the fast charging network.

2.5 Government and Policy

To transition mobility systems away from fossil fuels and ICE vehicles and incentivize shared mobility, governments need to implement policies aimed at addressing this reliance within the current mobility system. Policy instruments are the means for government to influence or effect goods and services (Howlett, 2000). Howlett categorized policy instruments as authoritative, treasure, nodal, or organizational depending on their characteristics, functions, and objectives. These policy instruments can be implemented at different levels of government, depending on their scope, and have a range of effects on the overall mobility system (Rietmann & Lieven, 2019). When developing policy tools, it is helpful to review policies and their effects in areas that have tested or implemented similar measures. Reviewing existing policy instruments and typologies provides a baseline for the government in creating their own instruments to influence shared and clean mobility.

Authoritative instruments are policies that directly affect goods and services in the market through regulatory means (Howlett, 2000). Authoritative instruments for the development of vehicles can include fuel consumption standards, emission standards, and vehicle weights (Banister et al., 2000). Governments can also use authoritative instruments, such as land use planning, parking controls, and vehicular access controls, to affect the mobility system. Land use planning and the land area directly controlled by governments varies significantly among the levels of government and between different cities or regions. While national and provincial or state governments can set urban growth boundaries and plan large-scale transportation networks, cities and regional governments influence the local and inner-city land-use policies (Rietmann & Lieven, 2019). Local land-use policies can include allocating public space and road space for parking, charging facilities, or development. In regions where governments have less direct control, zoning and permitting regulations are used to determine the locations and types of facilities the private sector can build. This contrast is illustrated in Amsterdam where the city owns a vast majority of the land but makes it available through ground lease schemes as compared to in American cities where the government owns right-of-way, parks, and government facilities but not typically the land beneath private buildings (Amsterdam, 2020a). Depending on the region and power of the levels of government, the ability to enact and effectiveness of authoritative instruments can vary significantly.

Treasure instruments are financial or economic policies aimed at incentivizing or discouraging goods or behaviors (Howlett, M., 2000). Treasure instruments are generally applied through taxes, grants, or fees and can be applied throughout the production cycle of goods or directly to the consumers. Through tax policy, governments have the ability to impose or waive taxes for specific purposes or uses, such as removing sales tax from the purchase or lease of EVs (Rietmann & Lieven, 2019). Direct subsidies can be offered either directly to the end user or through the supply chain. Amsterdam's subsidy of €3,000 for an electric taxi or €5,000 for van or delivery vehicle is an example of a direct subsidy (Amsterdam, 2020b). These fiscal incentives can be further combined with national-level subsidies (Reitman, N., & Lieven, T., 2019). In addition to the vehicles, governments have the ability to either partially or fully subsidize the charging infrastructure installations. These can provide pathways for commercial or office facilities to install charging infrastructure despite unsubsidized capital costs being prohibitive to their economic business case. Cities can also provide financial incentives to encourage citizens to use shared mobility options (Banister et al., 2000). Incentives can range from a number of free trips to providing mobility companies contracts to supplement public or paratransit operations. Through the use of treasure instruments, governments can address the financial barriers to transitioning to shared and clean mobility.

Nodal instruments are tools that provide information or education to influence market behaviors (Howlett, 2000 & Banister et al., 2000). Governments can use nodal instruments to heighten awareness or develop marketing campaigns aimed at educating the public about the availability of certain services, such as shared mobility. Other nodal policies can include eco-labeling of vehicles and services to bring awareness to consumers' choices (Bannister et al., 2000). Nodal instruments also include the availability of information provided by governments (Howlett, 2000). Through collaboration with market parties, government can use mobility-related data associated with spatial planning and mobility behavior as an instrument for innovation. As governments have a wide control of resources to disperse information, nodal instruments have the ability to nudge public choice, opinion, and consciousness toward sustainable mobility.

Organizational instruments are the tools that governments control through their administrative means or public infrastructures they manage (Howlett, M., 2000, Hood, C., 1983). Governments can form departments or groups, such as a smart mobility department, to lead initiatives and collaborations to advance shared mobility. Governments can also change and repurpose public space, such as parking, to promote sustainable mobility goals (Banister, 2000). Parking instruments can be used to incentivize EVs and shared mobility through reducing the availability of public parking and reserving or prioritizing parking for electric and carsharing vehicles (Rietmann & Lieven, 2019). Cities can also increase and decrease the availability of public parking facilities to create added pressure or cost on ICE vehicles and ownership of personal vehicles, especially when coupled with the prioritization of EVs. In Amsterdam, a range of parking incentives are leveraged for the public to transition to electric vehicles and for shared mobility options (van 't Hull & Linnenkamp, 2015). For example, EVs receive priority in waiting lists for parking permits over ICE vehicles and have reserved parking at charging locations (Amsterdam, 2020).

Electric vehicle policies can be implemented at every level of government, ranging from the supranational level at the EU to cities and neighborhoods with each level having different scales and authority to influence the market (Rietmann & Lieven, 2019). Supranational or national governments have larger budgets for subsidies of vehicle purchases and can invest in larger technical developments. They can set pollution standards, fuel economy standards, and design specifications, such as for plug type (Banister et al., 2000). These levels of government also have the ability to control policies over international and national highways, freight, and shipping. Regional governments, such as states or provinces, vary in level of influence in the EV market based on whether they affect larger policies like national governments or focus on specific regions and metropolitan areas (Albrechts, Healy, & Kunzmann, 2003). Soft spaces, clusters of multiple municipalities or regional governments, can be created to foster collaboration between different administrations (Allmendinger et al., 2015, van 't Hull, & Linnenkamp, 2015). Examples of soft spaces can include the Metropolitan Region of Amsterdam (MRA), Metropolitan Region of Rotterdam and Den Haag (MRDH) or community improvement districts (CID)s. City and metropolitan governments have the ability to set local rules including land use policies, operational policies, parking policies, and local roadway jurisdiction, but they also have smaller budgets which results in more limited subsidy options (Rietmann & Lieven, 2019).

Many European cities, including Amsterdam, Paris, and Ghent, have implemented various scheme types and scales for controlling vehicular access within their cities. Measures range from Amsterdam where through traffic is not permitted on a number of streets, to Paris with a low emission zone within the ring road of the city, to Ghent where the entire city center has been cut off from private cars and only public transit and para-transit vehicles can access (Lopez, 2018). In 2019, Amsterdam announced a ban on ICE shared and commercial vehicles in the inner-city beginning in 2025 and a ban on all ICE vehicles in 2030 (Amsterdam Clean Air Action Plan, 2019). These local policies have the ability to influence shedding a private vehicle for carsharing or transitioning to an EV much more attractive due to the associated added inconvenience and financial burdens of the policies.

2.6 Literature Review Conclusion

There are a range of technical, behavioral, and policy-related subjects to be considered when planning the charging infrastructure for shared electric mobility. Within shared mobility, there are two main classes, carsharing and ride-hailing, which have significantly different charging needs. Carsharing vehicles mostly use Level 2 charging where the vehicles are distributed throughout the urban area or at mobility hubs. As can be deduced from the charging patterns of Amsterdam taxis, ride-hailing vehicles use Level 2 charging when not in use or for opportunity charging but use Level 3 fast charging more commonly due to the longer distances traveled per day. The majority of technological charging developments center on dynamic and V2G charging for Level 2 and ultra-fast charging for Level 3. Level 2 developments result in better performance of the electric grid and Level 3 developments focus on reducing charging time. EVs are also developing longer ranges; however, these ranges are achieved through larger batteries which result in heavier vehicles and reduce the efficiency of power in the vehicle. As governments seek to increase the usage of EVs, a variety of policy measures can be implemented or tested, depending on the government level and budgets. Some of the higher-impact policies include prohibiting ICE vehicles from entering certain areas of the city and providing financial and priority incentives for EVs and shared EVs. The spatial distribution of charging infrastructure throughout an urban area can be planned through understanding the desire of users to have Level 2 charging nearby to their homes and Level 3 chargers along frequently traveled corridors or at waiting locations for ride-hailing services that will utilize the opportunity charging. With shared electric mobility and private EVs using the same charging infrastructure, the dynamic relationship of competition between them is in need of further study.

3 Baseline Analysis

The City of Amsterdam is aggressively pursuing the transition to electric vehicles; therefore, it is used as the case study for this research due to the availability of open data, aggressive goals in this field, and proximity to additional resources (Amsterdam, 2019b). In this section, the baseline data for the Netherlands and Amsterdam will be presented. The baseline data includes trends in shared mobility, personal vehicle ownership, parking, and a spatial analysis of the distribution of charging points and their corresponding utilization at a post code level. This baseline analysis is performed with data gathered through open as well as proprietary sources and informs the inputs and results for the system dynamics model at the center of this research.

3.1 Amsterdam Overview

The City of Amsterdam is located in the North Holland province of the Netherlands and has a population of approximately 872,000 as of 2020 (Amsterdam, 2020c). The Metropolitan Region of Amsterdam (MRA) has a population of approximately 2.5 million (Metropoolregio Amsterdam, 2020). Amsterdam is a dense city with a developed network of bicycle paths, roadways, motorways, and public transport. As of 2017, Amsterdam's modal share was 35% bicycle, 24% walking, 19% vehicles, and 19% public transport for workday travel (Amsterdam, 2019c). Amsterdam has a total land area of 174,315,110 m^2 with a large network of canals and waterways throughout the city (Amsterdam, 2020d). Figure 3 shows the overview of Amsterdam with the major regions of the city delineated. Additionally, the population is shown for each postcode.

3.2 Shared Mobility

Shared mobility services in the Netherlands and Amsterdam have experienced an increase in users and providers over recent years (CROW, 2019). As discussed in the Literature Review, shared mobility can be broken into two main categories: carsharing and ride-hailing. Below, available data will be analyzed to highlight important trends in the shared mobility sector.

3.2.1 Carsharing

As of 2019, the Netherlands has over 51,000 shared cars with over 9,000 located in Amsterdam (CROW, 2020a). The number of shared cars in the Netherlands has experienced continuous growth over the past five years with 14,352 shared cars in 2015 and over 51,000 shared cars in 2019 (CROW, 2020b). Shared EVs comprise 6.8% of the carsharing vehicle market for the Netherlands (CROW, 2020a). Amsterdam has experienced steady growth in the number of shared cars with approximately 2,700 shared cars in 2015 and 9,000 shared cars in 2019 (CROW, 2020b). Amsterdam's carsharing vehicle fleet is 88% electric, making it significantly more electric than the rest of the Netherlands carsharing vehicle market (CROW, 2020a). Figure 4 shows the trend of shared cars in Amsterdam from 2015 to 2019.

Through analyzing the data from CROW (2020b), both the Netherlands as a whole and Amsterdam have experienced significant growth in the number of shared cars from 2015 to 2019. The Netherlands has experienced an average growth rate of 36.7% during this period while Amsterdam has experienced an average growth rate of 31.1%. 2016 featured a spike in growth for both the Netherlands and Amsterdam while the other years average to about 30%.

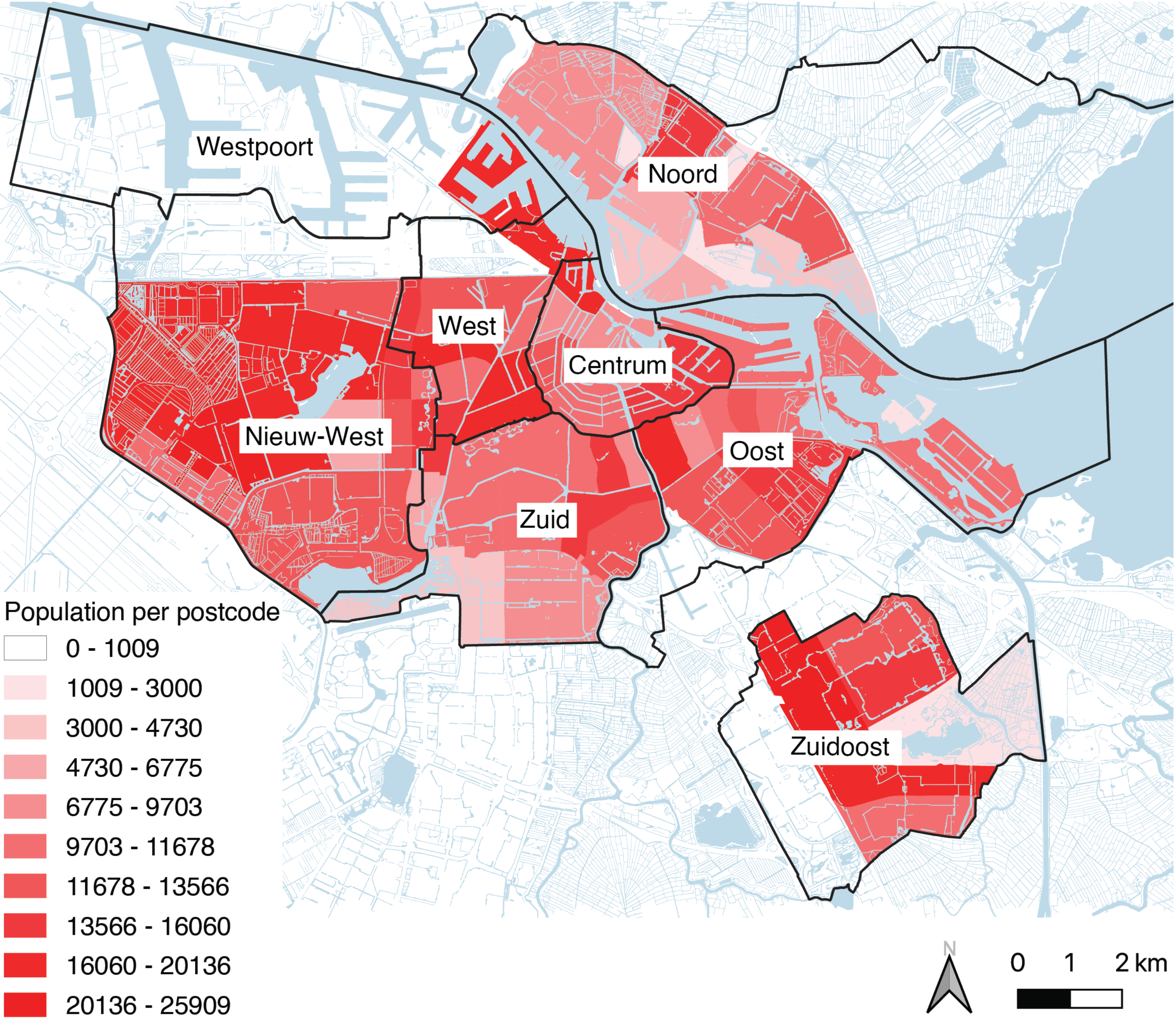

Figure 3. Map of Amsterdam regions with population per postcode. (Amsterdam, 2020d)

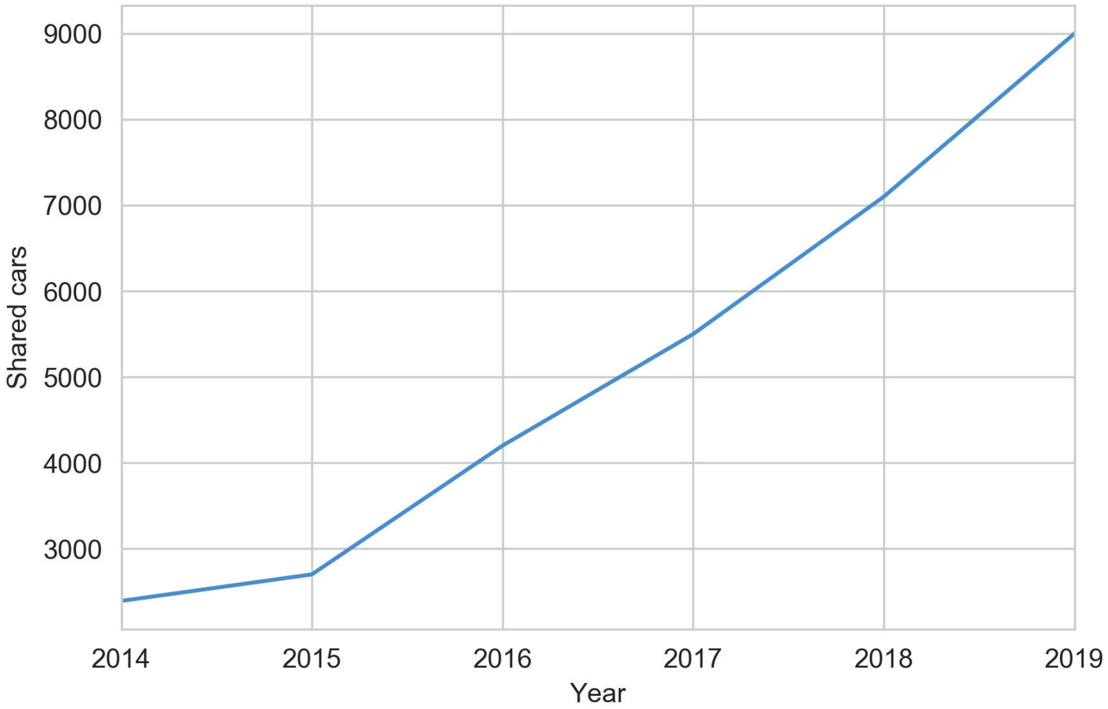

Figure 4. Carsharing vehicles in Amsterdam (CROW, 2020b)

3.2.2 Ride-hailing

Ride-hailing, for the purposes of this research, includes digital platforms (Uber, Lyft), on demand public transit (ViaVan), and traditional taxi services. Due to the regulations in the Netherlands and Amsterdam, similar permits are required for these services and distinguishing between them is not feasible (RDW, 2020). Approximately 35% of drivers for one service also drive for another service creating significant overlap between the ride hailing providers (Discussion with Uber, 2020).

In Amsterdam, 5000 to 7000 taxis operate, providing approximately eight million rides per year (Amsterdam, 2019d). These rides have experienced a 19% increase from 66% in 2013 to 85% in 2019 in using a digital platform for hailing rides (Amsterdam, 2019d). All taxis must be registered with the RDW, the Netherlands Vehicle Authority (Amsterdam, 2019d). Any taxi registered in the Netherlands can provide rides in Amsterdam through reservations or using a digital platform. To provide rides curbside or at a taxi stand, however, taxis must have a specific registration with the City of Amsterdam and have the corresponding roof light (Amsterdam, 2019d).

In addition to taxis, Uber and Via Van operate ride-hailing services in Amsterdam (Amsterdam, 2019b). The City of Amsterdam and Uber established a 'Social Charter' in 2019 that permits Uber to operate in Amsterdam on the conditions of additional provisions for sustainability and information sharing with the city (Amsterdam Smart City, 2020). Through the social charter with Uber, an agreement for 750 electric vehicles by the end of 2020 was established; however, actual data regarding the fleet size and share of electric vehicles for Uber and Via Van remains unavailable to the public and was not provided for use in this study.

3.3 Vehicle and Electric Vehicle Trends

In 2020, the Netherlands registered a total of 8.67 million passenger vehicles with 235,000 vehicles registered within the city limits of Amsterdam (RDW, 2020 & Amsterdam, 2020e). The Netherlands and Amsterdam have both experienced continued growth in the total number of vehicle registrations, although the growth rate has slowed from 2017 to 2019. The growth of vehicle registrations from 2015 to 2019 in Amsterdam is shown in Figure 5. This period has a mean growth rate of 0.69%. For Amsterdam residents, personal vehicles were used for approximately 19% of trips in 2017 and 46% of trips were visitors (Amsterdam, 2019c).

According to data from CBS (2020), the share of electric vehicles in the Netherlands has been growing over the past several years; however, the share of electric vehicles within Amsterdam is not available. With the Netherlands registering a 1.6% total market share for EVs in the beginning of 2019 and 2.3% at the beginning of 2020, a significant increase is needed to transition to zero-emission mobility (CBS, 2020). In total, approximately 197,600 plug-in electric vehicles are registered in the Netherlands (CBS, 2020). While PHEVs were adopted early and hold the majority of the electric vehicle market, data from CBS show sales for BEVs began to overtake PHEVs in 2017 and continue to grow. Figure 6 shows the total number of plug-in electric vehicles in the Netherlands. At the beginning of 2020, a growth rate of 139% was observed for FEVs over 2019.

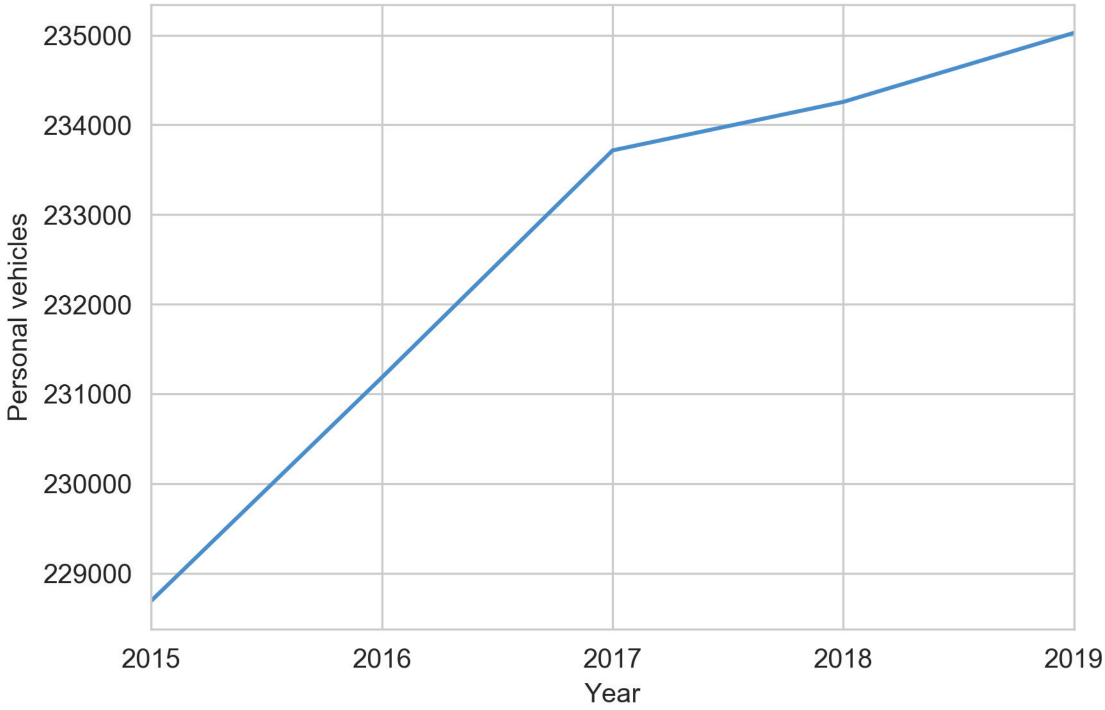

Figure 5. Number of vehicles registered in Amsterdam. (Amsterdam, 2020e)

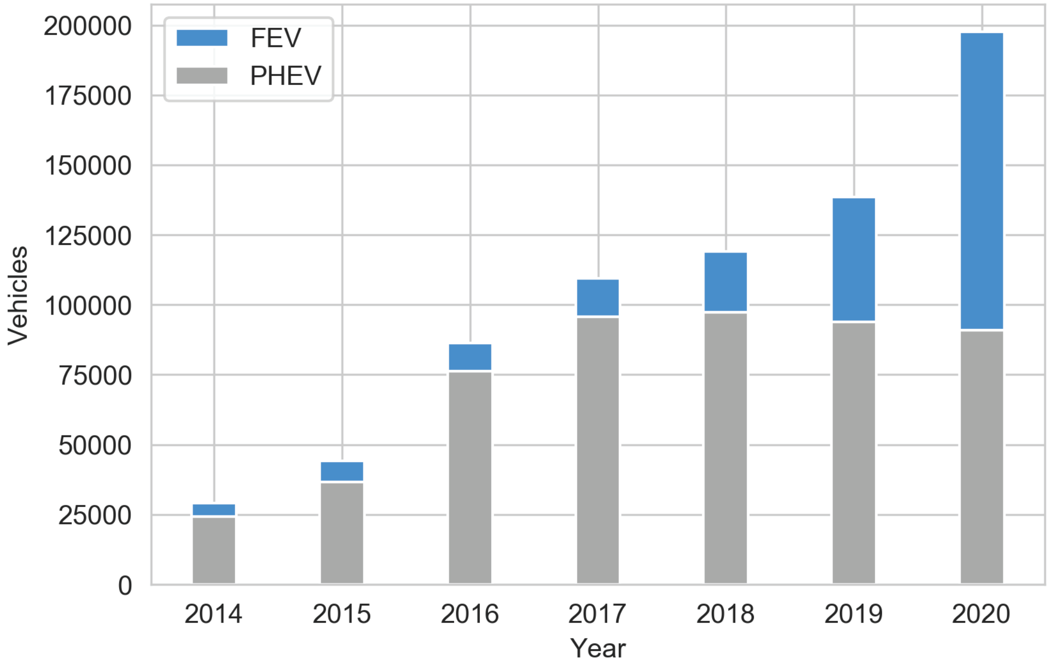

Figure 6. Growth of electric vehicles in the Netherlands (CBS, 2020)

3.4 Parking

Public parking in Amsterdam is administered through the City and citizens can apply for a parking permit through the city website (Amsterdam, 2020f). Parking permits cost between €15 and €280 per six months, depending on the neighborhood (Amsterdam, 2020f). Currently, there is a waiting list for parking permits ranging from one month to a year with electric vehicles given priority (Amsterdam, 2020f).

In Amsterdam, there are a total of 267,000 public parking places throughout the city with 13,795 reserved for special uses (Amsterdam, 2020d). The majority of parking in Amsterdam (approximately 70%) is classified as public parking with the remainder private (Ostermeijer et al., 2019). Through analyzing the spatial data from Amsterdam, the number of parking locations are found to be greater for the postcodes on the exterior of the city, which have high populations. Amsterdam's data also showed that of the special use spots, approximately 3,200 are reserved for EV charging with each Level 2 charger generally servicing two vehicles. Through the Autoluw Agenda, Amsterdam plans to remove approximately 1,000 parking spaces per year over the next ten years, specifically in the central neighborhoods (Amsterdam, 2019c).

3.5 Spatial Analysis

The spatial analysis for charging point data aims to answer the spatial aspects of the research question: where cities should plan electric vehicle charging infrastructure. This section analyzes the current spatial distribution of charging infrastructure in Amsterdam and recommends a spatial distribution strategy for future charging locations. As discussed in the Literature Review, there are three main categories for charging infrastructure. Level 2 chargers can take up to six hours to fully charge a vehicle and Level 3 chargers can reach approximately 80% charge in 30 minutes or less. These characteristics mean that the strategy for their spatial distribution should be different as vehicles remain parked for long periods of time during Level 2 charging and the user typically actively waits during Level 3 charging. The following sections discuss the current status of each charging level followed by recommendations for future expansion.

3.5.1 Level 2 Charging

For the purposes of this research, the analysis of Level 2 charging distribution is performed on a postcode level for Amsterdam. The accessibility of charging infrastructure to the population is also discussed at this level. The population of Amsterdam at a neighborhood level is available through Amsterdam's open data portal and is aggregated to the 4-digit postcodes in the city to conform with the charging data. Level 2 chargers have been installed throughout Amsterdam through a demand-driven system where residents request public charging points on their street through the city's website (Amsterdam, 2020g). Per the charging point dataset provided, Amsterdam had 1796 Level 2 chargers at the end of 2019 (Confidential source, 2020). Figure 7 shows the number of Level 2 chargers per postcode throughout Amsterdam.

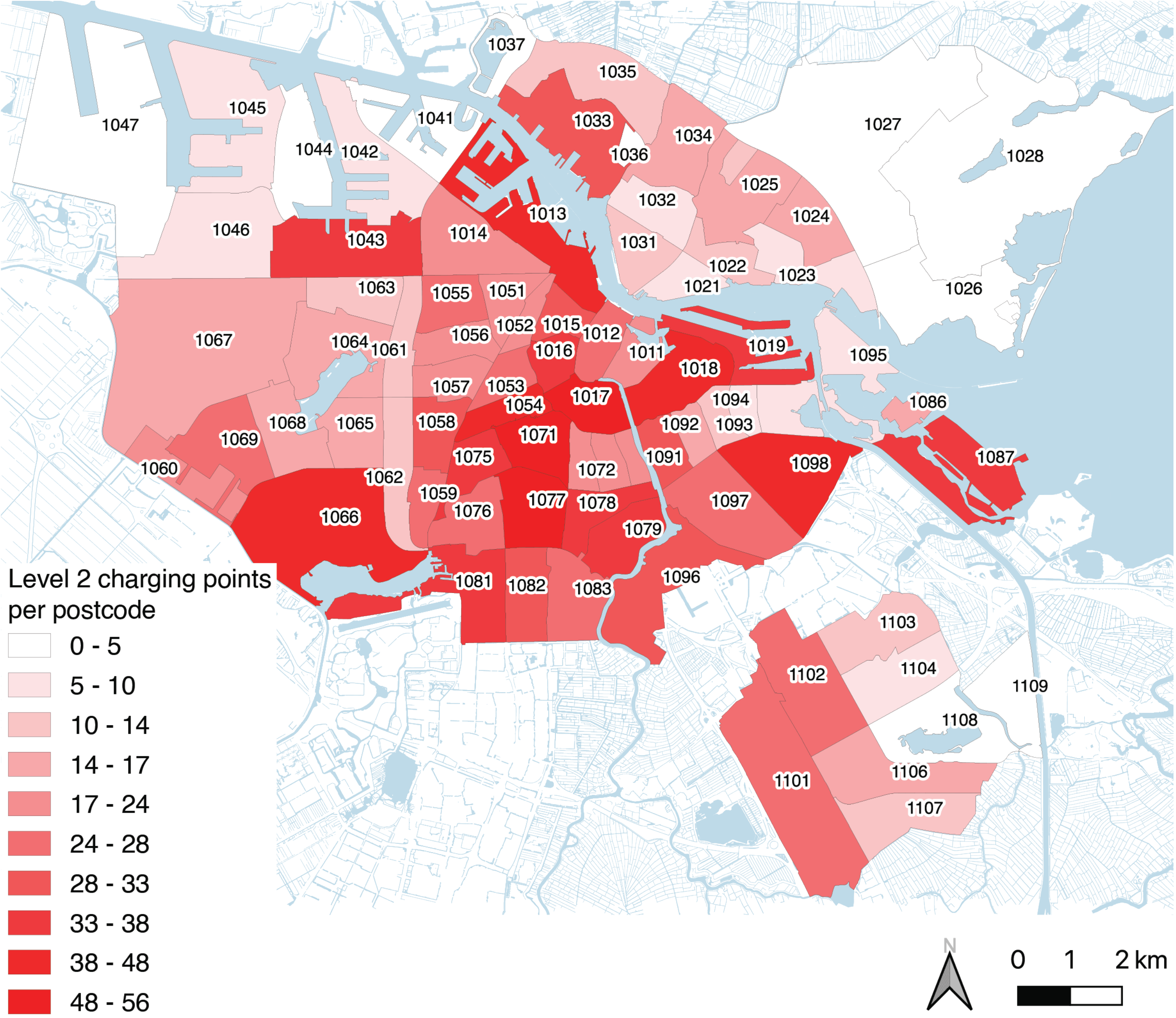

Figure 7. Level 2 chargers per postcode in Amsterdam

Comparing the population and number of charging points available provides insights into the availability of charging in that post code. Outer areas of the city have the highest populations per charging point, resulting in lower accessibility or there being less of a probability of finding a free charging point when needed. The center of Amsterdam and surrounding postcodes have a much lower population to charging point ratio meaning that residents here have a higher probability of finding a charging point when needed. Figure 8 shows the population per Level 2 charging point, indicating the areas with lower accessibility to charging.

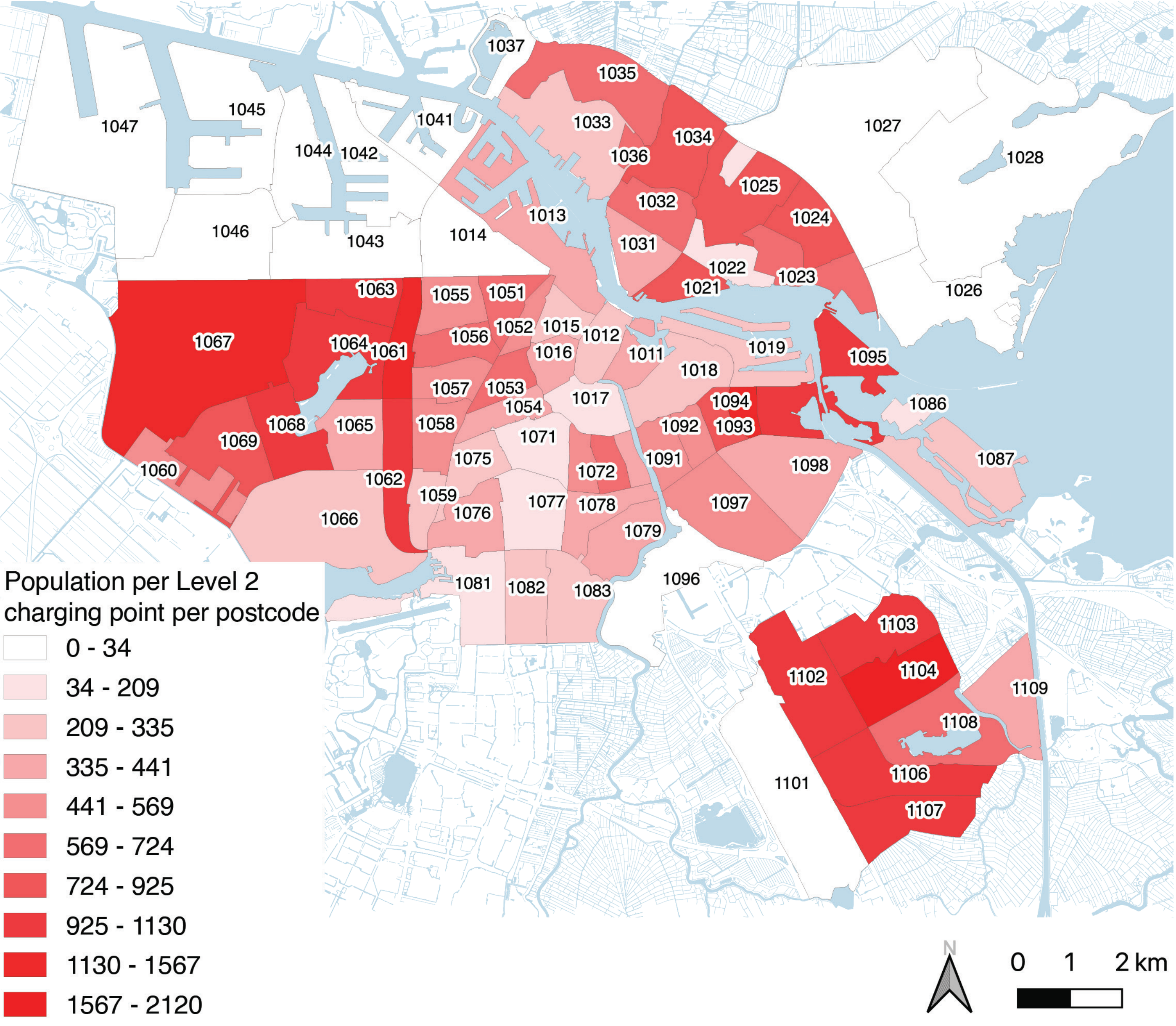

Figure 8. Population per Level 2 charging point in Amsterdam

The relative distance for the population to the charging points can determine how far people must walk to a charging point. Using a 200-meter radius buffer around Level 2 charging points across Amsterdam, the coverage is calculated per postcode. There are 26, or 34% of, postcodes with 90% or greater coverage and 21, or 28%, with less than 50% coverage. Several of these postcodes are industrial areas with very small populations. Additionally, some postcodes contain a high level of vacant land (postcode 1067) even though there is a relatively high population. Figure 9 shows the percent of each postcode within the 200-meter radius of a charging point. Notably, the Zuidoost and Westpoort neighborhoods have a relatively low proximity to charging points.

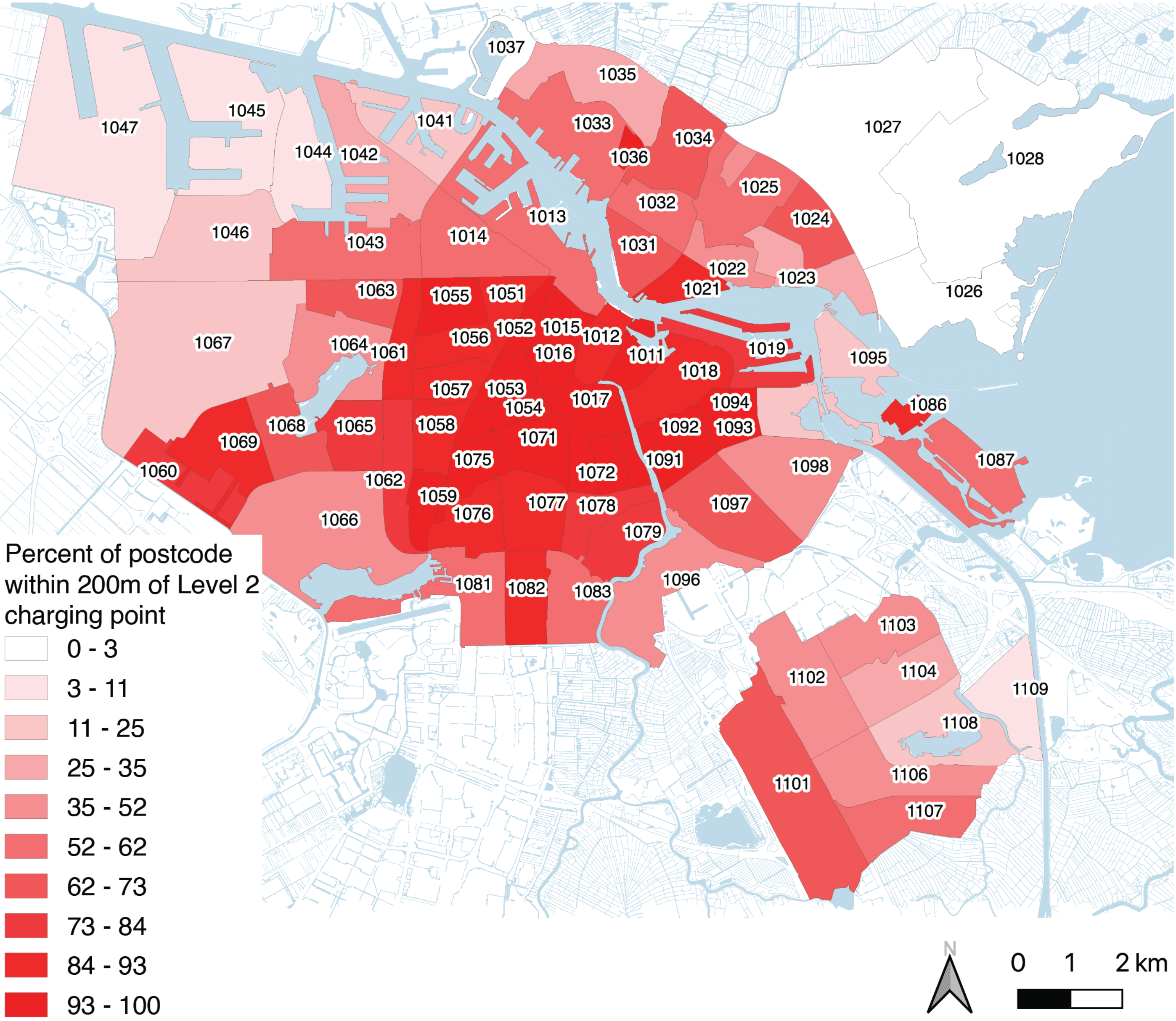

Figure 9. Percent of postcode within 200-meters of a charging point in Amsterdam

This spatial analysis shows that Amsterdam has a high level of spatial coverage for Level 2 charging infrastructure. With the central neighborhoods having a high proximity to charging points and a relative high number of charging points per population, this area is the best served for public EV charging. Other neighborhoods in Nieuw-West and Zuidoost have less spatial coverage of charging infrastructure and higher populations to public charging points. As additional charging infrastructure is planned, providing these neighborhoods with more points and a higher spatial distribution will make EVs a more attractive choice when purchasing a vehicle. Improving the quantity and distribution in these neighborhoods can also provide more opportunities for shared EVs to charge, increasing their attractiveness.

Public charging data, provided by EcoMovement (2020), was obtained for four months, from November 2019 through February 2020 for Amsterdam. The EcoMovement data is aggregated at the postcode level and provides the total minutes of charging time per hour, number of chargers, and a distinction between slow and fast chargers. Using this data, the average charging utilization is calculated on an hourly basis per postcode. Figure 10 shows the Level 2 charging utilization for each postal code from November through February. The figure shows that the majority of postcodes experience a mean charging utilization between 40 and 60 percent.

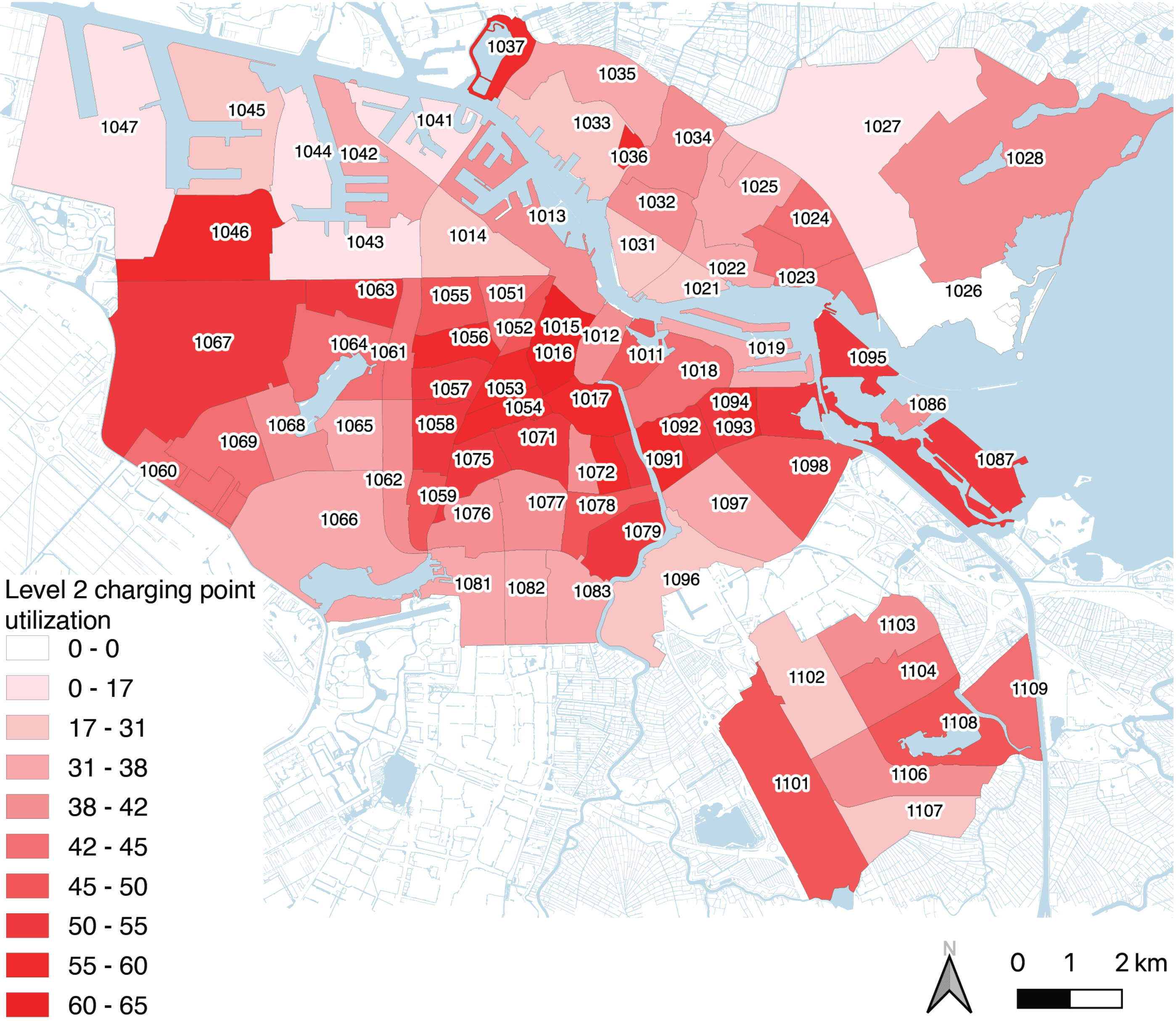

Figure 10. Mean Level 2 charging utilization for Amsterdam per postal code November 2019 - February 2020.

3.5.2 Level 3 Charging

Level 3 charging points are installed along motorways and arterial roadways in Amsterdam. This provides a high level of traffic and increases the accessibility of these points to the public. Additionally, a Level 3 charging point is located at Amsterdam Centraal train station with access only available to taxi drivers. Figure 11 shows the distribution of Level 3 charging points throughout Amsterdam.

As discussed in the Literature Review, drivers are generally willing to travel up to two kilometers out of their way to use fast charging (Level 3) when they are not able to use a Level 2 charger near their destination. The distribution of Level 3 charging indicates a need for additional charging points in Amsterdam Noord and along the outer edges of Nieuw-West near the A5 and A9 motorways.

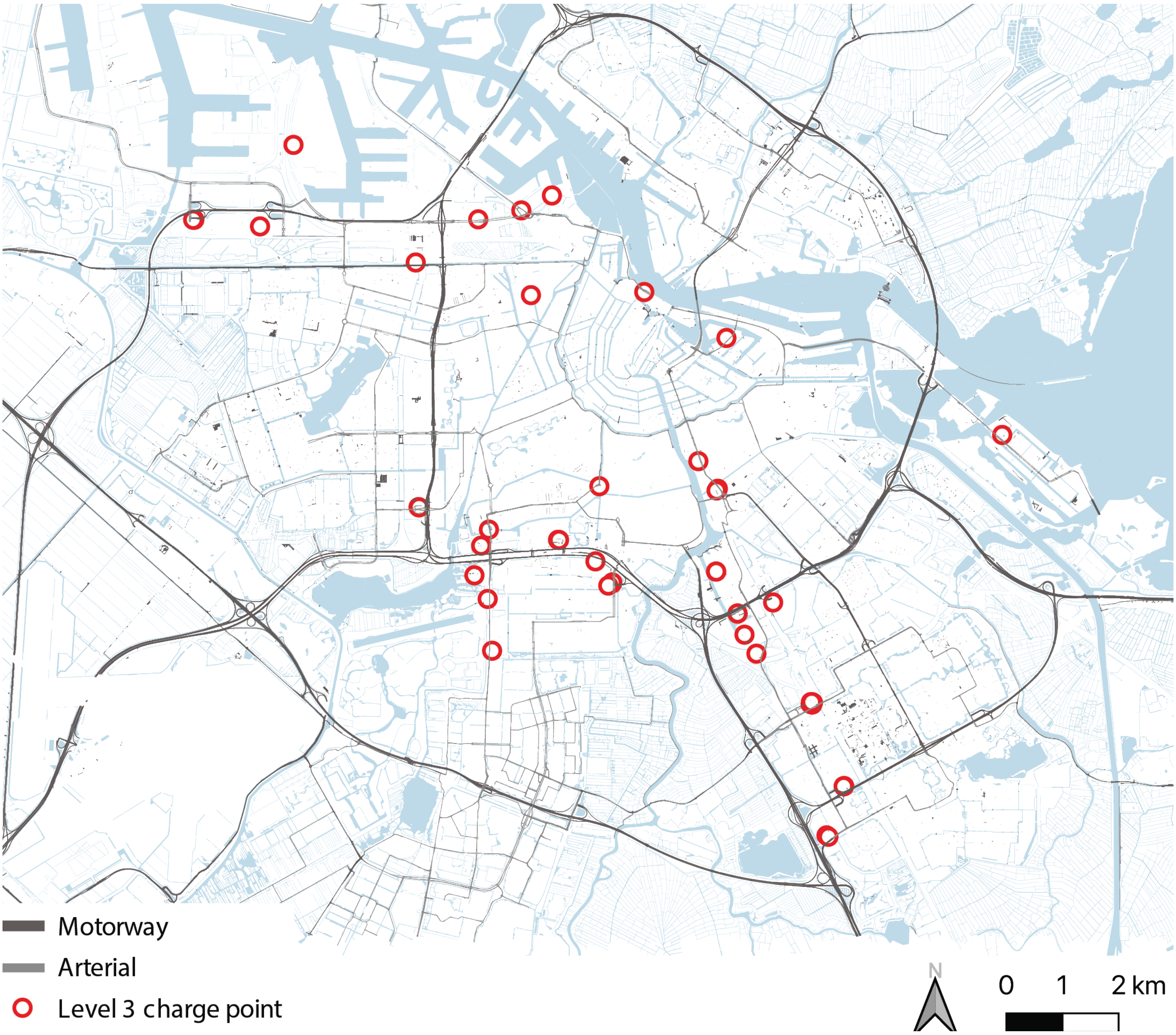

Figure 11. Level 3 charging points in Amsterdam.

The utilization of Level 3 charging is expected to be lower than for Level 2 charging as vehicles are not connected overnight and a typical charging time is approximately 30 minutes. Figure 12 shows the utilization of Level 3 charging infrastructure and has an overall mean utilization of 20%.

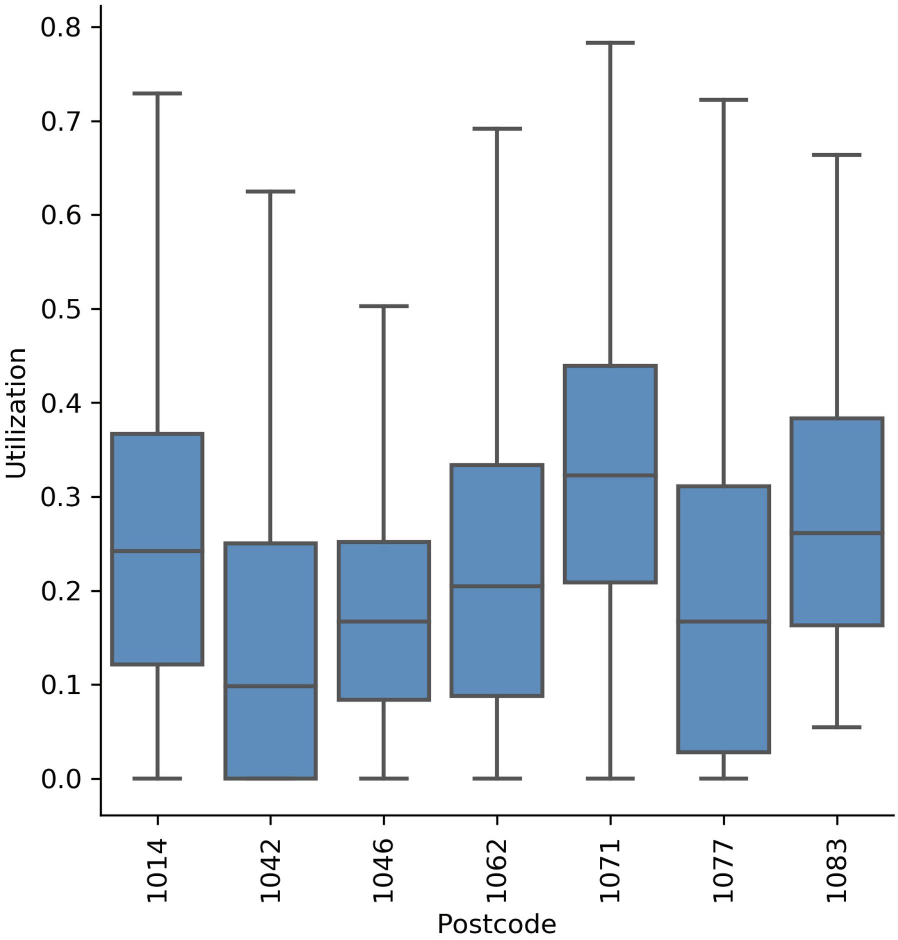

Figure 12. Level 3 charging utilization per postal code November 2019 – February 2020

3.6 Baseline Analysis Conclusion

There are many factors involved in the transition to zero-emission mobility and uptake in shared mobility for Amsterdam. Within shared mobility, carsharing has experienced a significant increase in the number of vehicles. While the growth in ride-hailing across the various services is not available, eight million rides provided annually gives insights into the large scale of this market. Additionally, a significant increase in ride-hailing through digital platforms has been observed. With a low growth rate of vehicle ownership in Amsterdam and increase in the availability of shared mobility services, reducing the total number of personal vehicles is attainable. For people that continue to own personal vehicles, a dramatic increase in EVs is necessary. To accommodate the growth of the EV market, additional charging infrastructure is needed throughout the City. By developing a strategy to install charging points in the less-served areas and increase the proximity of the population to charging points, the attractiveness and utility of both EVs and shared EVs will increase. With the baseline data and trends discussed, system dynamics can be used to model how these factors change over the next two decades.

4 Methods

Planning for the future of shared mobility and electrification of automobiles is a complex task due to the many uncertainties in this field. As described in the Literature Review, technology plays an important role in the increasing market share of shared mobility and EVs and with the planning of supporting infrastructure. With a large network of EV charging infrastructure, challenges surrounding the uptake and reliability of EVs have decreased and range anxiety is becoming less of a concern. The increase of EVs, however, creates challenges with higher demands on the electric grid. The relationships between these variables form the basis of a complex system with many uncertainties; therefore, system dynamics is proposed to model these relationships and determine future demands based on different scenarios. Backcasting methodology is used to develop the scenarios and future policy packages. Understanding the shared and EV market at the urban level and modeling the technical, policy, spatial, and use considerations provides the opportunity to evaluate how different scenarios affect the mobility landscape and as a result, the infrastructure requirements. This section discusses the methodology for developing the system dynamics model and backcasting. Figure 13 depicts the general process and components of the model with baseline data and policy packages acting as key inputs and the model results informing the policy recommendations.

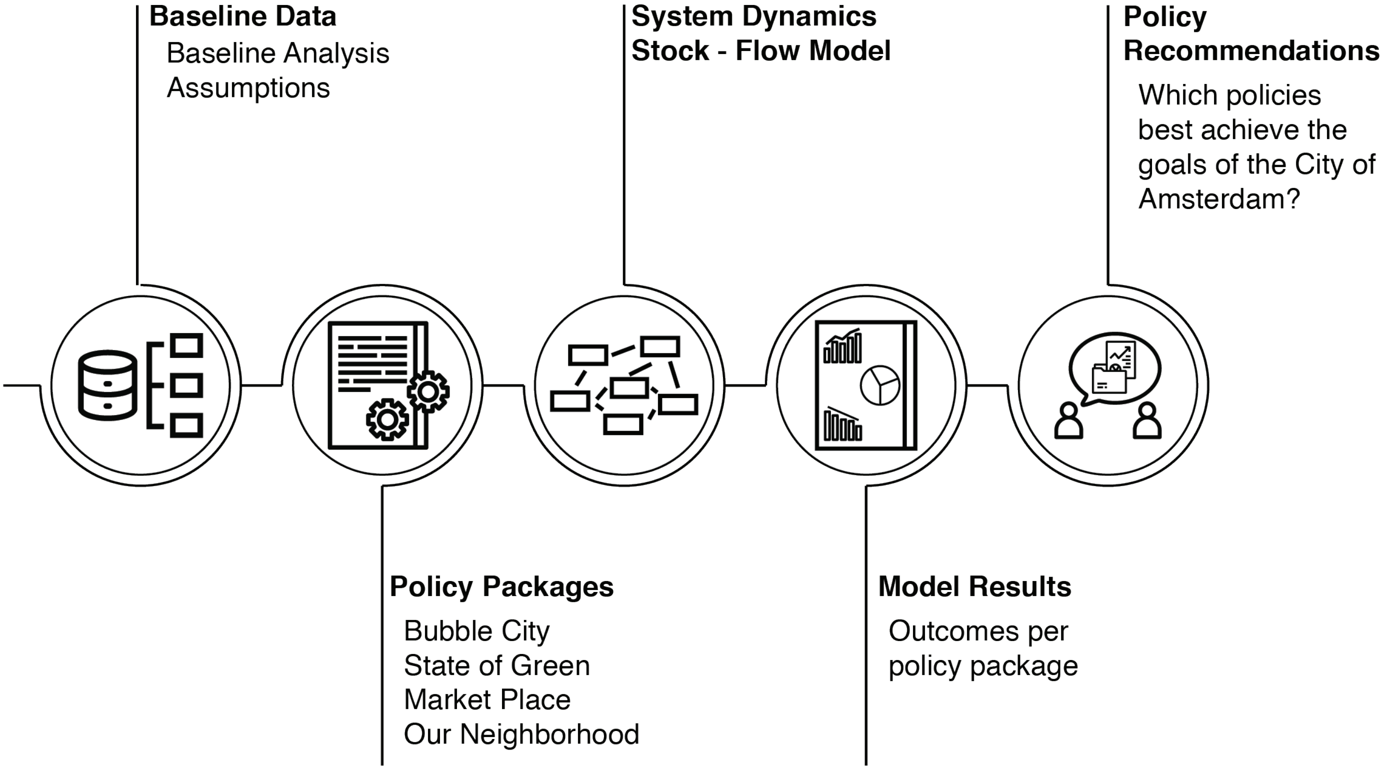

Figure 13. Process for System Dynamics study using Backcasting

4.1 System Dynamics

System dynamics is a modeling tool for understanding the interactions and feedback mechanisms between stocks, flows of information, or goods encountered in the real-world (Bala et al., 2017). This section aims to provide an introduction into systems thinking, provide the motivation for using system dynamics in this research, discuss the limitations of system dynamics, and describe the development of the system dynamics model used in this research.

4.1.1 Introduction to Systems

The introduction of shared mobility and MaaS into the mobility landscape, along with EVs and BEVs, impacts public space, modal split, and financial resources that cities must consider when adopting policies aimed at their implementation and expansion. The relationships between these sectors and their impacts on each other can be described in a systems approach as a complex system with stocks and flows of different resources along with feedback loops that reinforce each other and make the system robust (Meadows, 2008). Meadows discusses that due to the nature of systems, changes in one variable can have far reaching effects on other aspects throughout the system. System dynamics was pioneered by Jay W. Forrester in 1958 where he began studying the complex nature of industrial management and found that the various management practices deployed were deficient due to the complex and counter intuitive nature of industrial systems (Forrester, 1958). In response, Forrester and his team at MIT developed the field of system dynamics to model complex manufacturing systems (Forrester, 1989).

System dynamics has since been applied to a variety of challenges and is a tool for exploring policy interventions in various sectors, including urban dynamics, which was pioneered in 1979 (Forrester, 1989 & Forrester, 1979). Other sectors include energy sector's transition to renewable energy, housing markets, health systems, and ecological issues (Pruyt, 2013). These sectors are comprised of a large network of actors with interdependencies, making transitions and disruptions complex to enact and change. By using system dynamics models, policy makers, actors, and stakeholders can investigate how the system works, the effectiveness of various interventions, and the possible impacts to other sectors (Bala et al., 2017). System dynamics enables the testing of policies or technologies before exposing them in the market (Bala et al., 2017).

4.1.2 Motivation for Using System Dynamics

Transportation systems represent a complex networks of actors, technologies, operations, organizations, and behaviors where changes in one facet can have effects across the system (Abbas & Bell, 1994). These impacts are not always obvious or readily understood yet can have a wide range of consequences. Due to this complex nature, system dynamics provides a rational approach to model transportation systems and analyze effects for how policies, technologies, and behaviors respond over time. System dynamics can model the feedback mechanisms from land-use, energy, technology, policy, and behavior to the transportation system which makes it a holistic approach to answering the research questions in how shared mobility and EVs impact charging infrastructure and energy demand (Bala et al., 2017).

Several methodologies have been used in studies to evaluate the effect of policies on sustainable transportation systems. Transportation models are categorized as macroscopic, microscopic, or mesoscopic and study different levels of detail requiring representative data for the scales of the problems (Song et al., 2013). Agent-based models are performed at the microscopic level and study individual behavior based on rules, objectives, and relationships (Nieuwenhuijsen et al., 2018). As this research investigates a transportation issue across an urban or metropolitan region involving multiple sectors, microscopic models are not fitting for the study. Macroscopic approaches, including system dynamics and simulation-based optimization are more appropriate due to the scale of the problem studied (Song et al., 2013). The high degree of uncertainty and a lack of available data of this study reduce the validity of simulation-based optimization. An exploratory analysis with system dynamics, however, allows for the reasonable comparison of the different scenarios. Analyzing the effects comparatively provides insights into which policies have the greatest impact so that policymakers can make informed decisions for reaching their overall goals. Overall, an exploratory analysis using system dynamics is deemed the most fitting modeling approach for this study of the effects of different substantive policies (Howlett, 2000).

Modeling transportation systems using system dynamics has been conducted in the past to study the effects of transportation policies and technologies. Early transportation models in system dynamics investigated trip generation with land use in the transportation system (Abbas, & Bell, 1994). More recent studies including Armenia et al. (2010) investigated the impacts of sustainable transportation systems on the energy sector. Shepherd et al. (2012) studied future demand for electric vehicles, and Puylaert et al. (2018) and Nieuwenhuijsen et al. (2018) studied the implementation and uptake of autonomous vehicles. Legene (2018) used system dynamics to explore the spatial impacts of automated driving on Copenhagen using the Patient Rule Induction Method to create scenarios based on various uncertainties and select key performance indicators. The resulting scenarios from Legene's study were used to form policy recommendations associated with the preferred outcomes. These studies are summarized in Table 2 to illustrate the progression of system dynamics in transportation related studies; however, the table does not capture all transportation studies involving system dynamics. These studies indicate system dynamics to be the most appropriate methodology to account for the feedbacks and relationships to other sectors. As a result, system dynamics has precedence as an appropriate methodology for this research.

Table 2. Transportation Studies using System Dynamics Models

Author	Year	Subject	Case Study
Abbas and Bell	1993	Trip generation related to land use	NA
Armenia et al.	2010	Sustainable transport impacts to the energy sector	EU 1995 - 2001
Shepherd et al.	2012	Future demand of electric vehicles	UK 2010 - 2050
Puylaert et al.	2018	Automated driving impacts to mobility	Netherlands 2013 - 2050
Nieuwenhuijsen et al.	2018	Adoption of AVs and the impacts from policy and technology	Netherlands 2000 – 2100
Legene	2018	Transportation and spatial impact of AVs	Copenhagen 2070

4.1.3 System Dynamics Limitations

While system dynamics is a powerful tool for modeling future scenarios with large amounts of uncertainties, limitations exist for this approach. System dynamics models do not integrate spatial attributes effectively and this aspect of the research needs to be executed though different means (Abbas & Bell, 1994). While system dynamics models the impacts of various policy scenarios, Abbas and Bell discuss that the results are not exact and could be misconstrued if considered beyond a comparative basis. Lastly, the interpretation of the validity of the models can vary between different reviewers of the models (Forrester & Senge, 1979). Forrester and Senge suggest that models should be judged on the utility in shaping policy directions and not on their specific forecasts. These limitations should be understood and accounted for throughout the study so that the results can be reasonably used to reflect the system and its relationships and shape policy to achieve the desired goals.

4.1.4 System Dynamics Model Development

Developing the system dynamics model for this study includes identifying the system components associated with the research questions and the feedback mechanisms and loops between these components. The core system components and stocks identified include vehicle fleets, vehicle parking, electric vehicle charging infrastructure, utility of mobility platforms, and social exposure and consideration to the mobility platforms. The proposed model builds upon and adapts the system dynamics model of Struben and Sterman (2008) to focus on the impacts of the incorporation of shared mobility to the mobility system. As Struben and Sterman’s model investigated the uptake of alternative fuel vehicles, it concerns similar relationships and feedback mechanisms as the proposed study of shared mobility. The proposed model aims to represent the current state of this system and to model future scenarios to determine how different policy directions impact the mobility system and EV market.

The model by Struben and Sterman (2008) was developed to explore the transition to alternative fuel vehicles. Since the development of this model, significant progress has been made in EV technology for both the vehicles and the charging technology. Moreover, social exposure to EVs and awareness of their technological progress are important factors in the uptake in EVs. For carsharing, social exposure is an important aspect as people buying a car may not initially consider carsharing as a viable option or even consciously remember their availability or presence. The social exposure feedback loop proposed by Struben and Sterman (2008) is incorporated in the proposed model in determining the willingness to consider.

While exposure to EVs for potential vehicle buyers is a major contributor to their uptake, factors surrounding the utility, including costs are also primary drivers. EVs currently have higher initial capital costs than conventional ICE vehicles, although this price difference is being reduced as more vehicles are produced by major auto manufacturers. While the initial capital costs are generally higher for EVs, their maintenance and operating (charging) costs are lower. Accessibility to EV charging is a secondary driver for the buyer and should be incorporated in the utility.

The decision between purchasing a vehicle and using carsharing is proposed as a comparison of the combination of utility and willingness to consider of each. To compare utility, financial, accessibility, ownership sensitivity, and platform attributes are proposed as the primary drivers. For personal vehicles, higher capital costs, parking costs, and ownership sensitivity are hypothesized as the primary drivers. For carsharing, usage costs and vehicle accessibility are hypothesized as the primary drivers. With these assumptions, it can be hypothesized that as a vehicle is needed more for travel, personal vehicles will result in a higher utility and be more attractive. Conversely, when vehicle usage is less frequent, carsharing would become more attractive.

The core model in Figure 14 aims to show the relationships previously described. The social exposure components of the model are shown in orange. The platform utility components of the model are shown in green. The market share components are in red and the carsharing and personal vehicle components are shown in blue. The sections below describe the primary components of the model in further detail.

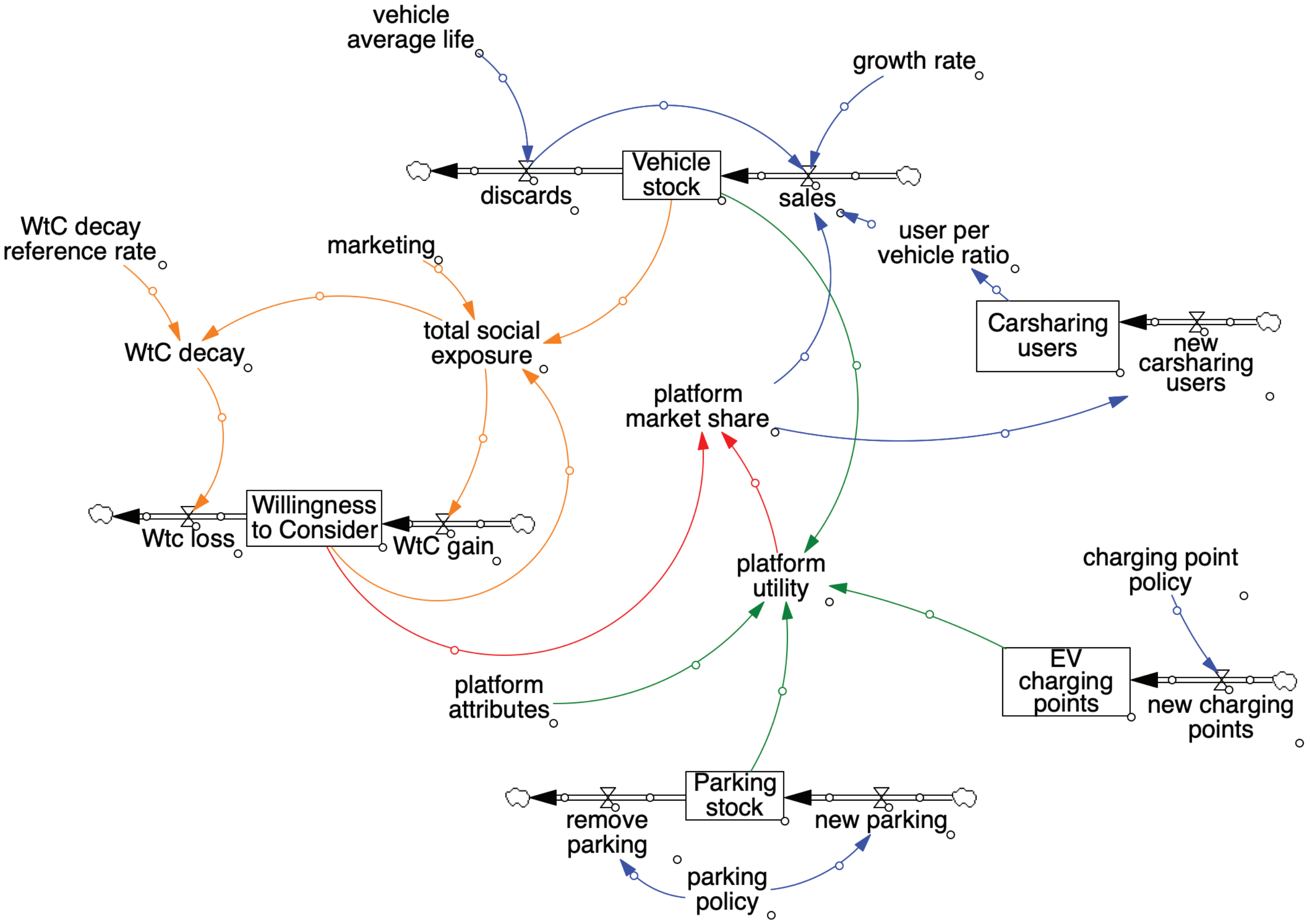

Figure 14. Core System Dynamics model (adapted from Struben and Sterman., 2008)

4.1.4.1 Vehicle Fleets

The various vehicle fleet stocks must be accounted for to determine the social exposure and demand for parking and charging infrastructure. These vehicle fleet stocks include privately owned ICE vehicles, privately owned EVs, and carsharing vehicles. Vehicle stocks increase and decrease as a result of vehicle sales, discards, and overall population growth. For simplification purposes, it is assumed that the total number of vehicle users will increase at the population growth rate and there are not people switching from other modes (public transport, bicycle) to using carsharing or purchasing vehicles. While in actuality these mobility types can be used in combination with each other, this study focuses on current vehicle owners and the effects of carsharing on them. Equation (1) is adopted from Struben and Sterman (2008) to calculate the change in vehicle stock of platform j as a function of the initial stock rate plus sales minus discards.

$$\frac{dV_j}{dt} = V_i + s_j - d_j \tag{1}$$

4.1.4.2 Vehicle Sales

Vehicle sales are a result of the market share for each platform multiplied by the sum of discards and growth rate times the initial vehicle stock as shown in (2) (Struben and Sterman, 2008).

$$s_j = \sigma_j\left(d_j + g * V_0\right) \tag{2}$$

4.1.4.3 Market Share

The market share is derived from the affinity of a platform divided by the sum of affinities for all platforms as shown in (3) (Struben and Sterman, 2008). The market share for each platform is relative to the affinity for all platforms; therefore, each market share will be a fraction of the total market.

$$\sigma_j = \frac{a_j}{\sum a_j} \tag{3}$$

The affinity for a platform is derived from the product of its willingness to consider and utility as shown in (4) (Struben and Sterman, 2008). This shows that the population must be familiar with a platform to consider it. The utility of the platform represents how the population perceives its attributes.

$$a_j = WtC_j * U_j \tag{4}$$

4.1.4.4 Platform Utility

The utility of each platform is the sum of the products of the attributes (μ) of that platform and the weight (β) for that attribute as shown in (5) (Struben and Sterman, 2008).

$$U_j = \sum_i \beta_i * \mu_i \tag{5}$$

The utility factors and weights are derived from academic literature and adopted to compare ICE purchases, EV purchases, and carsharing adoption. The system dynamics model for alternative fuel vehicles developed by Keith, Naumov, and Sterman (2017) used the factors of purchase price, operating cost, acceleration, top speed, range, and emissions from Brownstone, Bunch and Train (2000) and added fuel search cost and platform scope. These factors and their associated weights, however, only account for vehicle purchases and do not consider carsharing usage. Coffman, Bernstein, and Wee (2017) evaluated existing research and found that ownership costs and total costs of ownership are the most influential factors on EV adoption. Vehicle driving range, charging times, fuel prices, consumer characteristics, charging networks, public visibility, and social norms are other important factors (Coffman et al., 2017). Winter et al., (2020) found that car owners are sensitive to parking costs and parking availability which influence their decisions to switch to free floating carsharing vehicles. Additional research by Giesel and Nobis (2016) found availability of carsharing vehicles and vehicle ownership costs to be highly influential factors in car shedding. Based on these findings, this study utilizes four categories for utility factors: financial, accessibility, ownership sensitivity, and platform attributes. The value for each factor is normalized and the sum of all of the weights equals one.

The financial factors are comprised of capital cost, usage costs, parking costs, and environmental costs. Capital costs include the purchase price and insurance costs for vehicle purchases and membership fees for carsharing. These costs are amortized to a monthly cost, such as a monthly payment for a vehicle loan. Usage costs are comprised of fuel costs, charging costs, and maintenance for vehicle purchases. For carsharing the usage fee is a function of distance and time, depending on the provider.

The accessibility factors are comprised of parking accessibility and fueling / charging infrastructure for personal vehicles. Parking accessibility is determined by dividing the entire vehicle stock by the number of parking spaces available to that platform. The accessibility of carsharing is determined by the number of users divided by the number of vehicles.

Ownership sensitivity is included for factors of convenience, privacy, and identity associated with owning a personal vehicle. The level of importance for this factor is highly subjective to population, demographics, and culture. With the emergence of COVID-19, cleanliness is another contributing factor to ownership sensitivity. While carsharing vehicles may be cleaned regularly, a user may not be assured that the vehicle was cleaned after the previous user. This factor affects the attractiveness of a personal vehicle.

Platform attributes include platform scope, comprised of vehicle model options on the market, secondhand vehicle options, and vehicle range. The EV range and scope of carsharing vehicles available are factors included in platform attributes. The proposed weights, values, and estimates for utility are discussed in the next chapter.

4.1.4.5 Vehicle Parking

The stock of public vehicle parking and its relationship with designated or restricted EV charging will change as more spaces are designated as EV only. Additionally, the total stock may increase or decrease depending on policies and new developments. While private and semi-private parking also play a role, it is difficult to account for their quantities and utilization.

4.1.4.6 Energy Demand

As the demand for electricity is expected to grow with the adoption of EVs, it has a relationship with the EV charging technology and modal split. Flexible and V2G chargers are being developed to reduce the demand on the grid during peak times. High power chargers, on the other hand, have a significant demand for energy on the grid. While the different impacts on the energy grid of the types of charging infrastructure are not independently modeled, a monthly energy demand is generated using the average monthly distance traveled in the Netherlands. This shows how the EV stocks resulting from the different policy scenarios burden the energy grid.

4.1.5 Testing and Validating the Model

The developed model must be tested to validate the trustworthiness and utility of the results (Bala et al., 2017). Bala et al. discuss testing the model by running it against known empirical data and verifying that the model produces similar results. There are three classes of tests: structure, behavior, and policy implications (Bala et al., 2017). For the model to be valid, the structure and behavior tests are the most important. Validating the model means the results and behavior are reasonable and adhere to real world indicators (Forrester & Senge, 1979). Since system dynamics models are formed with high levels of uncertainty, Bala et al. explain that the goal of the model is to provide a better understanding for how the system works and how different scenarios develop. If the implications of the results are reasonable, the model meets its goals and can be considered valid.

4.1.6 Applying System Dynamics to Scenarios

Future scenarios are developed through the backcasting methodology where the policy packages are used as varying inputs for the system dynamics model simulations. In addition to the policy packages, estimates are provided for technological advances and societal behavior. As the scenarios and policy packages are tested, these results can be used to evaluate the preferred outcomes so that policy makers can steer policy decision to align with future goals.

4.1.7 System Dynamics Model Setup

The system dynamics model was developed and executed in VenSim Professional Version 8.0.9. The time boundaries for the model begin at time zero for 01 January 2020 with a final time of 240 months or 01 January 2040. The model uses a time step of 1 month and Euler integration.

4.1.8 System Dynamics Conclusions

The electrification of the vehicle market and the increase of shared mobility are part of a complex system including the transportation, land-use, government policy, and energy systems. Modeling this system using system dynamics provides the opportunity to review the relationships between the different factors and feedback mechanisms. The model uses both available data and estimates about uncertainties to mathematically represent how the system operates. Once the base model is validated, the model can be used to test how various scenarios compare. The results can then be used to compare future outcomes to guide policy makers towards their desired goals.

4.2 Backcasting

This section aims to provide an overview of backcasting for the purpose of policy development. An introduction to the backcasting methodology is provided followed by the motivation for using backcasting in this study. Next, the three stages of backcasting are presented for developing the policy recommendations to be evaluated by the system dynamics model. As this research focuses on the tools at the city level, the policies developed will be focused on policies that can be implemented at this level of government.

4.2.1 Introduction to Backcasting

When performing exploratory analysis on large scale transitions, two methods are prevalent, forecasting and backcasting (Banister et al., 2008). Banister et al. explain that forecasting can be applied when analyzing goals and metrics that are being investigated for forming policies on specific issues. Backcasting, on the other hand, is used to investigate what policies and regulations need to be implemented to achieve stated goals and policies (Banister et al., 2008). Both methods can be combined with system dynamics to model the relationships, feedback loops, and stocks and flows of the system. Applying backcasting to a system dynamics model can provide insights into the effects that various policies will have on achieving the stated goals. Backcasting has been used to study the pathway for various sustainability and energy transition policies to provide important feedback on how these policies can be implemented considering social, technological, and political factors (Banister et al., 2008).

There are three main stages of backcasting: baseline analysis and target setting, building scenarios for images of the future, and deriving policy packages (Banister et al., 2008). Banister et al. discuss that baseline analysis and target setting is performed by stating the goals of the study and applying key metrics to these goals. Next, data on the current state of the metrics is collected and analyzed providing the baseline analysis of the study. Banister et al. explain that building scenarios for images of the future is performed by creating or using scenarios about how technical and behavioral changes occur. These scenarios should result in four distinct descriptions of the future that achieve the goals established in stage one. Stage three, deriving policy packages, is the development of policy measures and tools that can be implemented following the outcomes of the scenarios (Banister et al., 2008). Policy pathways are established to determine when policy measures should be implemented and what resources are needed for their implementation (Banister et al., 2008).

4.2.2 Why Backcasting for this Study?

Transitioning cities to electric and shared mobility is a complex issue affecting many actors, stakeholders, and systems. Governments and cities are establishing visions and policies to accelerate the transition to EVs and shared mobility. With a focus on the city level and using Amsterdam as the case study for this research, backcasting serves as an appropriate methodology to study the implications and effects from various policies tools (Robinson, J. 1982).

4.2.3 Stage 1 – Baseline Analysis and Target Setting

The baseline analysis and target setting stage reviews the current situation and develops goals or targets for the future (Banister et al., 2008). For the shared mobility and personal vehicle system, this baseline has been outlined in the baseline analysis section for the case study of Amsterdam. Within the current system, transitioning to a more sustainable state can be seen as an overall goal with more explicit goals surrounding the transition to zero emission vehicles discussed in the Application to Case Study and Development of Policy Packages chapter.

4.2.4 Stage 2 – Images of the Future

Future scenarios provide the opportunity to imagine what the world will look like according to various drivers or uncertainties (Banister et al., 2008). Banister et al. explains that these scenarios should be designed to describe different alternatives of the future that are logical pathways from the current situation or baseline. Alternatives are modeled and studied to guide government and stakeholder policies and actions towards the described futures. Assumptions about these alternative scenarios are both internal, meaning they are directly influenced by policy decisions, and external, meaning they are not directly influenced or held constant (Banister et al., 2008).

4.2.5 Stage 3 – Policy Packages

Scenarios from the Images of the Future are used to model the impacts to shared mobility and EV charging infrastructure by creating policy packages and making assumptions for how different technologies will develop and be utilized (Banister et al., 2008). These policy packages describe the specific policy measures that align with each scenario (Banister et al., 2008). These policy packages include timelines for the implementation of the policies as certain policy measures may be more impactful at certain times. The combination of policy measures can interact to provide greater impacts than the measures alone or negate the impacts of one another. The derived policy packages should optimize impact and minimize detrimental conflict. Policies will be proposed within the four categories – authoritative, treasure, nodal, and organizational – described by Howlett (2000).

Policy instruments, defined as the tools and techniques of governance to deliver goods and services, have a range of effects on the outcomes (Howlett, M., 2000). Developing policy packages should incorporate primary measure which directly influence the prescribed outcomes while observing the immediate and collateral effectiveness (Givoni et al., 2013). The immediate effects are the direct consequences of the intended policy while the collateral effects are unintended or rebound effects. Givoni et al. discusses the importance of evaluating both effects as the collateral effectiveness can undermine the overall intentions of the policies.

There are three types of policy packages: horizontal, vertical, and chronological (Bemelmans-Videc and Vedung, 1998). Horizontal packages are the implementation of multiple policy measures simultaneously; vertical packages are the implementation of multiple policy measures at various levels of government (national, regional, city), and chronological packages are where policies are implemented in a sequential timeframe (Givoni et al., 2013). For the policies in this study, a mixture of horizontal and chronological packages are proposed. As the study focuses on the policies that can be implemented at the local level, vertical packages are omitted.

4.2.6 Policy Packages per Scenario

In the Literature Review section, policy measure types were identified that can be applied to the scenarios in the Images of the Future. These policy measures include financial and economic policies, land use policies, parking policies and regulations, and vehicular access restrictions. Depending on the characteristics of each scenario, combinations of policy types will be applied. Through these packages, four distinct paths to increasing shared mobility and personal EVs are created. The three stages of backcasting are applied and discussed for the case study of Amsterdam in the next chapter, Application to Case Study and Development of Policy Packages.

4.2.7 Backcasting Conclusions

Backcasting provides a suitable framework for the explorative study of shared mobility and charging infrastructure using system dynamics to model the impacts of associated policy. Using goals and baseline data from the case study, future scenarios are adopted, and policy packages and assumptions are derived. These policy packages are then used in the system dynamics model to understand the differences between each scenario's results in shared mobility usage and vehicle stocks, investments and infrastructure needs, and demands on the energy grid. The results of the model can then be used by the wide range of stakeholders to plan an effective transition to clean shared mobility.

5 Application to Case Study and Development of Policy Packages

The next step in exploring the transition to clean shared mobility is the application of the system dynamics and backcasting methodologies to the case study of Amsterdam. In this chapter, the system dynamics model application is discussed followed by the development of the policy packages.

5.1 System Dynamics Model Application

In the Methods chapter, the structure of the system dynamics model is presented. Application of the model to the case study requires setting baseline parameters, developing assumptions, and estimating utility for the mobility platforms. In this section, these items and their rationale are discussed.

5.1.1 System Dynamics Model Baseline Parameters

The data, previously presented in the Baseline Analysis chapter, on shared mobility, vehicles, parking, and electric charging points is used as the baseline for the system dynamics model. Table 3 summarizes parameters used at time zero for the model.

Table 3. Initial variables and parameters from baseline data.

Variable	Units	Initial Value
EV Charging Points	charging points	1,800
EV Parking	spaces	3,200
Open Parking	spaces	253,000
Population	people	873,000
Public Parking Stock	spaces	256,200
Carsharing Stock (EV)	vehicles	7,900
Carsharing Stock (ICE)	vehicles	1,100
Total Vehicle Stock	vehicles	251,595

5.1.2 Assumptions

To build and run the model, a number of assumptions are required for missing or unavailable data. Examples of unavailable data include the number of personal ICE and EVs and the number of users of shared mobility in Amsterdam. Additionally, the initial values for willingness to consider EVs and carsharing components of the model have to be estimated. Other assumptions include trends for EV development, such as range and scope of options available in the market. In this section, the assumptions and estimates for these variables are discussed.

The total number of personal vehicles registered in Amsterdam and the sales trends for the Netherlands are known. While using the sales trends and registered EVs for the Netherlands can be applied to Amsterdam, it is assumed that this will underestimate the number of EVs. Amsterdam is known to be a progressive and sustainability-focused city and its population is likely to outperform the country with EV adoption. While the Netherlands' market share for EVs is 2.3%, an estimate of 2.5% is used in the model, resulting in an initial EV stock of 6,000 vehicles. This is subtracted from the total vehicle quantity to estimate the ICE vehicle stock. Additionally, the secondhand vehicle stock for EVs is unknown but estimated to be relatively small. The model uses 1,000 vehicles as a base.

The number of shared mobility or carsharing users in Amsterdam is unavailable as this data is proprietary to the private companies providing these services. The initial value is set at 6,000 to estimate the number of users who have discarded or delayed a vehicle purchase as a result of using this service regularly. The number of users who are members and infrequently use carsharing services are omitted from the estimate as it is assumed that they would not purchase a vehicle even if the service is not available. This assumption is based on the mode share trends in Amsterdam.

The willingness to consider EV purchases and carsharing as a result of social exposure and marketing is unknown for the Amsterdam area. The willingness to consider for ICE vehicles is set at 1 as this is the default vehicle for purchase (Struben and Sterman, 2008). The model was tested with a range of initial values for EVs and ultimately run with 0.5 as this produced a reasonable monthly growth rate in the first several months between 3.5% and 4%. In 2020, there was a growth rate for EVs of 42.6% from 2019, yielding a monthly growth rate of 3.55%. The willingness to consider for carsharing was set at 0.2 as its awareness to consumers is assumed to be less based on related literature. The assumptions and estimates used in the model are shown in Table 4.

The trends for EV attributes, including purchasing price, vehicle range, and platform scope are estimated in the model to trend comparable metrics as ICE vehicles over time. As battery technology improves and more vehicles are manufactured, the purchase price for EVs is assumed to become equal to ICE vehicles by 2030. While there are many unknowns with this assumption, costs over the past five years have decreased for EVs and more cost-effective models have become available on the market. As a result of the battery technology improvements and innovation, the vehicle range for EVs has improved significantly over the past several years. The model assumes an s-curve where the range of EVs would equal ICE vehicles in 2040. Vehicle manufacturers continue to invest in EV technology and announce new EV models. While the current market scope of EVs is low, this is assumed to broaden significantly over the next several years. Descriptions of the functions for the vehicle attribute estimates are provided in Appendix A.

Table 4. Initial variables and parameters from baseline assumptions.

Variable	Units	Initial Value
New Charging Points	charging points / month	50
Private Parking Stock	spaces	1
Secondhand Vehicle Stock (EV)	vehicles	1,000
Carsharing Users	people	5,000
Carsharing Users / New Carsharing EV	people / vehicles	8
Vehicle Stock (ICE)	vehicles	229,595
Vehicle Stock (EV)	vehicles	6,000
Willingness to Consider (WtC-EV)	Dmnl	0.5
Willingness to Consider (WtC-ICE)	Dmnl	1
Willingness to Consider (WtC-SM)	Dmnl	0.2

5.1.3 Utility Estimates

As discussed in the Methods chapter, the utility is a major factor in determining the market share of each platform. There are a number of factors that can be used in determining utility; however, this study proposes using financial, accessibility, ownership sensitivity, and platform attributes. In this section, an overview for estimating the current utility score for the three platforms is provided along with the associated weight of each utility factor.

The financial factors are estimated for the case study in Amsterdam based on local statistics and costs. In the Netherlands, the annual vehicle kilometers traveled was 13,000 in 2018 (CBS, 2019). This is divided into twelve months to estimate usage costs. Parking permits are issued and charged every six months in Amsterdam (Amsterdam, 2020). On the other hand, Parking costs are not charged to the individual users for carsharing. Environmental costs in the Netherlands are assessed through vehicle registration taxes based on vehicle emissions every three months (Belastingdienst, 2020). The weights of the financial factors are determined by estimating the monthly costs at the average monthly distance traveled. Each subcategory is the fraction of the total monthly cost, with equal weights for capital costs and usage costs to account for the difference in pricing schemes for personal vehicles and carsharing. The financial category has an overall weight of 0.5.

The accessibility factors for each platform are estimated based on parking, fueling, and ratio of users to carsharing vehicle stock. As EV's have dedicated parking stock, they have access to a larger number of parking spaces. Fueling infrastructure for ICE vehicles is the current norm and expectation, therefore it has a value of 1. Charging infrastructure is estimated for Level 2 chargers and is the number of vehicles per charging point applied to a s-curve function. The s-curve function estimates less than 5 EVs per charger results in a utility of one, and utility decreases to zero as the ratio approaches 20 vehicles per charger. This function is derived from the likelihood of an EV driver finding an available charging point when needed and not needing to detour and wait for a Level 3 charger. Additionally, for implementing the vehicular access limits policy, the entire accessibility category is used to show the inconvenience drivers of this platform would experience with this policy. Accessibility for carsharing is determined by the total number of carsharing users divided by the carsharing vehicle stock applied to a function where a one to one ratio equals a utility of one and the utility is reduced to zero with 50 users per car. The two accessibility factors for personal vehicles each represent 50% of the category and carsharing accessibility is the sole factor for accessibility for carsharing. The accessibility category has an overall weight of 0.15.

Ownership sensitivity is based on the individual's perception of owning a vehicle. For the model, ICE and EV ownership result in a 1 for this factor and carsharing result in 0. The ownership sensitivity category has an overall weight of 0.15.

The platform attributes factor is comprised of estimates for platform scope for personal vehicles, carsharing vehicle model options, and vehicle range. The assumptions for the development of these attributes is discussed in the Assumptions section. The platform attributes category has an overall weight of 0.20.

A summary of the utility categories, factors, and weights is provided in Table 5. Additionally, a sensitivity analysis performed on the weights for the utility is provided in Appendix 2.

The weights of each category and subcategory are normalized to the highest cost or factor for that category. For the financial considerations, the higher the monthly cost, the lower the estimated utility. A Volkswagen Golf, Volkswagen eGolf, and MyWheels carsharing were used for the baseline estimate. The Volkswagen Golf had the third highest new vehicle sales from 2015 to 2020 and the highest sales when secondhand vehicles are included. Since this vehicle is very popular in the Netherlands and has an electric counterpart, it was used to determine the baseline for the utility. A detailed description of the utility estimates and assumptions is provided in the Appendix.

Table 5. Platform utility factors and weights.

	Utility Factors	Factor split	Weight (β)
Financial Considerations	Capital Costs		0.22
	Monthly Payment	0.8	
	Insurance	0.2	
	Membership Fee	1	
	Usage Costs		0.22
	Fuel	0.84	
	Maintenance	0.16	
	Usage Fee (hourly+distance)	1	
	Parking Costs		0.02
	Monthly Permit		
	Environmental Considerations		0.04
	Carbon Tax		
Accessibility	Accessibility		0.125
	Available Parking	0.5	
	Fueling / Charging Infra	0.5	
	Shared Vehicle Availability	1	
Ownership	Ownership Sensitivity		0.125
	Ownership / Identity		
Platform Attributes	Platform Scope		0.15
	Options on Market	0.75	
	Secondhand Market	0.25	
	Shared Vehicle Options	1	
	Range		0.1
	Vehicle Range		

5.1.4 Conclusions

Applying the system dynamics model to the case study of Amsterdam requires understanding the baseline trends, making assumptions regarding the uncertainties or lack of data, and estimating the utility for each platform in the study. With these baseline parameters and trends established, the policy packages from which the model will test various scenarios must be developed. The next section discusses the policy package outcomes from the backcasting methodology.

5.2 Policy Package Development

As discussed in the Methods chapter, backcasting is a suitable methodology for exploring future scenarios though the development of policy packages. In this section, the process and outcomes of backcasting are discussed as applied to the case study of Amsterdam.

5.2.1 Stage 1 – Baseline and Target Setting

Baselines are established in the Baseline Analysis chapter of this study. Baseline categories include shared mobility, charging infrastructure, vehicle stocks, charging behavior, policy, and spatial considerations.

Transitioning to more sustainable modes of personal transport is an overarching goal of governments across the world. Several cities have produced aggressive targets for this transition. Plans such as Amsterdam's Clean Air Action Plan, San Francisco's Electric Vehicle Roadmap, and Los Angeles' Zero Emission's 2028 Roadmap outline aggressive targets with respect to EVs. A summary of these goals is included in Table 6 noting the share of electric vehicles and associated targeted timeframes (Amsterdam, 2019, San Francisco, 2019, Los Angeles Cleantech Incubator, 2019). This research uses the targets set by the City of Amsterdam in the Clean Air Action Plan with a goal of all shared mobility vehicles being electric by 2025 and all passenger vehicles electric by 2030 (Amsterdam, 2019).

Table 6. City Policies Establishing Electric Vehicle Targets. (Amsterdam, 2019, San Francisco, 2019, Los Angeles Cleantech Incubator, 2019)

Amsterdam Clean Air Action Plan

2025	2030	2040
All shared mobility vehicles emission free	All vehicles emission free	All trips emission free

San Francisco Electric Vehicle Roadmap

2025	2030	2040
50% new vehicle registrations electric All shared mobility vehicles electric	100% new vehicle registrations electric	All trips emission free

Los Angeles Zero Emission Roadmap 2028

2022	2028	2040
10% taxis and shared vehicles electric	30% all vehicles electric 80% new vehicles electric 100% shared vehicles electric	All trips emission free

5.2.2 Stage 2 – Images of the Future

PBL conducted an explorative study, Multi-dimensional Scenario Making, which describes four possible scenarios for the Netherlands in 2049 (Hamers et al. 2019). Across three categories of governance, sustainability, and society and technology, eleven uncertainties are evaluated (PBL, 2019). The eleven uncertainties include the level of importance from the EU, national, regional / city, market, and civic society governances; the inclusiveness for people; attention to the planet and environment; focus on economic growth and profit; societal care; culture; and technology acceptance. By making assumptions on the levels of interaction for these variables, future scenarios are created which describe the qualitative aspects of development patterns, mobility, and how society and institutions act. These four scenarios are titled Bubble City, State of Green, Market Place, and Our Neighborhood (PBL, 2019).

Bubble City represents a future with a fragmented society that operates in tribes and connects with one another through the use of digital infrastructure (PBL, 2019). According to PBL, Bubble City creates an urban environment where the importance of property and material possessions is drastically reduced, altering the way buildings and space are utilized. Buildings and space becoming flexible allowing for different uses based on the users' needs. With a heightened focus on the digital realm and technology, investments in public and mobility infrastructure are reduced. Personal mobility patterns change where people move from one bubble to another and mobility as a service becomes dominant. In Bubble City, the market and civil society play the dominant role in planning with reduced influence from the regional and national governments. The European Union's role in this scenario is mainly to define and coordinate international relations (PBL, 2019).

State of Green is a future where society is completely focused on the well-being of the environment and people (PBL, 2019). PBL describes a planet point system is developed to account for the environmental impact of people's actions so that stresses and pressures on the environmental and ecological systems are minimized. Circularity becomes the focus for business and the economy where waste is significantly reduced. Livability and personal health are significantly improved with cleaner air, water, and greater access to green space. Walking and bicycling become the dominant transport modes with their low environmental impact and no planet points required. Overall mobility of citizens is reduced because other modes including cars, trains, and flights require significantly more planet points. In the State of Green, governments at the European Union and national levels play central roles in planning with a decreased emphasis on market and civil society (PBL, 2019).

Market Place is a future where the market dominates all aspects of society (PBL, 2019). PBL discusses that private business parks and districts are developed with luxury services provided to those who can afford them. Efficiencies emerge in the workplace through technological innovations and industry utilizes robots for a greater share of jobs. Spatial development is further spread into suburban areas for the affluent and lower quality neighborhoods emerge around the city with lower spatial quality for the less affluent. Urban sprawl is a result of the spatial development which leads to a greater number of trips and increased distances. All modes of transport are available; however, they are market-driven with special highways developed for those who can afford to pay. Governments act in a way to support the market and the market assumes some government functions, such as infrastructure and development planning. Through this scenario, inequality is further exacerbated, leaving behind large segments of society (PBL, 2019).

Our Neighborhood is a future where local communities are central to society (PBL, 2019). PBL depicts everyone being integrated into their local community and the neighborhood provides a healthy sustainable living environment. All modes of transportation exist in this scenario; however, longer distance travel is much more difficult due to the disengagement of communities from each other. Additionally, large multi-national corporations play a lesser role and business operates at the local scale in this scenario. The European Union and national government play a less important role in planning with the city or regional government and civil society taking the lead role (PBL, 2019).

These images of the future describe four different scenarios that could all be achieved through policies and governance practices. With the emphasis on sustainability and corporate profitability varying with each scenario, the spatial development patterns and mobilities will have different implications. Figure 15 provides a comparison of the eleven uncertainties for each of the four scenarios. While most of the uncertainties have a larger or smaller impact and influence, all scenarios except Our Neighborhood assume technology will have an increased impact on society.

↑ High Importance / Influence
— Moderate Importance / Influence
↓ Low Importance / Influence

		Bubble City	State of Green	Market Place	Our Neighborhood
GOVERNANCE	European Union	—	↑	—	↓
	National	↓	↑	—	—
	Region / City	↓	—	↓	↑
	Market	↑	↓	↑	↓
	Civic Society	↑	↓	↓	↑
SUSTAIN-ABILITY	People	—	—	↓	↑
	Planet	—	↑	—	—
	Profit	—	—	↑	↓
SOCIETY & TECHNOLOGY	Society	—	—	↑	↓
	Culture	—	—	↑	↓
	Technology	↑	↑	↑	—

Figure 15. Levels of importance and interaction for the four PBL scenarios. (Adapted from Hamers et al., 2019 & PBL, 2019)

5.2.3 Stage 3 – Policy Packages

Using the Images of the Future scenarios described in the previous section, policy packages are developed with a focus on policies that can be implemented at the city level with the city's resources. In this section, the policies are proposed and followed by their application to the scenarios.

Numerous policies have been identified in literature that can be used at the city level to influence sustainable mobility. Based on the challenges with shared electric mobility and personal EV purchases, the policies are proposed from the four categories described in the Literature Review chapter: authoritative, treasure, nodal, and organizational. The proposed authoritative measures include restricting open public parking spaces to EV or carsharing vehicles, requiring private parking for new construction, and implementing vehicle access limits on ICE vehicles. The proposed treasure measures include subsidies for EV purchases, subsidies for carsharing usage, and costs for parking permits. The proposed nodal measures include marketing for EV purchases, marketing for carsharing, and marketing against ICE vehicle purchases as a result of vehicle access limits. The scale at which these policies are implemented is determined though the scenario dialog and is described further below.

The proposed policies are selected to address shortcomings identified in the platform utility and willingness to consider elements of the model. The subsidies and parking permit costs aim to influence the financial element of the utility. The parking quantities and vehicle access limits aim to influence the accessibility elements of the utility. The marketing policies aim to influence the willingness to consider component of the model. Using these motivations, the following policy packages are proposed with the level of action for each policy adjusted based on the description of the scenarios.

Bubble City transitions to a shared economy and lifestyle with less focus given to private property (PBL, 2019). Market and societal actors have the highest levels of influence. This policy package prioritizes shared mobility through carsharing subsidies and marketing. Subsidies for carsharing are provided for the first three years. Personal vehicles will still be allowed; however, overall parking will be removed with minimal new parking for new residential construction. Additionally, subsidies will not be provided for purchasing vehicles. Vehicle access limits will be implemented in 2030 for ICE vehicles as the market and civil society have a high level of influence and implementing the limit sooner would reduce accessibility for many citizens.

State of Green pushes to significantly shift towards emission-free travel, with an additional focus on active modes (PBL, 2019). Policies aimed at minimizing personal vehicles and transitioning to emission free vehicles are prioritized. This policy package prioritizes EVs with subsidies for both personal EVs and shared EVs for the first five years. The city will limit access to non-EVs in 2025 to accelerate the transition away from ICE vehicles. Additionally, pressure will be applied to personal vehicles by removing significant amounts of parking, permitting no new private parking for new residential construction, and increasing public parking costs. Marketing for carsharing and EVs will be higher than the other policy packages.

Market Place allows the private market to drive decision making; therefore, private vehicles are prioritized with little influence from the government (PBL, 2019). This policy package focuses on private vehicles as these have the largest economic impact for the private market and suburbanization of the city. Public and private parking will increase to aid in the accessibility of private vehicles. Vehicle access limits will not be implemented as they hinder the accessibility of ICE vehicles. There no subsidies for EVs or carsharing. EVs receive marketing for their sales but carsharing does not.

Our Neighborhood provides local government and societal actors with the highest levels of influence with low regard to the private market. This scenario, however, has low regard for technology which results in less priority given to the carsharing platforms. This policy package reduces public parking and does not require private parking for new developments. Vehicle access limits will be implemented in 2030 for ICE vehicles. Financially, subsidies are provided for personal EVs but not carsharing as the local governments do not have same financial budgets as the larger governments. Marketing for EVs and carsharing is not provided to account for the lack of priority with technology.

Figure 16 shows the comparison between the four scenarios and the policies used in this study. The level of action or influence is relative between the four scenarios.

++ Significant Increase / Investment
\+ Increase / Investment
/ No Action
– Reduction
–– Significant Reduction

PROPOSED POLICIES	Bubble City	State of Green	Market Place	Our Neighborhood
Private parking for new dwellings	/	/	++	+
Change in total quantity of public parking	–	––	++	–
Change non-restricted to EV parking	++	++	/	+
Vehicular access limits - EV only	+	++	/	++
EV purchase subsidies	/	++	/	+
Carsharing usage subsidy	+	++	/	/
Public parking costs	+	++	/	+
ICE marketing	–	––	/	–
EV marketing	+	++	+	/
Carsharing marketing	++	++	/	/

Figure 16. Policy packages per scenario and level of action or investment.

5.2.4 Policy Package Development Conclusion

To test future scenarios in the system dynamics model, backcasting methodology is applied to the case study of Amsterdam to explore how different scenario pathways impact the transition of clean shared mobility. Policy packages are developed at the city level for Amsterdam. By using the goals stated in Amsterdam’s Clean Air Action Plan for zero emission shared mobility by 2025 and a complete zero emission mobility system by 2030, the scenarios by PBL (2019) describing the future in 2049 provide a pathway for how these goals can be achieved. The policy packages use the narratives from these scenarios to influence how the trends for various factors, including vehicle stocks, shared car usage, charging infrastructure pressure, parking pressure, and vehicle emissions are affected. In the next chapter, the results from the model are shown through the year 2040.

6 Results

The policy packages developed for the four scenarios are applied to the system dynamics model to discover differences in the associated long-term projections of shared mobility usage, vehicle stocks, parking, charging infrastructure, vehicle emissions, and energy demands. While the results provide quantitative outcomes, these outcomes should not be relied upon at face value. As previously discussed, there are many uncertainties and assumptions built into the model which can significantly impact the overall system if incorrect or if technological development occurs at different rates in the future. The overall trends and differences between the trends are more useful in understanding the impacts of the policies implemented in the model. The results of the model are discussed in five sections: carsharing usage, vehicle ownership, public parking, charging infrastructure, and air quality.

6.1 Carsharing Usage

The system dynamics model shows the number of users for carsharing increasing throughout the simulation for all scenarios. State of Green has the highest usage in 2040 with Bubble City and Our Neighborhood achieving slightly fewer users. The variance between State of Green and Bubble City and Our Neighborhood is 17%. Market Place has 47% less users than State of Green, indicating a significant higher share of vehicle ownership. Figure 17 shows the trends for the total number of users for each scenario throughout the simulation. While starting with different trajectories, Bubble City and Our Neighborhood converge in 2037.

The growth rate for carsharing users is between 4% and 120% annually. The trends show an early rapid increase in the growth rate which levels off in 2022 for State of Green while Market Place gradually levels off throughout the entire simulation. The differences in trends can be contributed to the marketing campaigns near the beginning. The second jumps in State of Green, Our Neighborhood, and Bubble City result from the ICE vehicle access limits and corresponding negative ICE marketing as these vehicles are no longer attractive due to the added inconvenience of not being allowed in the city causing people to switch to carsharing or EVs. A small jump is observed in 2023 for Bubble City and 2025 for State of Green as carsharing subsidies expire. While the current number of carsharing users is unknown, its growth according to the model is expected to rise to more than 1,000 new users per month after 2030 except in the Market Place scenario which achieves 700 new users per month. The trends for the adoption of carsharing are shown in Figure 17.

The results show that the policies incentivizing carsharing and limiting vehicle ownership in the Bubble City, State of Green, and Our Neighborhood scenarios result in a higher and earlier uptake in carsharing than in the Market Place scenario. The end of the 36-month carsharing subsidy results in a drop of 10 new members (-1.7%) per month for Bubble City. This drop is attributed to the sensitivity of price in the utility calculation for the model. For State of Green, the expiration of the carsharing subsidy and ICE vehicle access limits occurs simultaneously resulting in a net increase in carsharing users.

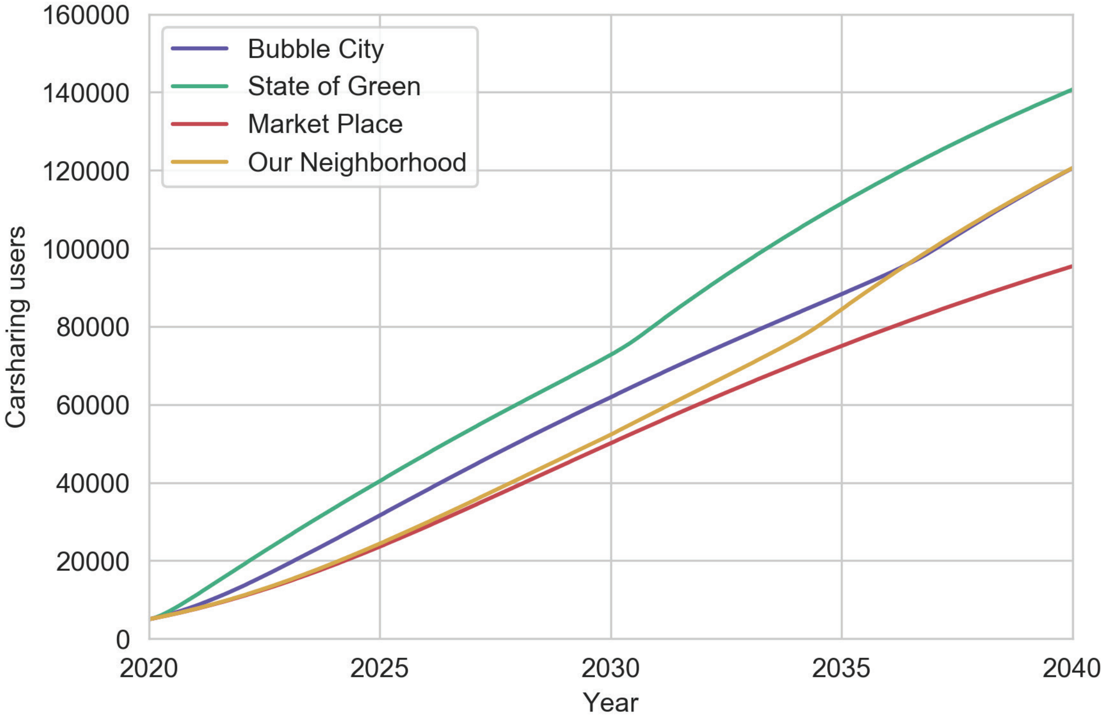

Figure 17. Car sharing users per scenario

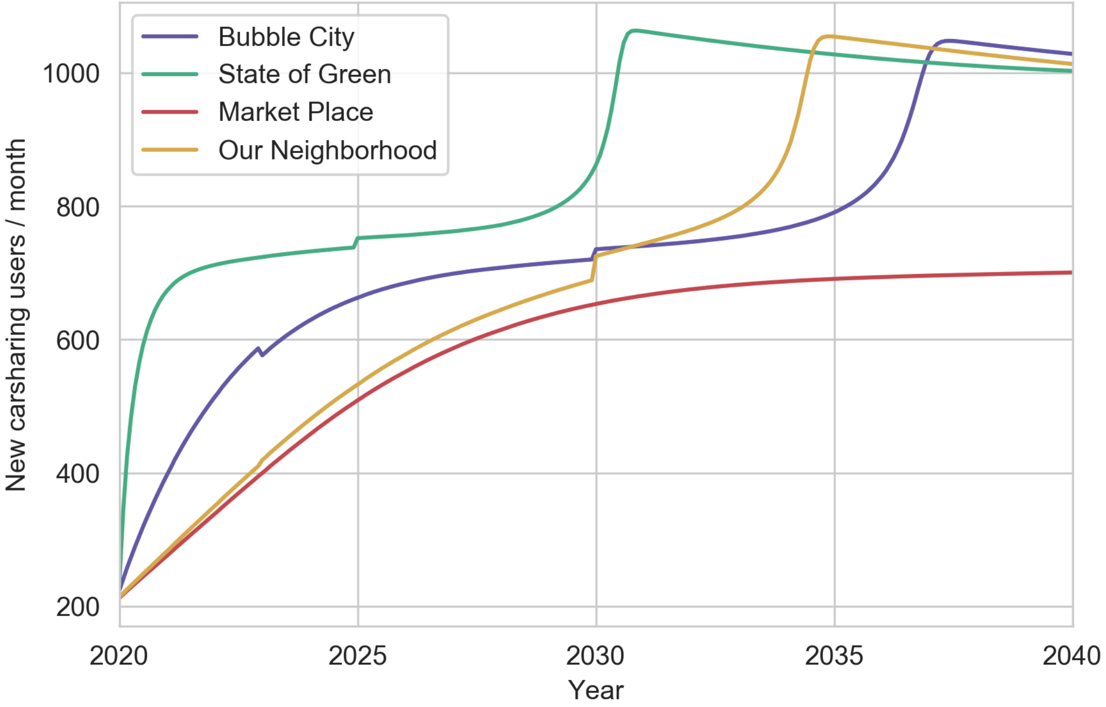

Figure 18. New shared vehicle users per month per scenario

6.2 Vehicles

There are three classes of vehicles in the model: personal vehicles, carsharing vehicles, and ride hailing vehicles, each with ICE and EV subclasses. The trends for these vehicle stocks are discussed in the following section.

6.2.1 Total Vehicles

The overall vehicle stock is reduced in all four modeled scenarios from 251,595 at the start to 197,123 for State of Green and 233,605 for Market Place in 2040. This yields an overall reduction in vehicles of 22% and 7%, respectively, while incorporating an annual population growth of 10,000 people. State of Green immediately reduces vehicles with a continued downward trend, while Bubble City peaks in 2021 and the other two scenarios peak in total vehicle stock by 2023. Figure 19 show the total vehicle stock trends per scenario from the simulation.

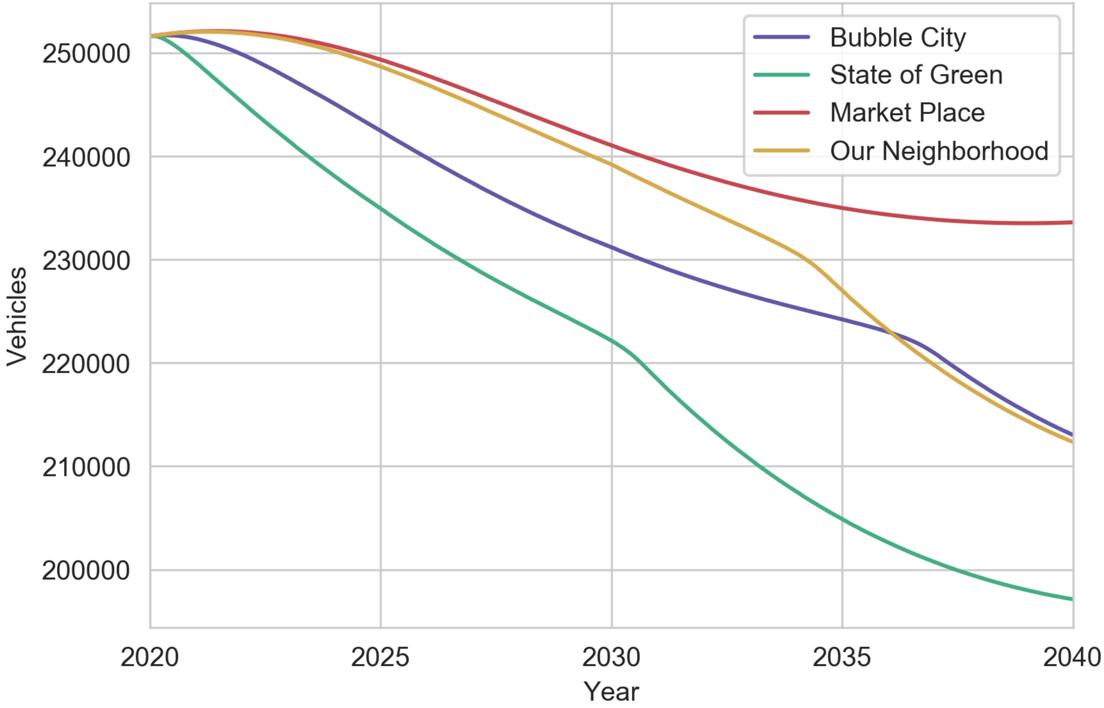

Figure 19. Total vehicle stock per scenario per month.

6.2.2 Personal ICE Vehicles

The ICE vehicle stocks experience significant declines in all four scenarios, indicating that as carsharing and EVs become more well-known and attractive, the ICE market share will reduce over time. The model shows the largest reduction of 187,500 vehicles or 78% for State of Green and the lowest reduction of 112,600 vehicles or 49% for Market Place by 2040. The ICE vehicle stock reduction for Bubble City and Our Neighborhood result in comparable outcomes in 2040 with Our Neighborhood having 12% fewer vehicles than Bubble City; however, Bubble City experienced earlier reductions due to the early uptake in carsharing as a result of the marketing policy while Our Neighborhood experienced more reduction following the implementation of the vehicle access limits in 2030. Figure 20 shows the trends of for the ICE vehicle stock throughout the simulation.

ICE vehicle sales for all scenarios trend downward initially with State of Green achieving the highest early reduction and Market Place the least. The initial trends are a result of the marketing campaigns for carsharing and EVs. The vehicle access limit policy results in an immediate drop at the time of its implementation in addition to the downward trend resulting from the contra-ICE marketing associated with the policy. This trend reduces to zero as the willingness to consider drops to zero, simulating consumers awareness of the access limits prior to implementation and resulting in a sharp decline after the implementation as these vehicles are no longer attractive due to the added inconvenience. Since vehicle access limits are not implemented for Market Place, sales reduce as the other platforms gain market share to 760 vehicles per month, a 48% decline from 2020. Figure 21 shows these trends for ICE vehicle sales.

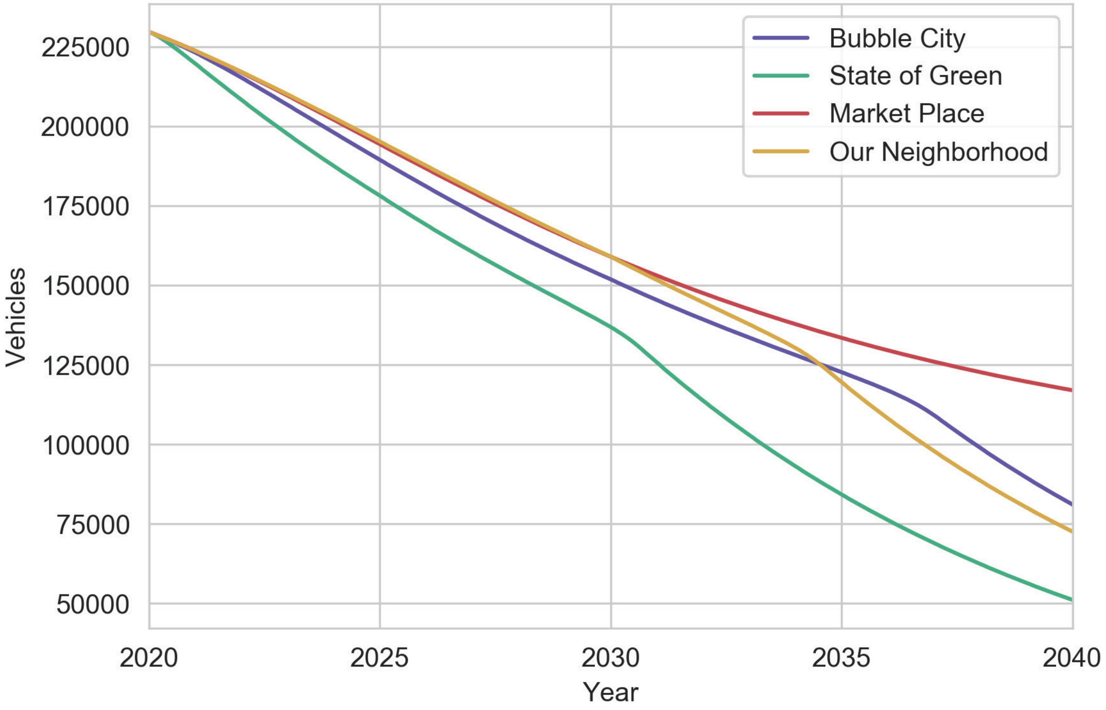

Figure 20. ICE vehicle stock per scenario per month.

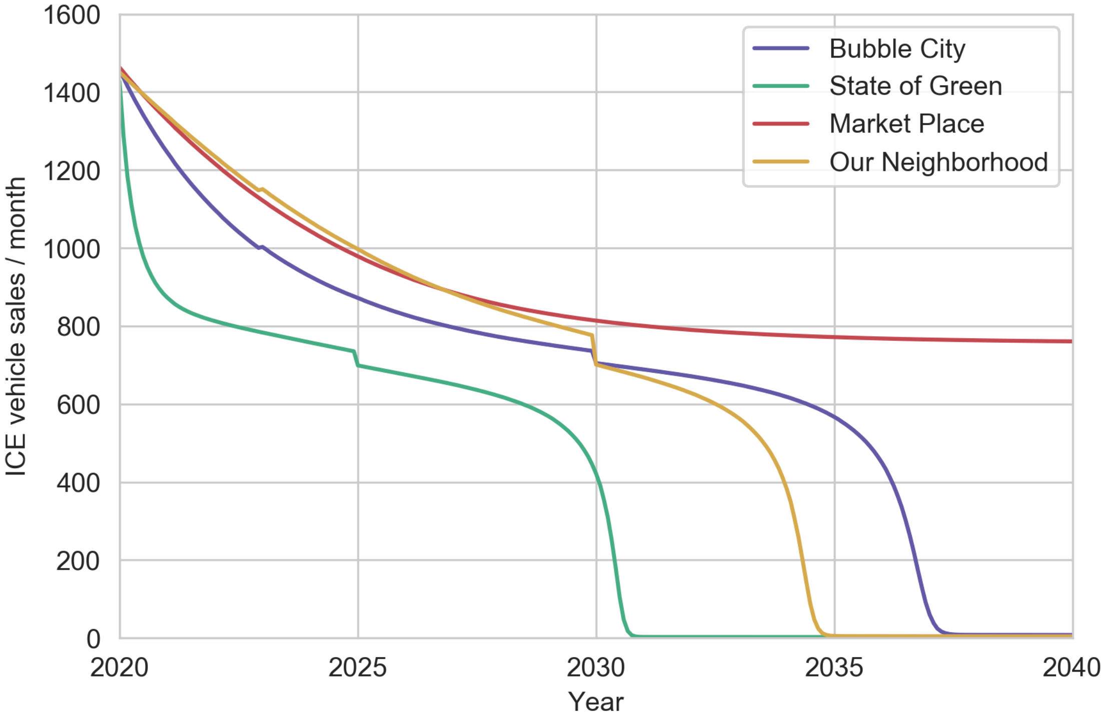

Figure 21. ICE vehicle sales per scenario per month

6.2.3 Electric Vehicles

The stock of personal EVs grows throughout the simulation resulting in 102,000 vehicles for State of Green and 81,500 vehicles for Market Place. This represents a significant growth of the EV stock over the 20 years. Figure 22 shows the trend of personal EVs throughout the simulation. The trends show that the stock of EVs in the four scenarios grow throughout the entire simulation with Market Place initially exhibiting the highest number of EVs through 2030 but lowest in 2040 due to the implementation of the vehicle access limits in the other scenarios.

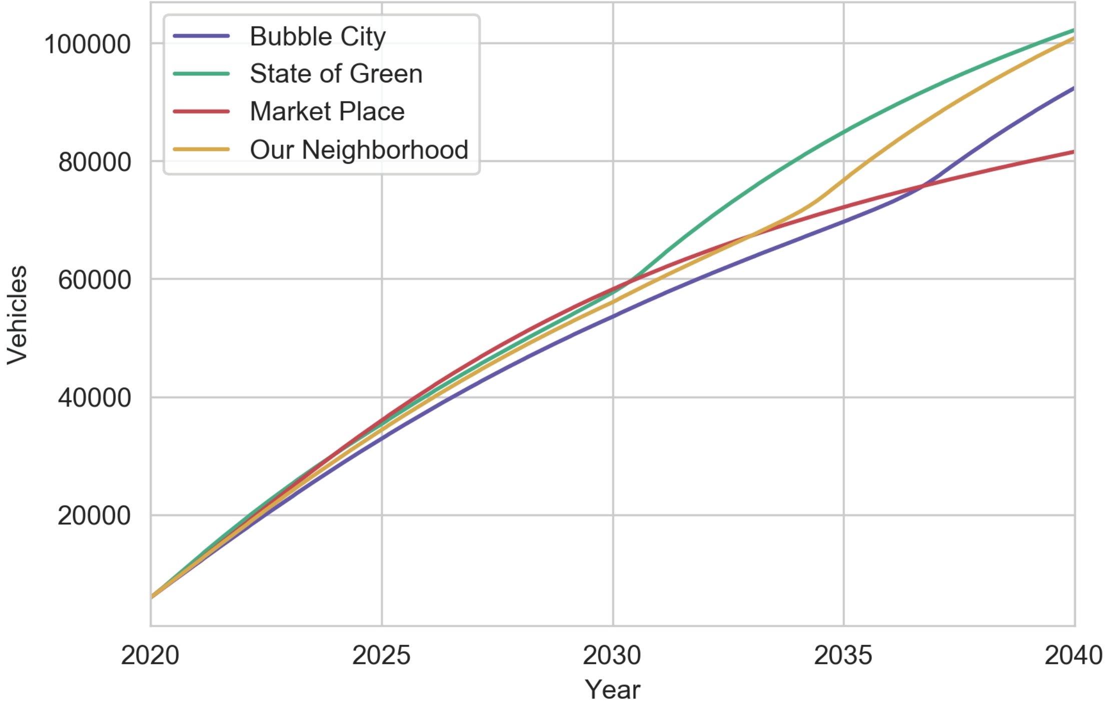

Figure 22. Personal electric vehicle stock per scenario per month

EV sales experience continual growth through most of the first half of the simulation and peak at 1070 vehicles per month for State of Green in 2031. State of Green achieves the highest growth rate within the first year; however, the growth rate for Market Place exceeds the other scenarios in 2023 until 2028 when State of Green surpasses it again as a result of the vehicle access limit policies on ICE vehicles. Figure 23 shows the vehicle sales per month for each scenario. Jumps in the trends are observed for the State of Green, Bubble City, and Our Neighborhood as a result of the subsidy expirations and vehicle access limits.

6.2.4 Carsharing Vehicle Stocks

The vehicle stock for carsharing is comprised of EVs and ICE vehicles, with EVs representing 88% of the initial vehicle stock (CROW, 2020). The model assumes that all new vehicles are electric and that shared ICE vehicles are retired based on an average lifespan of 5 years. The total carsharing vehicle stock reaches 35,000 with State of Green in 2040, a 346% increase. Market Place achieves the lowest total carsharing vehicle stock, with 26,500 vehicles or a 235% increase. Bubble City and Our Neighborhood achieve similar stocks of 31,000 and 30,400, respectively, in 2040. The trend for Our Neighborhood follows a similar path of Market Place through 2030 since there are no marketing campaigns for carsharing for either scenario. After 2030, however, Our Neighborhood experiences more growth as a result of the vehicle access limits on ICE vehicles. Figure 24 shows the carsharing vehicle stock with continued growth of EVs and the ICE vehicles diminishing in 2028.

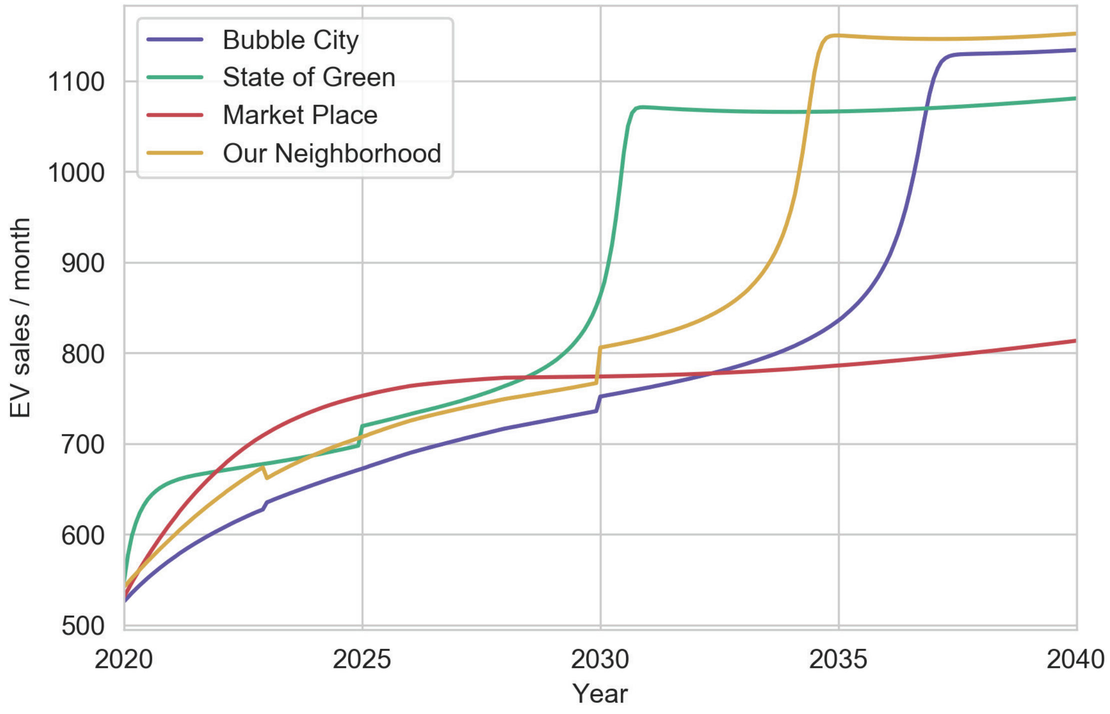

Figure 23. Electric vehicle sales per scenario per month

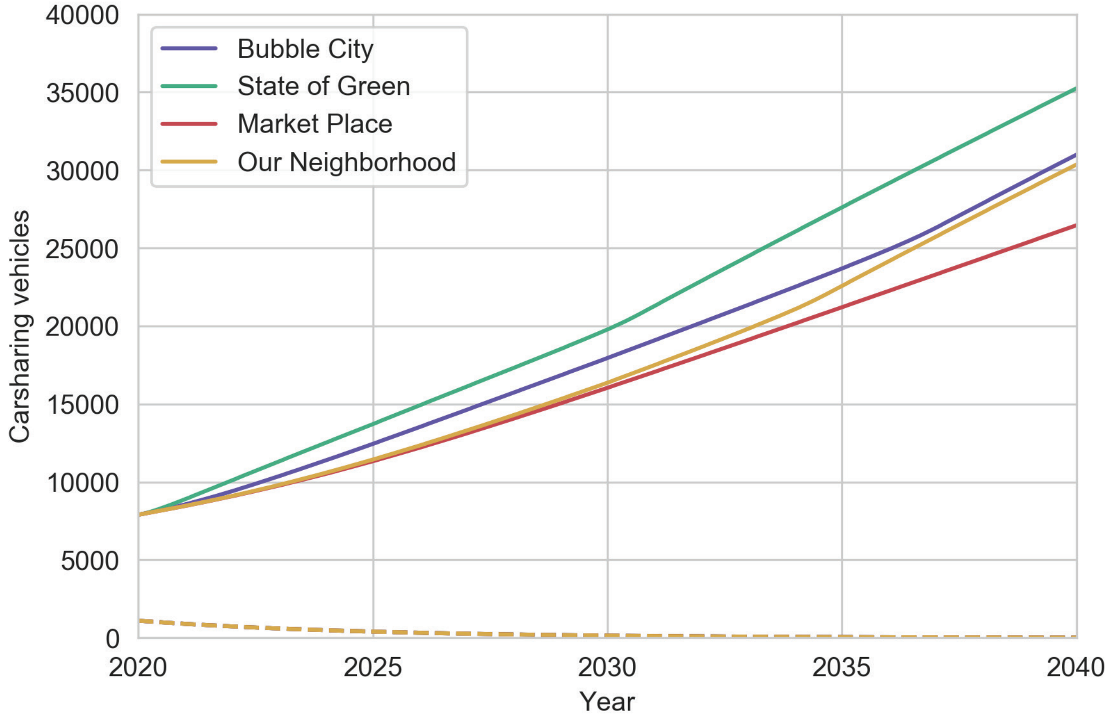

Figure 24. Total shared vehicle stock per vehicle per month

6.2.5 Ride Hailing Vehicle Stocks

Ride hailing vehicle stocks show a continual growth of EVs and decline of ICE vehicles. Because the four scenarios do not separately account for ride-hailing, a service available to all people with a smart phone and a utility for users of all platforms, ride hailing trends act independently. Additionally, the usage and growth of ride hailing is unknown for this study; therefore, the model uses the overall population growth for the growth of ride hailing vehicles. The trends show EVs overtaking ICE vehicles in 2022 with ICE vehicles diminishing to nearly zero shortly after 2030. Figure 25 shows the trends for ride-hailing EVs and ICE vehicles through the simulation.

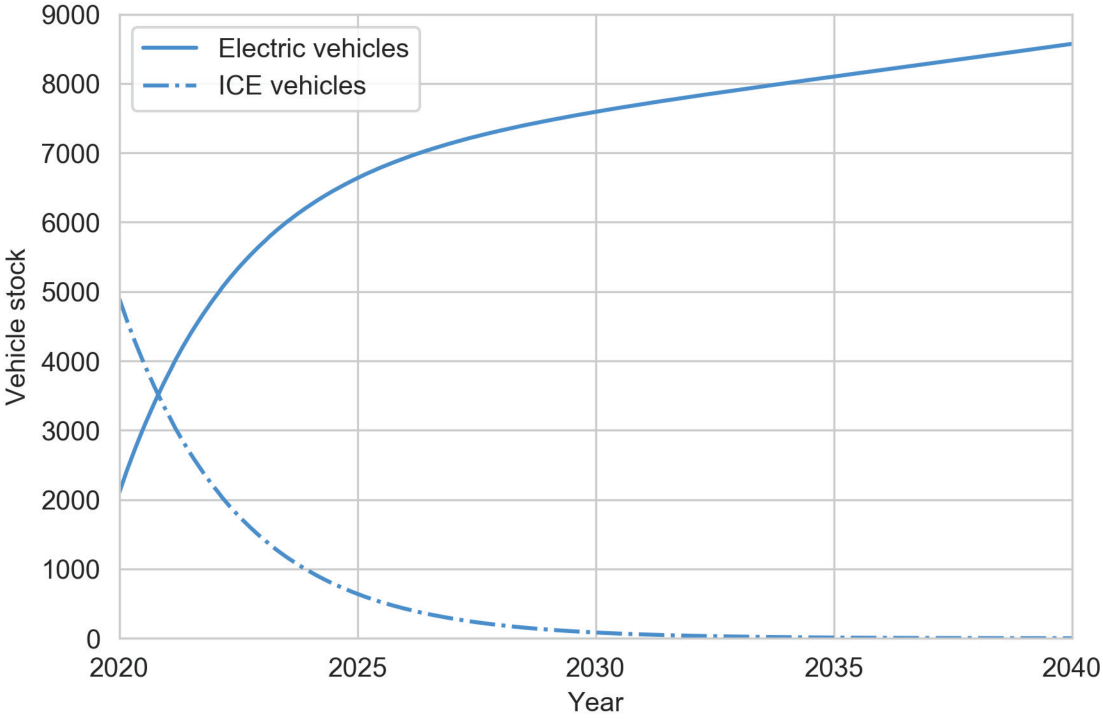

Figure 25. Ride-hailing vehicle stocks

6.3 Parking

Changes to public parking spaces are dictated by the policy packages with the growth or decline being a linear function of spaces per month. Market Place is the only scenario where there is a net increase in public parking. The other scenarios reduce the overall parking quantities, with State of Green achieving the most significant reduction. Analyzing the public parking spaces per vehicle shows the pressure on or accessibility of personal vehicles in the city. Currently, in Amsterdam, there are 1.05 public parking spaces per vehicle. Market Place results in the highest parking space per vehicle ratio with 1.34 spaces per vehicle in 2040 and State of Green achieves the lowest ratio with 0.71 spaces per vehicle. The trends for the ratio of total parking to vehicles is shown in Figure 26.

The number of EV-designated parking spots is directly affected by the policy packages where open public parking spaces are designated as EV-only. As more parking spaces are designated EV-only, the accessibility for EVs, both personal and shared, increases. Market Place achieves the highest EV parking space per EV ratio with 1.78 spaces per vehicle in 2040. State of Green achieves 0.7 spaces per vehicle, indicating a continual pressure on EV owners. These results and trends are shown in Figure 27.

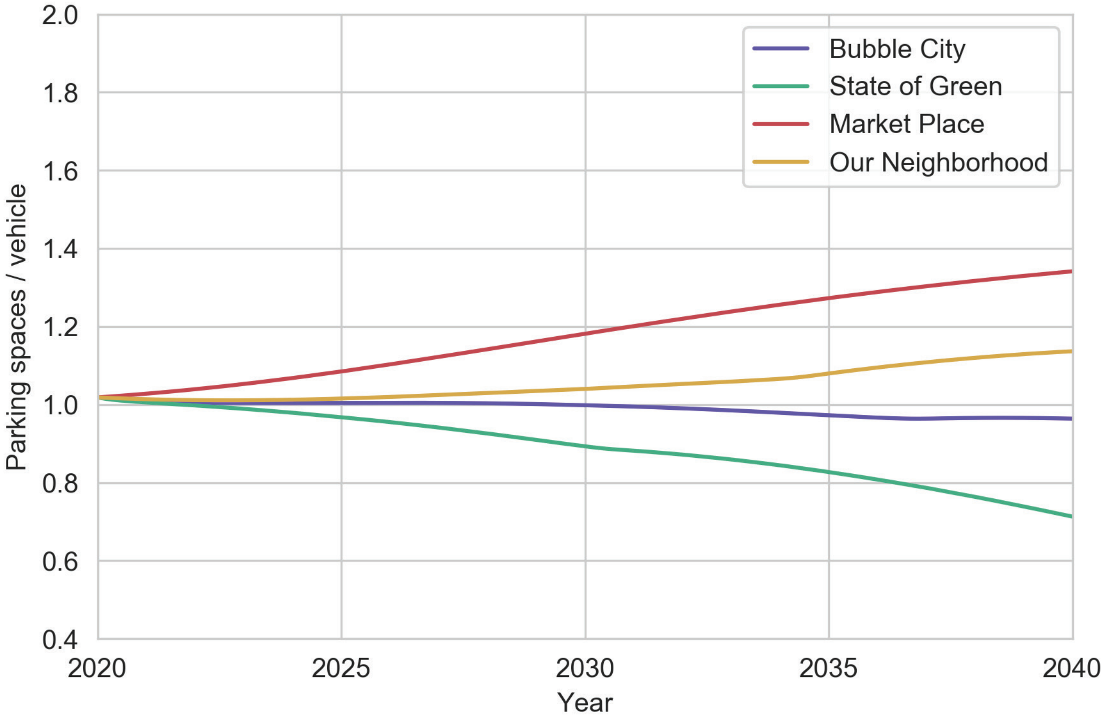

Figure 26. Public parking spaces per vehicle per scenario per month

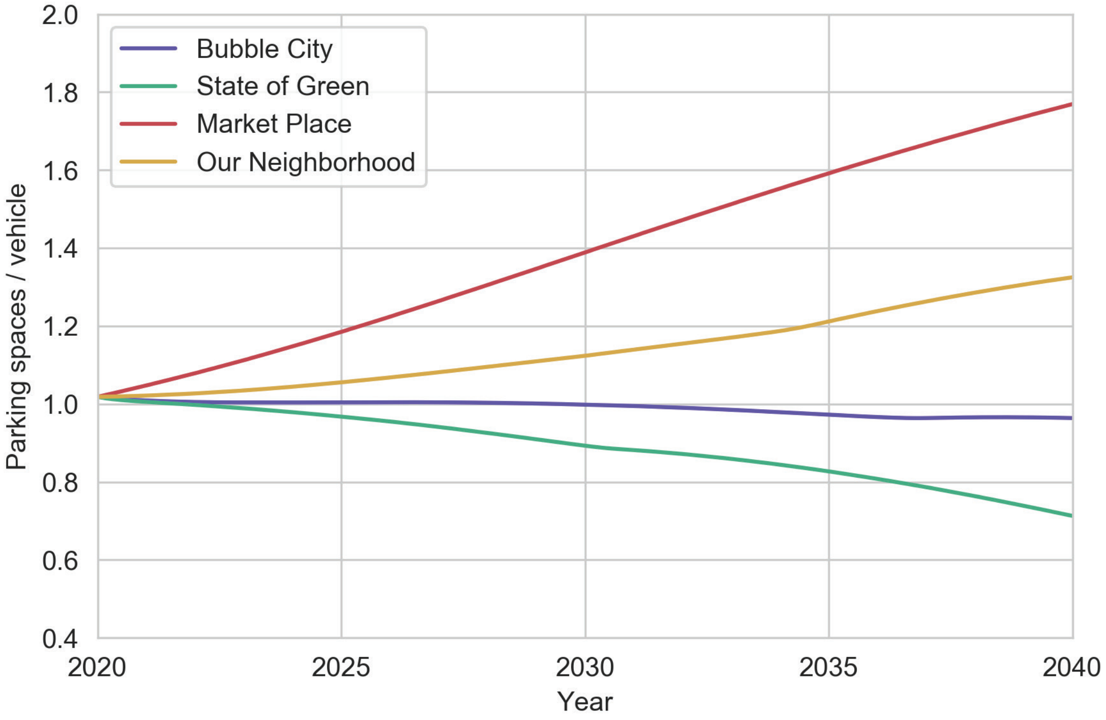

Figure 27. EV parking per electric vehicle per scenario per month

Changes to parking stocks affects public street space as each parking space requires 15m2 (Agenda Autoluw, 2019). As a result, State of Green makes available 1.74 million square meters while Market Place demands an additional 857,000 m2 compared to existing conditions. A summary of these changes is provided in Table 7 for the year 2040.

Table 7. Public parking space changes per scenario in 2040

Scenario	Change in number of spaces	Street space (m^2)
Bubble city	-50,880	-763,200
State of green	-115,680	-1,735,200
Market place	+57,120	+856,800
Our neighborhood	-14,880	-223,200

6.4 Charging Infrastructure

All four scenarios add 50 new (Level 2) EV chargers per month. At this rate, the total number of EV chargers by 2040 is 13,800. The number of vehicles per EV charger indicate the accessibility of charging infrastructure for EV drivers. Amsterdam's current ratio is approximately 8.9 EVs per charging point. The model shows that EVs per charging point peaks at 11.8 in 2023 for State of Green. Bubble City's peak ratio is the lowest at 10.8 EVs per charging point in 2024. The ratios for all scenarios except Market Place experience a second jump in beginning in 2030 for State of Green and 2034 and 2036 for Our neighborhood and Bubble city, respectively, as a result of the increase in EV market share due to vehicle access limits on ICEs. The ratio for Market Place peaks around 2024 and continually declines to lower than 8.5 in 2040. Figure 28 shows the ratios for the four scenarios across the simulation.

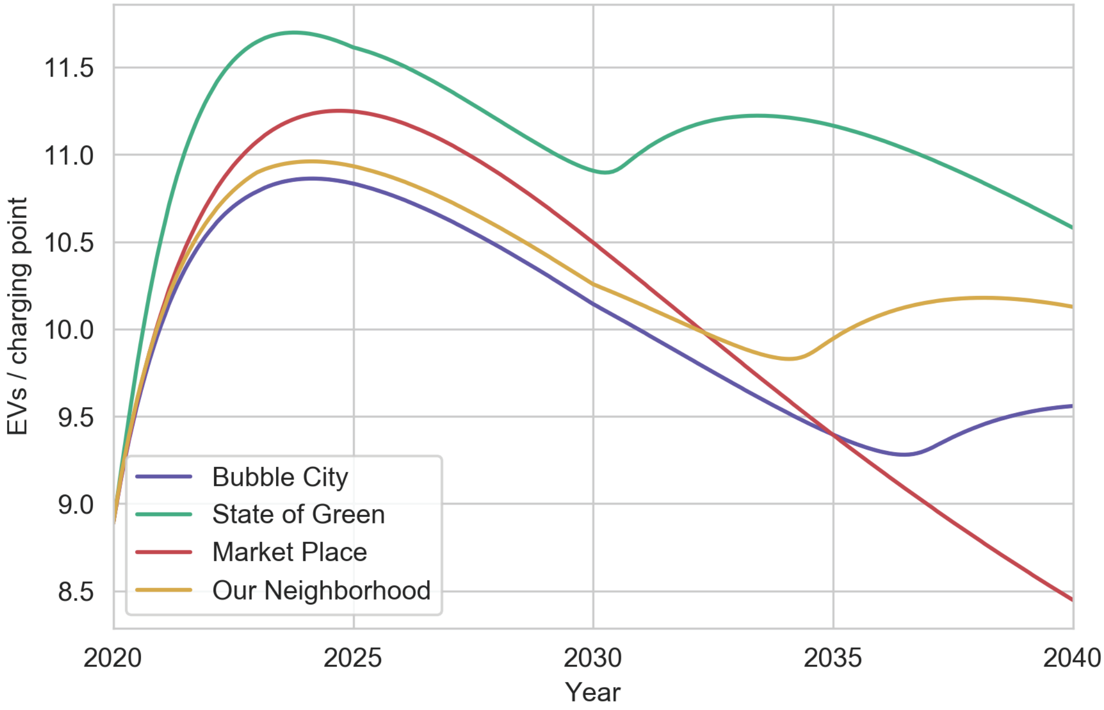

Figure 28. Electric vehicles per charging point per scenario

As a result of the uptake in EVs, energy demand increases. Although the exact energy demand is unknown and is dependent on travel patterns, the demand is estimated in the model using the number of EVs multiplied by a vehicle efficiency and the average monthly distance traveled. The vehicle distance traveled used to calculate energy demand is adjusted from the national average based on the reported energy for Amsterdam in January 2020 of 1,822,000 kWh (evdata.nl, 2020). This adjustment results in an average distance traveled of 500 km per month, much lower than the national average of 1,300 km. This difference can be explained by people charging at locations outside Amsterdam and overall less vehicle travel by people in Amsterdam. Figure 29 depicts the trends for energy usage as a result of EVs. The trends show an 800% increase in monthly kWh over the next 20 years.

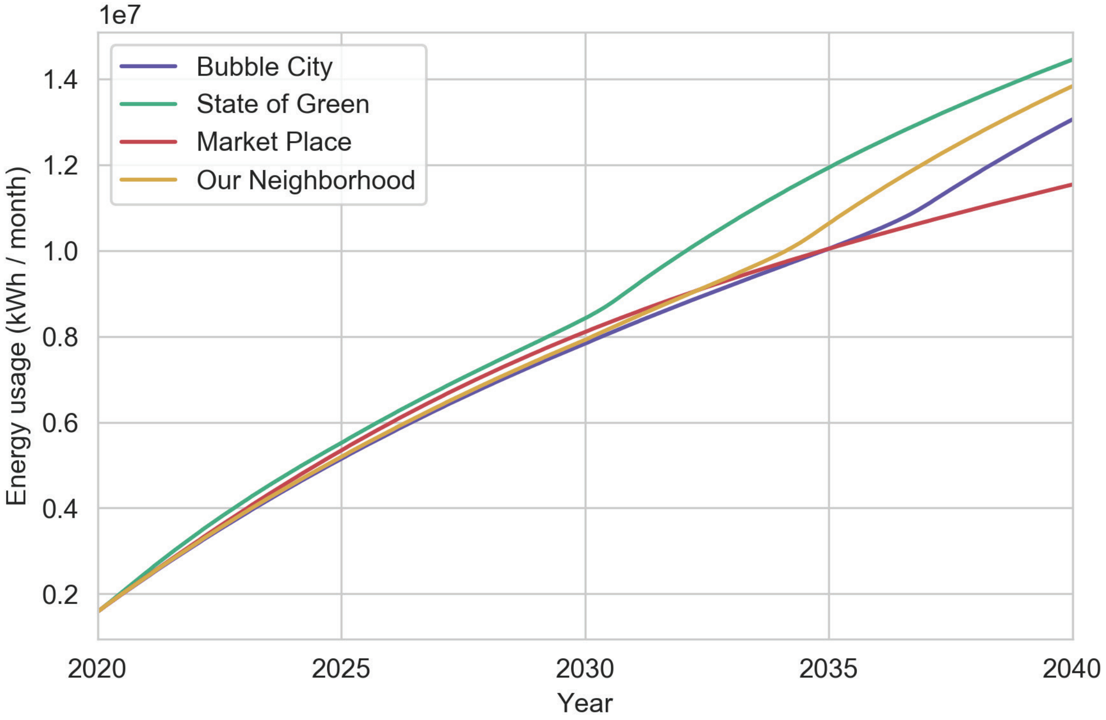

Figure 29. Monthly energy usage per scenario (kWh)

6.5 Air Quality

Air quality is impacted in this study through the reduction in personal ICE vehicles. As the stock of ICE vehicles decreases in the four scenarios, vehicle emissions are forecasted to also decrease. While it is difficult to estimate effects on local air quality, the model results can be used to estimate the magnitude of the decrease in emissions of the scenarios. The emissions are estimated in kilograms of carbon dioxide (CO2) and show an 80% reduction for State of Green and a 65% reduction for Market Place in 2040. The trends for CO2 emissions are shown in Figure 30. While CO2 is used for this estimate, other pollutants, such as nitrous-oxide, and particulate matter would also decrease.

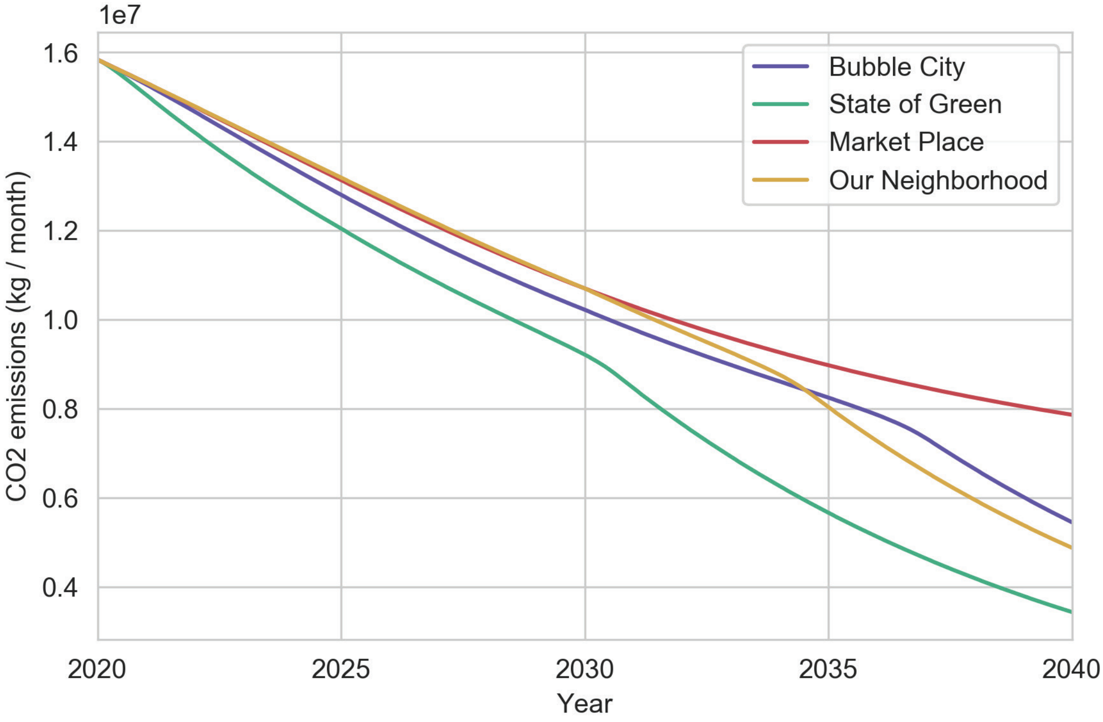

Figure 30. Monthly vehicle emissions per scenario

6.6 Results Conclusion

The results show that for all four scenarios a large increase in shared mobility usage and EV uptake and associated significant decrease in ICE vehicles are feasible. As a result, the total vehicle stock is reduced for all scenarios with State of Green achieving the most significant reductions. The various policies used in the model influence vehicle stocks, public parking, and charging infrastructure demand in varied ways. With the reductions to parking and ICE vehicle stocks, positive gains are seen in public street space and air quality. In the following section, the implications of these results are discussed.

7 Discussion

This chapter aims to provide an interpretation of the results, discuss the validity of the model and results, provide an overview of the limitations, and reflect on the relevance and consistency of the research. This section strives to interpret the impacts of various policy tools on the users and effects of shared and electric mobility in cities. Next, the validity of system dynamics models is discussed for the application of the model to this research. While the research aims to include the significant aspects of the transition to shared and electric mobility, this section discusses the limitations of the information available for the model, the model itself, and researching the topic. The reflection further discusses the contributions of this research to the topic and scientific knowledge. Lastly, the research is evaluated to discuss its consistency with related studies.

7.1 Interpretation of the Results

The results of the system dynamics model show interesting trends in regard to the potential that shared mobility, and specifically carsharing, has for cities. The model projects an overall decrease in personal vehicles as carsharing services become more widespread. This provides the opportunity to reduce the overall public parking stock and create new green spaces, terraces, playgrounds and other amenities in the city. The model also shows the pressure on EV charging infrastructure as personal and shared EVs become more widespread in the city. In the following section, the results and implications of the study and model will be discussed in addressing the research questions.

The first research question; *what type, how many, where, and when should cities plan charging infrastructure for shared mobility fleets*, contains several components for planning charging infrastructure in cities. The type of charging infrastructure is discussed through the technological trends and recommendations. The number of charging points is derived from the system dynamics model. The spatial considerations are based on user preferences from the literature review and the spatial analysis of Amsterdam from the baseline analysis. The temporal aspects are also based on the results of the system dynamics model.

For the type of charging infrastructure, the charging behavior section in the Literature Review revealed that Level 2 charging is preferred over Level 3 fast charging for normal, daily use. Level 2 chargers allow the user to charge the vehicle when it is not in use and does not create the inconveniences of downtime or detours. As charging infrastructure technology develops, flexible and V2G Level 2 chargers should be prioritized as they provide benefits to the power grid and have potential to support renewable energy initiatives as backup batteries. Level 2 chargers are also beneficial for carsharing as they allow the vehicles to charge when not in use and provide a secondary income stream when used with V2G charging. Level 2 chargers provide added benefits to ride-hailing providers as they do not require downtime during the workday, unless the vehicle depletes its battery range. In this situation, Level 3 chargers can be used to supplement the charging to complete the workday.

For the number of new charging points, a rate of 50 Level 2 charging points per month was established for the system dynamics model to analyze the effect on the ratio of EVs (personal and shared) to charging points. While the optimum ratio is unknown and would require a different type of analysis, the results show between 8.5 and 11.7 EVs per charging point. Additionally, the shape of the curve shows a steep increase to a peak withing the first five years. The curve then slowly falls with a second increase beginning in 2031 for State of Green, 2034 for Our Neighborhood, and 2036 for Bubble City. The curve is a result of the high growth rate of EVs and carsharing users early in the model and the second jump is a result of imposing vehicle access limits for ICE vehicles. If cities seek to accelerate the uptake in EVs and electric shared mobility, a lower ratio of EVs to charging points should be prioritized, especially during the first few years of the planning cycle. The challenge remains that flexible and V2G technologies are still in development and more expensive; however, investing in these technologies enables benefits to be realized sooner and costs to be reduced as economies of scale are achieved.

The spatial concerns of charging infrastructure are highlighted in the Literature Review chapter. Further, the Baseline Analysis chapter provides a spatial analysis of charging infrastructure in Amsterdam and finds that Level 2 charging infrastructure within 200 meters of a user's home is preferred (Wolbertus, R. & Van den Hoed, R., 2019). The spatial analysis of Amsterdam shows a considerable number of postal codes outside the city center with high populations and low percentage of the population within 200 meters of a charging point; therefore, new charging points should be prioritized to ensure that each resident has a charging point within a close proximity of their residence. Next, additional charging infrastructure should be installed with a focus on reducing the population per charging point. In Amsterdam, this would prioritize the Nieuw-West, Zuidoost, and Noord neighborhoods.

The temporal aspects for the strategy of new charging infrastructure are influenced by technological advances in charging infrastructure, battery range advances with new EVs, and spatial rollout. Early investments in charging infrastructure to increase convenience will continue to make personal and shared EVs attractive. Additionally, flexible and V2G chargers should be prioritized early so that energy grids can benefit from their use, offsetting need for power generation investments and helping with power intermittency challenges of renewables.

The second research question; *what policies and regulations can cities use to facilitate shared electric vehicles,* is addressed throughout the research and simulated in the system dynamics model. Focusing the study at the city level, policies that can be influenced or enacted at this level are proposed. The city, however, does not operate in a vacuum and national, supranational, market, and civil society actors play important roles in the future development of spatial and transport development. The policy question is addressed through the four scenarios which describe political, sustainable, and technological influences. The policy packages are developed to reflect how these influences interact with policy.

The results of the system dynamics model indicate that the policy packages produce different trends in the uptake in shared mobility, EV purchases, public parking accessibility, and EV charging accessibility. Each policy, except marketing, influences the utility of each platform, which directly influence the market share of new users or purchases. As a consequence, subsidies make the financial component of the utility more attractive early in the simulation when ICE vehicles are more cost effective; parking policies make the accessibility more or less attractive as the accessibility of that platform changes, and vehicular access limits of ICE vehicles significantly reduce their accessibility and attractiveness. Marketing policies or investments for carsharing and EV purchases affect the social exposure and increase the willingness to consider of these options. The willingness to consider component of the market share calculation is a significant hinderance for the uptake in EVs and carsharing. Even as the utilities of these services increase and surpass that of ICE vehicles, an insufficient amount of the population is aware of the technological advantages or conveniences of these platforms early in the simulation. The effects of the policy packages can be seen in the market share for carsharing, EVs, and ICE vehicles in Figure 31.

The third research question; *how many charging points per (shared) electric vehicle are required to service demand,* can be answered through understanding the trends in EV charging technology and how public charging infrastructure is used by both personal and shared EVs. As public charging infrastructure in Amsterdam is used by both shared and personal EVs, a trade-off must be considered between accessibility and convenience of charging and investment costs of charging infrastructure. A lower average EV to charging point ratio results in higher accessibility to EV drivers, making EVs more attractive and ensuring shared EVs have the necessary range for their users. An abundantly low ratio could result, however, in a lower average utilization of the charging point leaving charging points underutilized. As cities have limited budgets and private investors seek to maximize their investments, higher utilization rates are more attractive. As vehicle to grid charging technology becomes more widely available, there will be a desire to provide a larger number of these charging points to provide storage capacity for the energy grid and shared EVs will desire access to more

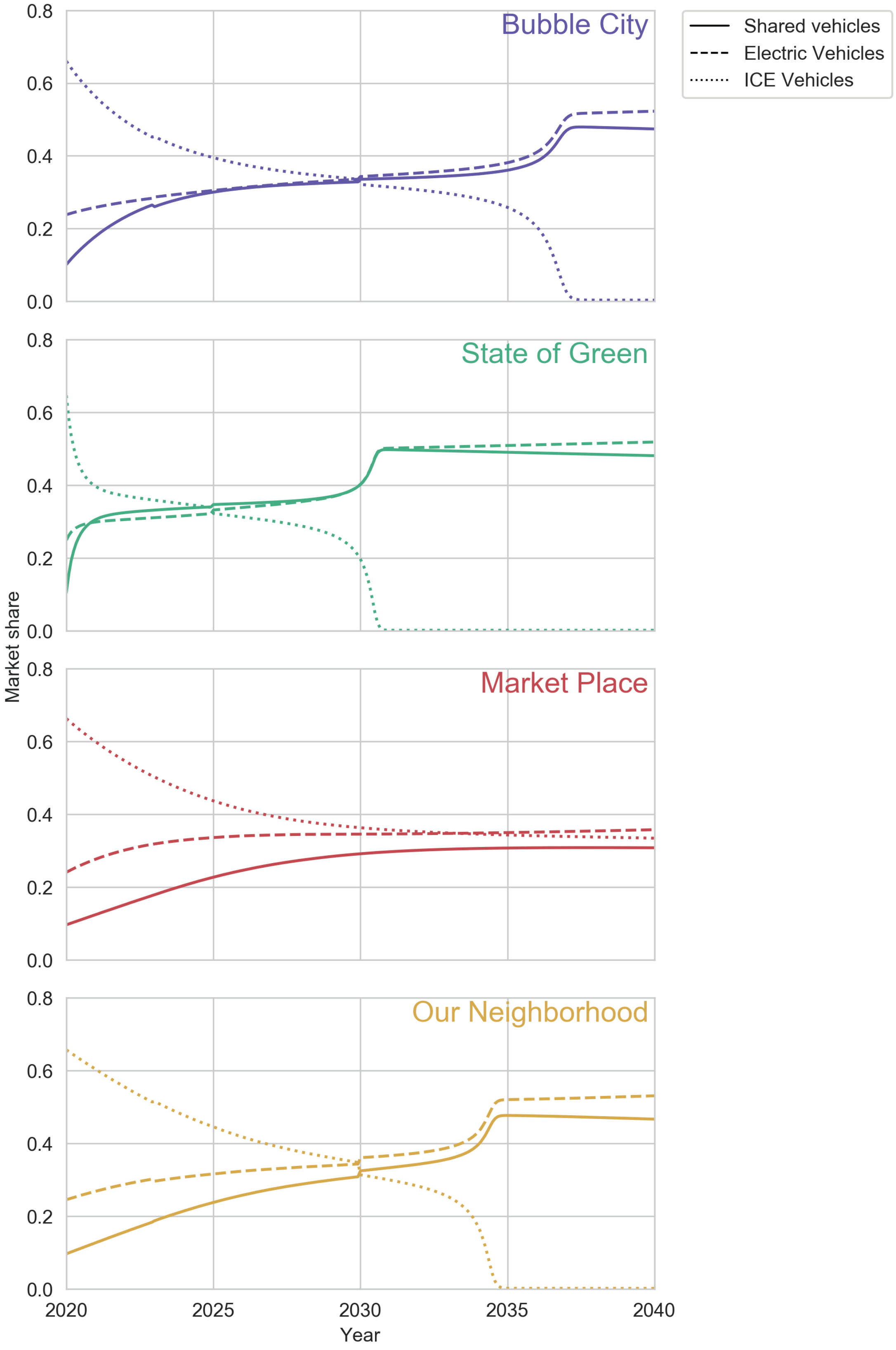

Figure 31. Market share per scenario

of these charging points as a secondary revenue stream when the vehicle is not in use. From the data analysis, the utilization is approximately 60% for charging points at the current ratio of 8.9 EVs per charging point; however further research is needed to determine the optimal ratio. Furthermore, the distance traveled per day per shared car determines how often these vehicles need to connect to a charging point. To ensure that carsharing vehicles are able to charge when needed, it is recommended that certain charging points are designated for these vehicles and located within 200 meters of high population areas.

The last research question; *what are the effects on public street space as a result of shared mobility,* is answered through the results of the model. In three of the four policy packages, the public parking stock was reduced. Due to the reduction in total vehicle stock as a result of carsharing, further parking reductions are possible beyond what is proposed by the policy packages. State of Green, the scenario with the most aggressive parking removal, removed 45% of its total public parking stock, making available 1.7 million square meters of space. If shared mobility experiences growth similar to these scenarios, large amounts of public space can be reclaimed from vehicle parking.

Overall, local government policies and planning for charging infrastructure play important roles in the transition to clean shared mobility and personal EV uptake. While the model indicates that ICE vehicles will still exist in the future scenarios, personal vehicle ownership can be reduced as a whole through the promotion of shared mobility. Policies and investments in making EVs more attractive have the potential to drastically alter the way public space is used. Additionally, improvements to air quality and local climate challenges can be realized with the uptake in EVs and reduction in total vehicles in the city. The model shows that while policies at the city level have the opportunity to facilitate positive change, national, supranational, civil society, and market parties should also be engaged early in reducing ICE vehicles from the market. With the support of these other actors, banning the sales of ICE vehicles could occur in the near future, paving the way for a quicker transition to zero-emission mobility.

7.2 Validity

Validating system dynamics models is the process in which confidence is built in the structure and behavior of the model (Forrester & Senge, 1979). First, Forrester and Senge discuss that the model-builder should become confident in the model then transfer confidence to the target audience. This confidence should be established based on the model's structure resembling the real-world system and its behavior showing logical and realistic results and effects for input variables (Forrester & Senge, 1979). Forrester and Senge stress that target audiences may consist of scientists, policy makers, or other stakeholders, adding to the complexity of validation as different members of the target audience evaluate models through different objectives and criteria. Forrester and Senge state that the highest objective in validation is achieved through the model's usefulness as a tool for policy evaluation. As discussed in the Methods chapter, three types of tests are used for validating models: structure, behavior, and policy implications (Forrester & Senge, 1979 & Bala et al., 2017). Forrester and Senge (1979) propose a number of structural and behavioral tests, some of which will be discussed and applied to this study.

The base structure of the model is built upon several highly cited system dynamics models and papers. Struben and Sterman (2008) provide the core structure of the model in their research on transitioning to alternative fuel vehicles. This research established the willingness to consider stocks resulting from a social exposure loop and the willingness to consider decay as a result of forgetting. The willingness to consider component of the model is designed to simulate people's awareness and actual consideration of the platform. The willingness to consider and the utility of the platform are then used to determine the share of sales to each platform. This structure has been replicated and expanded in several other system dynamics models evaluating vehicle platforms. Studies include Shepherd et al. (2012) which evaluates the future demand of EVs and Keith et al. (2017) which uses a flight simulator tool for the US vehicle market. The structure of the model for this study is expanded to include a carsharing user stock and its influence on the shared and total vehicle stock. The model is also adapted to include different drivers with respect to the urban context, including charging infrastructure and parking.

The structure of the model in this study has been discussed with a group of stakeholders and industry experts at APPM Management Consultants in a working session on 2 June 2020. During this session, the components, interactions, feedback loops, and boundaries were discussed and reviewed to determine whether the model was structurally complete, relevant aspects were included, and if the boundary of the system was a logical representation of the real-world system. While the model is a simplification, as all models are, the stakeholders agreed that the model was a logical representation of this system.

The parameters used in the model are a combination of actual data for the City of Amsterdam, the Netherlands, and assumptions based on the data estimates, extrapolations, and trends. The baseline data and trends show a significant increase in the uptake in personal EVs and an increase in carsharing vehicle stock and carsharing users. The model was calibrated with the willingness to consider and utility showing a similar growth rate of EV purchases to the available data trends, resulting in an initial willingness to consider of 0.5. This could, however, have also been achieved with different utility weights, factors, or different estimates about the parameters of the vehicle platforms. The lack of available data corresponding with the recent progress in carsharing and EVs poses challenges for the baseline parameters which causes a high reliance on assumptions and estimates. While these baseline assumptions could be challenged, they are based on research and discussions with experts in the field and can be altered as more accurate data is made available.

The model's structure is built upon previously accepted models for alternate fuel vehicles and is similar to several other studies of similar topics. The model uses parameters based on data and similar research and has been reviewed and accepted by a group of experts in the field; therefore, the structure of the model has achieved an initial or preliminary level of validity. The model should be discussed and reviewed further with additional stakeholders to expand its structural validity and gain wider acceptance for its results.

The behavior of the model is tested through behavior prediction tests. As this model focuses on predicting how EVs and carsharing affect the vehicular system within a city, the results should correlate with what is feasible within the parameters of the model. The results of the model are checked with the scope and growth rate of the population for the city and the sum of personal vehicle stocks and carsharing users are reflected in the expected population with little variation. The model is built with the assumption that the overall modal split will remain constant and that vehicle owners today will choose between purchasing another ICE vehicle, an EV, or using carsharing. Since shared cars can be used by multiple people at different times and the model accounts for 8 people per new shared EV, the total vehicle stock decreases as expected with the scenarios encouraging higher shared car usage.

Extreme policy tests were also performed on the model during model calibration. These tests were done by prohibiting the sale of new ICE vehicles at certain dates, drastically increasing the willingness to consider for EVs and carsharing through the marketing parameters, and drastically increasing and decreasing the different policies to see the effects on vehicle stocks. These tests were performed independently of each other and behaved as expected with significant changes to vehicle sales and long-term changes to the stocks. Further behavior tests are recommended, however, due to the limitations of this study, have not yet been performed.

Sensitivity analysis of estimated parameters in the model provides insights into how sensitive the model is to these estimates. As the weights for the utility calculations were estimated to compare vehicle purchases with carsharing usage, sensitivity tests were conducted to test their effect on the variability of the results. As a result, these parameters were adjusted to align with recent trends and expectations from the expert workshop. These tests showed high sensitivity to the ownership sensitivity parameter and platform scope categories as the values for ownership is a zero for carsharing and one for vehicle purchases and current platform scope is low for EVs compared with ICE vehicles. Overall, the sensitivity analysis shows that the values used in the model are within a standard deviation of the mean for these parameters.

Understanding the limits of system dynamics models and challenges with validating these models, it is argued that the model passes an initial validation. For developing policies for real-world scenarios, the model can be used for an initial investigation but should be further validated and revised based on the various tests proposed by Forrester and Senge (1979). Additional stakeholder input through expert engagement and workshops would make the model more robust and build confidence in how the system operates.

7.3 Limitations

There were several limitations experienced with developing the model and in the usage and implementation of the results. These limitations include access to data, other research to support and contribute to the various aspects of the model, limitations with system dynamics models in general and this model specifically, and limitations with the focus on the city for policy recommendations. While assumptions were made and documented to address some of the limitations, addressing these limitations through actual data would make the overall research more robust. Additionally, the limitations with the system dynamics model in this study, and models in general, cannot be ignored. This section elaborates on these limitations.

Limitations attributed to data include data that is not provided or open source through the various government entities and proprietary data with shared mobility companies. Throughout the study, multiple attempts were made to obtain data from the City of Amsterdam related to the number of EVs registered in the city, including waiting lists, and other trends. While it was assumed that Amsterdam experiences a higher growth rate of EVs than the Netherlands, this information was not obtainable, and assumptions were required for these differences via conservative estimates. Proprietary data includes the number of users and growth rate for shared mobility as well as charging trends and behaviors for the charging infrastructure in Amsterdam. Insights into the number and frequency of shared mobility users could provide a better baseline for the social exposure of these services, growth rate, and ratio of users to carsharing vehicles. Charging behaviors and trends, especially on an anonymous user level, could be used to better estimate the number of vehicles per charging point to improve the utilization of the charging infrastructure. If postal code information was provided for the users of Level 3 fast chargers, deficiencies in the spatial placement of chargers could be addressed through new chargers as the research showed Level 2 chargers are preferred when located near residents' homes.

There are limited academic studies and data related to consumer preferences with respect to EVs and shared mobility. Studies focusing on consumers' choices to forgo vehicle purchases for carsharing usage could provide great insight in building the utility and corresponding weights of the platforms. Additionally, understanding of the social exposure of these platforms would provide a better baseline from which the model could simulate the real-world scenario. These insights could be used to better target individuals and influence their decision when making a mode choice for various trip purposes. Studies using other models, including agent-based models, would provide insights into the modal split for Amsterdam with the increase in shared mobility options or optimize the number of EVs per charging point with the dynamic nature of vehicle travel.

Models, including system dynamics models, are simplifications of real-world systems and cannot account for every aspect of the complexity in real life. Models are useful, however, as they provide insights into these complexities and allow simulations of various events. Specific limitations related to system dynamics models are that they use assumptions to account for uncertainties where empirical data is not available. They are also based on mathematics and economics and use the assumption that rational, economic choices are made by individuals. In the real world, however, it is widely accepted that irrational decisions are frequently made. Accounting for and acknowledging these deficiencies when developing or evaluating these models helps with building validity.

The system dynamics model in this study is limited by both available data, as discussed earlier, and simplifications. The model has three main stocks of mobility choices, including ICE vehicles, EVs, and carsharing users. These are simplified as there are a wide range of types of personal ICE vehicles, hybrid, plug-in hybrid, BEVs, hydrogen fuel cell, light electric vehicles, and other types of mobility that could be factored into the overall model. The model simplifies the plug-in hybrids and battery electric vehicles under EVs and omits light electric vehicles, scooters, and other platforms. While this simplification was made to analyze the macro-level trends and account for the growing popularity in BEVs, rapid technological advances in another platform could greatly alter the future growth of the system.

Limitations also exist in the utility calculation and static weights of the various utility components of this system dynamics model. Different factors influence consumers' choices when deciding which type of vehicle to buy or whether to use a shared mobility service. This model, like other models, is not able to fully account for all factors for decisions. The importance and significance of each factor varies within the population and system dynamics models do not account well for individual behavior. While this study attempts to use a variety of factors based on academic research, it is understood that this is incomplete. Variables or policies could also drastically alter the weight of one or more factors, such as the accessibility component of this model. If ICE vehicles were prohibited from entering the city, it is assumed that this would cause more than a 12.5% drop in the utility of these vehicles. Once the policy is adopted but before it goes into effect, there would be a decreasing trend in the attractiveness of this platform until only people who are extreme enthusiasts would consider these vehicles. This is acknowledged in the model with a negative marketing campaign implemented five years before the vehicle access limits go into effect which reduces the willingness to consider. The effect of the negative marketing is dependent on the function used in the model for reducing willingness to consider, a sigmoid function or s-curve. Changes to the equation or use of different functions to estimate this effect could significantly alter the reduction in market share for ICE vehicles and sales. The implementation of the vehicle access limits policy would signal to the market and vehicle manufacturing industry to transition to EVs or other platforms if enacted on a large or broad enough scale. This complex scenario is omitted from the model due to a lack of information or studies about how this should be implemented in the model or how it would work in real life. The assumptions made indicate that the results of the model are a conservative estimate of the effect this type of policy would have in actuality.

This study focused on the implementation and effects of policies at the city or urban level. While a deliberate choice, this limitation does not account for the feedback that results at a provincial, national, or supranational level, especially given the clout a capital city like Amsterdam has with shaping public policy. Amsterdam's aggressive policies pave the way for other cities in the Netherlands and in Europe to follow. This would result in higher awareness about these policies and signal to the market and industries to expedite the shift to EVs.

While limitations exist, the model and similar models provide useful insights into the way these systems work in the real-world and the effects different policies or technologies can have on these systems. Understanding the limitations make the models and studies more useful and provide avenues for refining them over time as new information and technologies are available. Overall, these limitations should be considered but do not render the model impractical.

7.4 Reflection

Reflecting on the research is an important aspect in the learning process and understanding the role the study plays in society, academia, and practice. The reflection process provides an avenue to discover the knowledge gained that may not be completely explicit in the study. Additionally, it allows deficiencies in the research process to be discovered through critical thought. This section provides the reflection of this study.

Through this study, I have developed a new understanding for developing and executing a research project from scratch. In my previous work and studies, research has been a result of assignments or projects. This endeavor required developing the work on my own, meaning that at the outset, I had to think critically about the type of study I wanted to undertake. With mobility as the focus of my previous professional career, I wanted to remain within this domain but also expand into spatial planning and the transition to sustainable mobility. As I seek to continue my career after this master's program, the work of this thesis has confirmed my passion for this field and has given me insights into how my future career can differ from my predominately engineering-focused past.

Performing a research study that combines transport and spatial planning, the transition to emerging technologies, and public policy through system dynamics has given me a new perspective into the challenges and opportunities in making substantial, sustainable progress in urban areas. Prior to this study, I had a slight awareness of systems-thinking and was not aware of system dynamics as a tool for understanding and evaluating complex environments. Adapting and developing a system dynamics model has transformed my way of thinking for not only transport and spatial planning, but also the many other complex systems encountered in life. This way of thinking shows that many problems transcend policy, infrastructure, or design fields and requires many actors across a diverse field of professions and stakeholders to make substantial change to improve the quality of life, adapt and mitigate climate change, and make the world more equitable. The development and implementation of system dynamics models provides an enormous opportunity for understanding how these 'wicked problems' work and test the implications of different solutions. As a result of this study, I feel that I am better equipped to lead, manage, and advise on problems that are encountered across the world, especially within the urban mobility context.

While I consider the overall study and process a success for my personal development, it is important to reflect on other aspects of the study as well. There are several components of this study that went well and several that I would improve, if I were to undertake this study again. The successful aspects include the collaboration between me, my advisors, and APPM; the development of the system dynamics model for studying the challenge; and using Amsterdam as the case study. Areas of improvement for the study include gaining earlier exposure to system dynamics and development of system dynamics models, creating a better collaboration with the City of Amsterdam or other regional actors, delineating more specific components in the model, and improving the integration of the spatial aspects in the model. These items are elaborated in the following paragraphs.

Several elements were key factors contributing to the success of this study. My advising team steered the research towards using system dynamics and maintained a critical view of the process as the research developed. They ensured that I was aware of the necessity of moving from data collection and reviewing previous work to developing the model and pursuing new knowledge with the research. Significant efforts are required to develop a working system dynamics model and my advisors were integral in ensuring I was aware of and focused my efforts on this important process. Working with APPM on this study was an additional positive aspect of the research. APPM provided collaboration with industry experts to guide the practical application and need of the research. This collaboration provided new insights in the challenges experienced with deploying charging infrastructure for both shared mobility and personal vehicles as well as the different strategies and goals that cities in the Netherlands are applying in new developments, policies, and pilot initiatives.

Developing research that was both academic and practical concerning an immediate challenge was a personal goal for the research. The collaboration and enthusiasm between my advisors and APPM allowed the research to achieve this goal.

System dynamics proved to be an exceptional tool for exploring the relationships between shared mobility, personal vehicles, infrastructure, policy, and technological development in this field. Developing the conceptual model and examining similar studies allowed me to gain a better understanding for the interactions and feedback loops between the components of the system. With the study by Struben and Sterman (2008), the market share between the platforms is a result of both willingness to consider and the utility of each platform. This relationship and the mechanisms from which willingness to consider and utility increases or is improved creates an interesting dynamic where a platform with the highest level of utility may not enter the market if people do not know about it or consider it a viable option. It also shows that specific aspects can play oversized roles in the uptake of a certain platform. The model requires assumptions about various uncertainties in the system. Making these assumptions and incorporating them into the model allowed me to think about ways the future development may occur. System dynamics requires uncertainties regarding future developments to be included in its models, such as research and development used in other studies, or to make mathematical or graphical assumptions about how future trends may develop. This required expanding my understanding of how different technologies, such as EV batteries, have developed and may develop in the future. Several of these uncertainties, including battery range development, were estimated using Sigmoid functions in comparison to the market standard for ICE vehicles. The result of these assumptions and functions show their components reaching equality with the ICE vehicles, but not where they may overtake capabilities through further technological innovation.

The assumptions in the development of the utility calculation for the vehicle platforms were another interesting aspect of the model's development. Throughout the research, I had conversations with different industry experts, shared mobility providers, and friends about what makes people opt for a vehicle purchase, what types of policies would cause them to make different decisions regarding vehicle purchases or shared mobility usage, and what are their opinions regarding the state of vehicles in the city. In a discussion with the head of policy for Uber's Benelux region, it was discovered that the lack of a secondhand EV market makes transitioning Uber's fleet to electric extremely difficult and harms the business case for this endeavor. This also led to the realization that although many people would like to purchase an EV, with a small secondhand market, they may not have an option based on their financial means. As a result, a secondhand market component was added to the vehicle utility calculation. Vehicle identity is another important element that came to light during these conversations. Many people who have a vehicle have developed a personal attachment to it as well as with the idea of this being safe personal space for them. This was supported with the research from Coffman, Bernstein, and Wee (2017). The emergence of COVID-19 during this study, however, exacerbated this element as people may be less inclined to use shared mobility or public transport as a result of the risk of infection. There are many factors that go into consumers choices regarding mobility and the development of this study made me more aware of these factors, especially the ones that are of low importance to my own personal decisions.

Using Amsterdam as a case study for the model supported my desire to learn more about the city as well as see how the city's ambitious goals regarding mobility can be implemented and achieved. Amsterdam's various initiatives, including the Clean Air Action Plan and the Autoluw Agenda, are highly ambitious with regard to transitioning the city to emission free mobility and as front runners on city-led initiatives (Amsterdam, 2019 & Amsterdam, 2019). This research allowed me to gain a stronger understanding for how the goals and vision for Amsterdam may be implemented and achieved through policy. The model shows that it will be difficult to remove all ICE vehicles from the city by 2030. Even under extreme scenario tests, there would still be ICE vehicles in the vehicle stock by 2040. This highlights the need for Amsterdam to use its platform as a capital city and leader in mobility to influence higher levels of government to push more drastic initiatives in transitioning away from fossil fuels. Through this learning process, I was also made aware of the governmental structure and spatial planning aspects of Amsterdam and the Netherlands. These learnings benefit me in the context of my future career in this practice area.

If I were to undertake this study again or a similar study in the future, there are several areas in which I would improve. As previously discussed, I believe system dynamics is an important tool in understanding the complexity of making transformative changes. If I could go back to the beginning of this research or perhaps the master program, I would have begun working with system dynamics earlier or taken a course on system dynamics. While I was able to develop a working model though this research, there are still aspects of system dynamics that I would like to learn more about and gain more experience using different functions in the models. The more familiar one is with system dynamics, the more useful it is as a tool and the more opportunities are present to develop better models. The second area of improvement, which was complicated by the COVID-19 epidemic, would be to have more collaboration with stakeholders at the City of Amsterdam and various shared mobility providers. Additional insights could be gained through a workshop with these actors and the model could be refined further with their input. While some actors, like Uber and APPM, were involved, having a larger industry presence in the refinement of the model would benefit the robustness of the study.

During the development of the model, it was determined to focus on the three types of vehicle stocks: ICE vehicles, EVs, and carsharing. This simplification was helpful in ensuring a working model was developed and that the larger objectives could be achieved. This simplification, however, meant that older hybrid vehicles, plug-in hybrid vehicles, and hydrogen fuel cell vehicles were either categorized as EVs or omitted. Small EVs and other mode choices were also omitted. Additionally, ride hailing usage was not specifically addressed in the model due to data limitations. Incorporating these different components into the study could have provided additional insights into how certain technologies could be better suited for the urban context and distinguish opportunities for their future development.

The spatial component of the research was addressed in the Literature Review and Baseline Analysis. It was not, however, integrated into the system dynamics model. As each postal code was shown to have different attributes, this higher level of granularity could provide further insights for policy makers and make the model more robust. This was omitted due to the lack of complete data at this level and the additional complexity of incorporating it in system dynamics. The incorporation of this level of data poses the potential to develop an implementation strategy for the mobility system of Amsterdam.

The research and knowledge gained from this study highlight the potential of shared mobility on personal transportation in urban areas. Other models focus on personal vehicles, carsharing, or the emergence of autonomous vehicles. They do not, however, focus on a specific urban context with the current trends in EVs and shared mobility. This research contributes to the body of knowledge by highlighting the potential of shared mobility, specifically carsharing. The model shows that with the estimates and assumptions of carsharing, they have a strong potential to redefine how significant public space currently used for parking can be transformed for other uses. While there are still challenges in this transformation, its potential cannot be ignored as cities invest in charging infrastructure, subsidies, and create policies to incentivize EVs and carsharing.

Overall, this reflection shows the personal value gained through this study, the value of system dynamics models, opportunities with shared mobility, and contribution to the body of knowledge in mobility planning. As cities, governments, and the general population look to transform how their mobility systems function, this study can be used as a benchmark for the opportunities with the emerging technologies and policy implications. While all research has limitations, conscious decisions were made regarding the simplifications and assumptions made in this study. In the end, this study can be used as a starting point for developing this body of knowledge further.

8 Conclusion

The following chapter aims to conclude the major findings of the research. First, recommendations for future research are discussed. Next, the major conclusions of the paper are presented.

8.1 Recommendations for Future Research

From this study, there are several recommendations for future research to deepen the knowledge within the topic of transitioning to sustainable mobility. It is known that different factors play into consumers' choices regarding mobility type and the decision of whether to purchase, lease, or share mobility; however, there is limited research on how these decisions are made with today's options aggregated to urban populations. System dynamics is a powerful tool for modelling transportation systems and in many studies focuses on national transportation schemes. Developing more complete models of the urban transportation system can provide cities and urban regions greater insights into how their goals, policies, and agendas could be modified to achieve sustainability impacts. While this study was aimed at policies at the local city level, future research could investigate the feedback, interaction, and influence city-led policies have on higher levels of government and other cities and urban regions. Using the knowledge and findings from this study, the model can be adapted and strategies developed for other cities and regions with regard to expanding shared mobility, planning charging infrastructure, and policy development aimed at sustainable transport. In this section, these ideas for future research are elaborated and discussed.

Consumer choice with regard to mobility plays an important role in developing new technologies and services. As a result, there are numerous studies related to demographics and motivations for transitioning to EVs, using public transport, or the future uptake of autonomous vehicles. These studies, however, lack the immediate motivations and decisions for purchasing a vehicle, shedding a vehicle, and using shared mobility services. A study could be established where, when people register a vehicle purchase, they take a survey asking which factors contributed to the vehicle purchase over using other modes. Other studies could replicate the Zuidas mobility experience in Amsterdam where participants were required to give up their vehicles and use other modes for a test period (Mobiliteitsfabriek, 2018). The results from these studies could greatly benefit modeling and policy studies aiming to motivate people to use other modes and forgo vehicle purchases.

The development of comprehensive urban-focused system dynamics models could benefit cities as well as academia and consulting or advisory firms in better understanding the complex transportation and land-use system. While system dynamics studies exist at this level, they are limited in both scope and application. Web-based models, similar to Keith et al.'s (2017) Flight Management Simulator of the US Vehicle Market, could become useful tools in understanding cities' current transportation systems and planning for interventions when focused on more granular levels. The development of the model, working sessions on determining inputs and policy packages, and results of the model could help optimize the limited resources of cities for the greatest impact. This type of model could also guide cities on data collection and management needed to continually improve the model. As this model is implemented, empirical data resulting from policies can feed back into the model continually, making it more robust.

While this study is aimed at policies at the local city level, additional influences on the transportation system and market are made through the interactions and feedback loops within and between metropolitan regions, provinces, countries, and supranational governments. When a capital or major city takes the lead through implementing an ambitious sustainable transport policy, it may influence other cities or levels of government to implement similar measures. Studying this magnification effect and sharing the gained knowledge can expedite the transition as more players signal the demand for change in the market. Researching the effects of bottom-up policy making can help policymakers and academia understand the impact of progressive goals and policies.

The development and results of this study reveal many important factors and implications of incentivizing shared mobility that can be refined and used in future research or the development of strategies for cities. The development of the model and policy packages shows the importance of vehicle technology, accessibility, parking, and charging infrastructure on incentivizing people to abandon traditional ICE vehicles and switch to more sustainable modes. As cities develop and update plans for charging, parking, and shared mobility, this study can be used as a basis for justifying aggressive policies. This study, along with other research, shows the importance of reducing parking to nudge people into using other modes. It also shows the development of charging infrastructure as instrumental in reducing range anxiety and making EVs more attractive. While many improvements are needed in vehicle technology for EVs to compete equally with ICE vehicles, the current shortcomings can be dampened through effective policy.

Future research is necessary to refine and deepen the knowledge gained through this study. A better understanding for how people perceive the benefits and downsides of various transport modes would greatly assist in modeling and developing policies for sustainable transportation. More comprehensive and robust system dynamics models focusing on the urban region could aid policymakers in determining the effectiveness of their agendas and efforts. Additionally, researching the effects of cities acting as front runners and early adopters on other regions and levels of government could empower elected officials and policymakers to be more aggressive and ambitious in their agendas. This can lead to accelerated transitions to sustainable initiatives as a larger presence of these initiatives signal the market the demand for change. From this study, an understanding of the relations between different factors for shared and electric mobility and policy influence the transition to more sustainable transport. Overall, there are opportunities to expand many facets of this research to provide a more robust understanding for what is needed to transition away from personal, greenhouse gas emitting vehicles.

8.2 Conclusion

Several conclusions can be made from both the results and methods of this study. First, the results of the model indicate significant opportunities for policy creation for cities to affect the transition to clean shared mobility. Second, system dynamics is a powerful tool that can be used to better understand the complexities surrounding sustainable transitions and has significant potential at the urban or city level. Third, elected officials and policymakers have the ability to make significant impacts on sustainable transitions at the city level and these impacts can be magnified when combined with policies at higher levels of government. In this section, the final conclusions from the study are presented and discussed.

The results of the model indicate substantial opportunities for cities to improve public space, air quality, and livability by incentivizing shared and electric mobility. Shared mobility presents the opportunity to reduce vehicle ownership meaning less space is needed for parking and can be repurposed for other uses. While the model showed a significant number of ICE vehicles still in use in 2040, this number is reduced by half across all four scenarios resulting substantial improvements in air quality. Through this reduction, people are either switching to carsharing services or purchasing EVs. As a result of the uptake in carsharing services, the total vehicle stock in the city is reduced by 7% for the Market Place scenario and 22% for the State of Green scenario while accounting for population growth. This reduction in vehicles allows up to 1.7 million square meters of public street space to be repurposed. Through facilitating the transition to shared EVs, citizens who would not normally own a vehicle are able to access these vehicles for less frequent trips which reduces the financial burdens of citizens who decide to shed their vehicles. These gains for cities should motivate policymakers to prioritize shared mobility policies and reimagine their urban space.

System dynamics presents a powerful tool for understanding the complex nature of transport systems and testing various policy scenarios for maximizing the return on investment or achieving desired results. Through the development of the system dynamics model, a strong understanding of the different components, their relationships with each other, feedbacks, and the potential of different interventions is formulated. Additional insights into types and sources of available data, challenges with changing the system, and interactions with other systems or sectors are developed. The development of system dynamics models provides valuable insights into the effects of different policies, technologies, or interventions. These insights allow policy and decision-makers to focus their resources in areas with the highest reward. System dynamics shows itself to be a powerful tool for sustainable transformations.

Per the research and results of the model, policies at the city level can have significant impacts on sustainable transitions. With the use of subsidies, parking regulations, and vehicle access restrictions, changes can be observed in the shedding of vehicles for shared mobility or purchase of EVs, especially when barriers exist due to inadequacies in certain technologies. The research also shows that aggressive plans for charging infrastructure reduce the challenges of vehicle range anxiety. When cities, like Amsterdam, commit to a sustainable future in mobility, other governments reconsider their policies as well. While this aspect is not included in the model, these policies are expected to have a snowball effect that push other cities and government levels in a similar direction, especially when positive results are demonstrated.

Through this study, insights are developed for the challenges and opportunities for transitioning to clean shared mobility. This transition is highly correlated with personal vehicle ownership and a system dynamics model is used to understand the relationships in the system. Using Amsterdam as a case study, policy packages are derived based on future scenarios for the city. The results show significant opportunities with shared mobility over the next twenty years to impact mobility and urban space. The research shows that deliberate policies with regard to charging infrastructure, parking, subsidies, and marketing have the opportunity to influence citizens toward shared mobility. Overall, investments and energy into promoting clean shared mobility present opportunities for cities to improve the quality of life for their citizens by freeing up public space, improving air quality, and making vehicles more accessible.

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Appendix A. Utility Estimates and Calculations

The Utility for the three platforms, ICE vehicles, EVs, and carsharing are estimated across four main categories: financial considerations, accessibility considerations, ownership sensitivity, and platform attributes. As discussed in the Methods chapter, the utility estimates are normalized to 1 with as the highest achievable score. An overview of the baseline estimates is provided in Table 1. The method for calculating these estimates are discussed in the following section.

Table 8. Utility Baseline Estimates

			ICE	EV	Carsharing
Financial Considerations	Capital Costs, $\mu 1$		0.239	0.010	0.986
	Monthly Payment	0.8	0.701	0.987	
	Insurance	0.2	1	1	
	Membership Fee	1	0	0	0.0143
	Usage Costs, $\mu 2$		0.756	0.820	0.117
	Fuel	0.84	0.150	0.144	0
	Maintenance	0.16	0.733	0.367	0
	Usage Fee (hourly+distance)				0.883
	Parking Costs, $\mu 3$		0.5	0.5	1
	Monthly Permit		0.5	0.5	0
	Environmental Considerations, $\mu 4$		0.106	1	1
	Carbon Tax		0.895	0	0
Accessibility	Accessibility, $\mu 5$		0.768	0.674	0.8
	Available Parking	0.5	0.536	0.548	
	Fueling / Charging Infra	0.5	1	0.8	
	Carsharing Availability				0.8
Ownership	Ownership Sensitivity, $\mu 6$		1	1	0
	Ownership / Identity				
Platform Attributes	Platform Scope, $\mu 7$		1	0.175	0.2
	Options on Market	0.75	1	0.2	
	Secondhand Market	0.25	1	0.1	
	Available Options				0.2
	Range, $\mu 8$		1	0.5	0.5
	Vehicle Range		1	0.5	0.5

A.1 Financial Considerations

The financial considerations proposed include capital costs, usage costs, parking costs, and environmental costs. These costs are proposed to take into account the total cost of ownership instead of relying solely on the purchase price. Additionally, the costs associated with purchasing a vehicle and using shared mobility are significantly different as the main costs with owning a vehicle are capital costs and the main costs with using shared mobility are usage costs.

Using a 2020 Volkswagen Golf, a 2020 Volkswagen eGolf, and a MyWheels shared vehicle, the monthly costs are estimated based on the kilometers driven. Figure 32 shows that using a shared vehicle service is significantly more attractive financially than purchasing or leasing a new vehicle. A shared vehicle is the most cost-effective option until 2600 km, at which a leased EV becomes less expensive and 3000 km, at which a purchased EV becomes less expensive. Additionally, while a purchased ICE vehicle is more cost effective than an EV at lower usage, the EV becomes less expensive when more than 1600 km are driven each month.

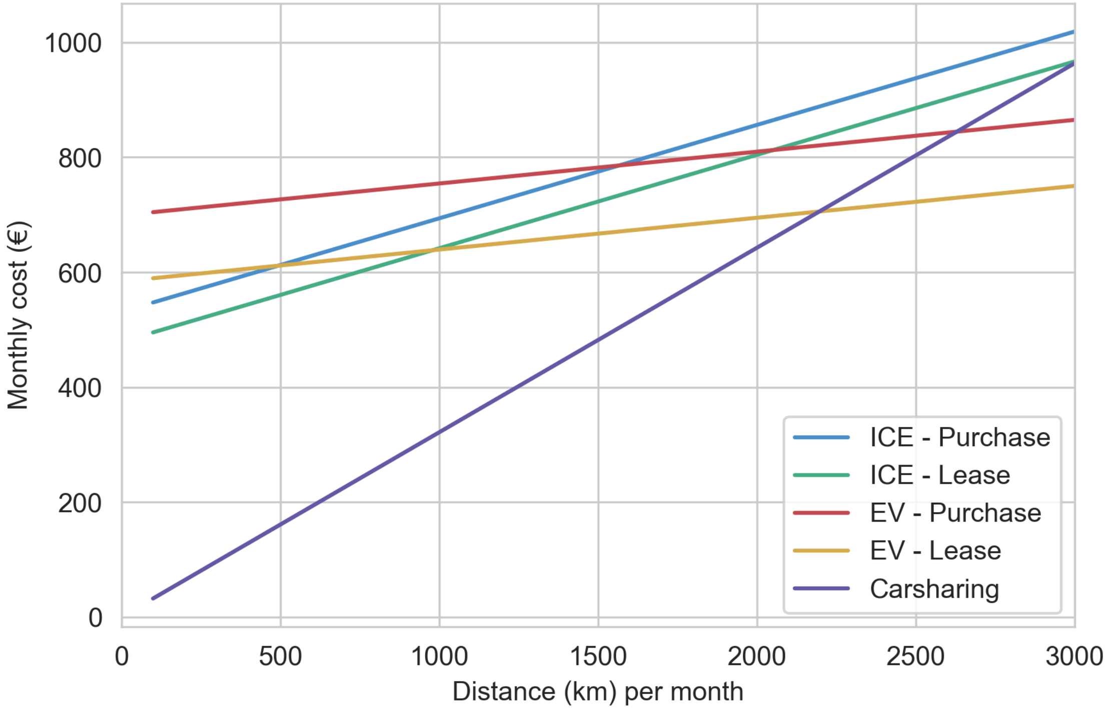

Figure 32. Vehicle monthly cost comparison

As a result of the comparative analysis, the capital costs and usage costs are weighted equally in the utility calculation to reflect the total cost of ownership and make the financial comparison between owned and shared vehicles equal.

The capital costs for purchasing a vehicle include the purchase price, insurance payments, and taxes. While a consumer has the choice to pay for the vehicle outright or make monthly payments, an annuity based on the MSRP is calculated for this estimate. The capital cost for a shared vehicle is the membership fee, if applicable. Each shared vehicle service offers different packages and membership fees. Additionally, some of the membership fees come with ride credits i.e. Fetch car sharing.

Using the monthly annuitized cost for the purchase of the Volkswagen Golf and eGolf, the costs are divided by €700 to normalize their costs. This provides the 'score' for monthly payment. This same calculation is applied for a membership fee for carsharing with an estimate of €10 to account for the varying membership fees and deposits from the various service providers. The EV purchase subsidy policy is applied through the calculation for EV monthly payment, reducing this value and increasing the categories' score.

It is assumed that as EVs gain a larger market share and achieve higher technical innovation, their prices will reduce over time. While using market share and research and development investments as a driver for this category would be preferred, this study focuses on the city level and is not taking into account the overall industry. Therefore, a Sigmoid function of time is used to estimate the EV price reduction as a comparison to ICE vehicles. Equation 6 provides this function with time in years.

$$EV\ price(t) = \frac{\frac{7 * e^{\frac{t}{4}}}{3}}{1 + \frac{7 * e^{\frac{t}{4}}}{3}} \qquad (6)$$

As insurance is only applicable to personal vehicles and not carsharing, this value is either a 1 or 0. Insurance is set at 20% of the monthly capital cost component to highlight this not being a factor for carsharing and to account for secondhand vehicle purchases. The sum of the products from the categories and weights are then subtracted by 1 so that the lowest cost option receives the highest score.

The usage costs are comprised of fuel and maintenance for personal vehicles and a usage fee for carsharing. A total monthly budget of €400 is used for this component and is estimated using a monthly driving distance of 1,200 km (100 km lower than the national average as Amsterdammers are assumed to drive slightly less distances) and calculating the costs for using MyWheels carsharing. Using the hourly and distance rates, a monthly usage cost for carsharing is estimated at €353.50. The carsharing usage subsidy policy is applied to the carsharing usage costs to reduce the monthly cost, increasing its category score. Usage costs for personal vehicles is estimated using 1200 km / month with fuel and maintenance at rates of €0.053 / km for fuel and €1.00 / 100 km for ICE vehicles and €0.051 / km for energy and €0.50 / 100 km for EVs. The sum of the products from the categories and weights are then subtracted by 1 so that the lowest cost option receives the highest score.

Parking costs are derived from monthly permit costs with personal vehicles having a score of 0.5 and carsharing a score of 0. The 0.5 for personal vehicles was chosen so that the policy for parking permits can increase this score to 1, reducing the categories' value to zero.

Environmental costs are derived from the Dutch vehicle tax based on carbon emissions. For the Volkswagen Golf, this is assessed at €161 / 3 months. The estimate uses a category cost of €60 / month to estimate the score. For EVs and carsharing, there are no vehicle registration taxes.

A.2 Accessibility Considerations

Accessibility is estimated using available parking, fueling / charging infrastructure estimates, and carsharing availability. Parking and infrastructure are applied to personal vehicles using the stocks of parking available to that platform. ICE vehicles can only parking in ‘open parking’, therefore they compete with the other platforms for each space. EVs can park in ‘open parking’ as well as ‘EV parking’ and compete with ICE vehicles for open parking but only carsharing EVs for EV parking. The vehicle utility parking is calculated in the system dynamics model using a linear function where one car per two parking spaces equals a utility of one and three cars per two parking spaces equal a utility of zero. This function is shown in equation 7.

$$parking\ accessibility_j = -\left(\frac{V_j + V_{competing}}{Parking}\right) + \frac{3}{2} \tag{7}$$

For charging infrastructure, the total stock of EVs (personal and carsharing) are divided by the number of Level 2 chargers providing the accessibility of charging infrastructure. A sigmoid function is used to estimate the resulting utility with the ratio of EVs to charging points as shown in the equation 8. For ICE vehicles, as these are the norm, have a static weight of 1. Although not incorporated in the model, it can be assumed that once a high enough distribution of Level 2 chargers is reached, EVs would have higher utility for charging than ICE vehicles as there would be no fueling time or detours for normal travel.

$$EV\ charging\ accessibility = \frac{e^{\left(\frac{-EV\ ratio}{2}+8\right)}}{1 + e^{\left(\frac{-EV\ ratio}{2}+8\right)}} \tag{8}$$

Carsharing accessibility is calculated with the ratio of user to number of vehicles available where one user to one vehicle is a utility of one, 10 users to one vehicle is a utility of 0.9, and 50 users to one vehicle is a utility of zero.

For personal vehicles, accessibility is equally weighted for the two categories and carsharing has the single component. For ICE vehicles, when the vehicle access limit policy is implemented, the full accessibility component for this platform is reduced to zero as these vehicles will not be allowed to enter the city or limited to certain areas.

A.3 Ownership Sensitivity

As discussed in the Methods chapter, ownership sensitivity is attributed to the connection and hygiene associated with a personal vehicle. As a result, both personal vehicles receive a one for this category and carsharing a zero.

A.4 Platform Attributes

Platform attributes are a combination of the platform scope (available options on the market, secondhand market, or available options for carsharing) and vehicle range. As ICE vehicles are the norm for this category, all components receive a one. For EVs, an estimate of the number of EVs produced by the major manufacturers and an analysis of the vehicles with the highest market share in the Netherlands is used. It is assumed that there are roughly 20% of the options available today on the market. A Sigmoid function is used to estimate the growth in scope through the simulation, eventually reaching 0.99, or being comparable with ICE vehicles in 2035. Equation 9 provides this estimate as a function of time (years).

$$available\ options\ on\ the\ market\ (t) = \frac{\frac{e^{\frac{t}{2}}}{10}}{1+\frac{e^{\frac{t}{2}}}{10}} \tag{9}$$

The secondhand market for EVs is quite small as they are relatively new to the overall marketplace. This is calculated as a ratio of two times the secondhand EV stock divided by total vehicle stock. This estimate shows the secondhand market reaching a utility of one after 2035 for all four scenarios.

For the carsharing platform scope, it is assumed that carsharing EV options will be available by 2030 for any vehicle type. A Sigmoid function is used to estimate this parameter and is shown in equation 10 as a function of time (years).

$$carsharing\ platform\ scope\ (t) = \frac{\frac{e^{\frac{t}{2}}}{3}}{1+\frac{e^{\frac{t}{2}}}{3}} \tag{10}$$

Platform driving range is estimated in comparison to ICE vehicles, which have a score of one. The vehicles with the highest market share in the Netherlands are compared with comparable EVs and an estimate of 0.5 is estimated for EV range. As EVs are experiencing significant research and development with their batteries and new models are continually exceeding previous generations of EVs, a Sigmoid function is used to estimate the progress as a function of time (years) for the simulation. Equation 11 shows this function with these reaching 0.95 in 2035 compared with ICE vehicles. While this variable contains a high level of uncertainty regarding this technological progress, it is assumed that the estimate provided is conservative.

$$EV\ range\ (t) = \frac{e^{\frac{x}{5}}}{1+e^{\frac{x}{5}}} \tag{11}$$

Appendix B. Utility Factor Sensitivity

Utility weights for the model are estimated from existing literature on consumer choice with regards to EVs and carsharing as well as discussions throughout the thesis. Sensitivity analysis is run in Vensim to determine the sensitivity to the total vehicle stocks as a result of these parameters and weights.

B.1 Financial Considerations

Sensitivity of the total vehicle stock through the simulation for capital cost (β1) is shown in Figure 33 using a random uniform distribution with a minimum of 0.1 and a maximum of 0.5. The figure illustrates this variable has a high level of sensitivity through the model with a final result of +/- 20,800 vehicles.

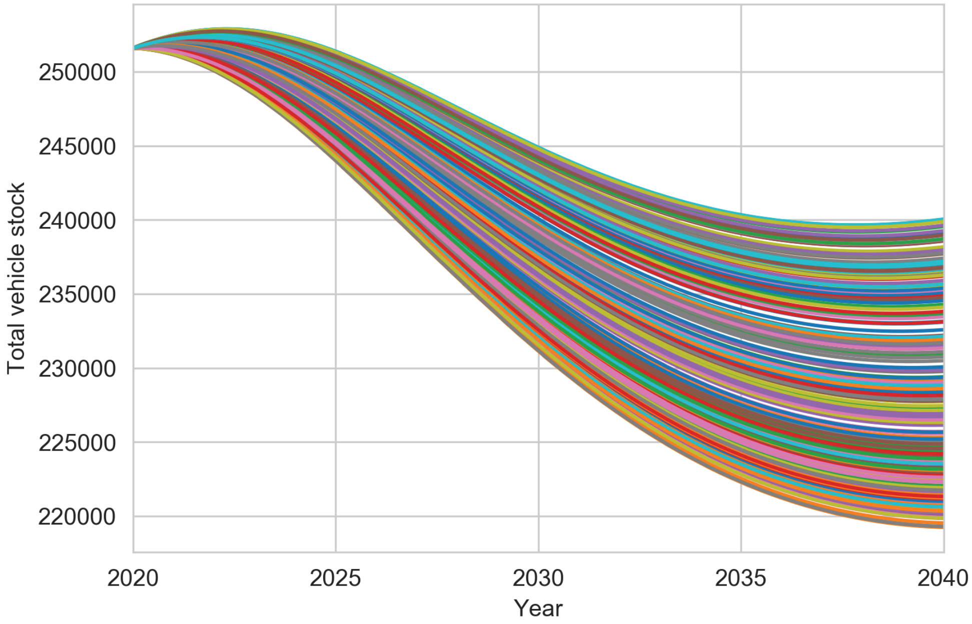

Figure 33. Total vehicle stock sensitivity to utility weight for capital cost

Sensitivity of the total vehicle stock through the simulation for usage cost (β2) is shown in Figure 34 using a random uniform distribution with a minimum of 0.1 and a maximum of 0.5. The figure illustrates this variable has a high level of sensitivity through the model with a final result of +/- 16,000 vehicles.

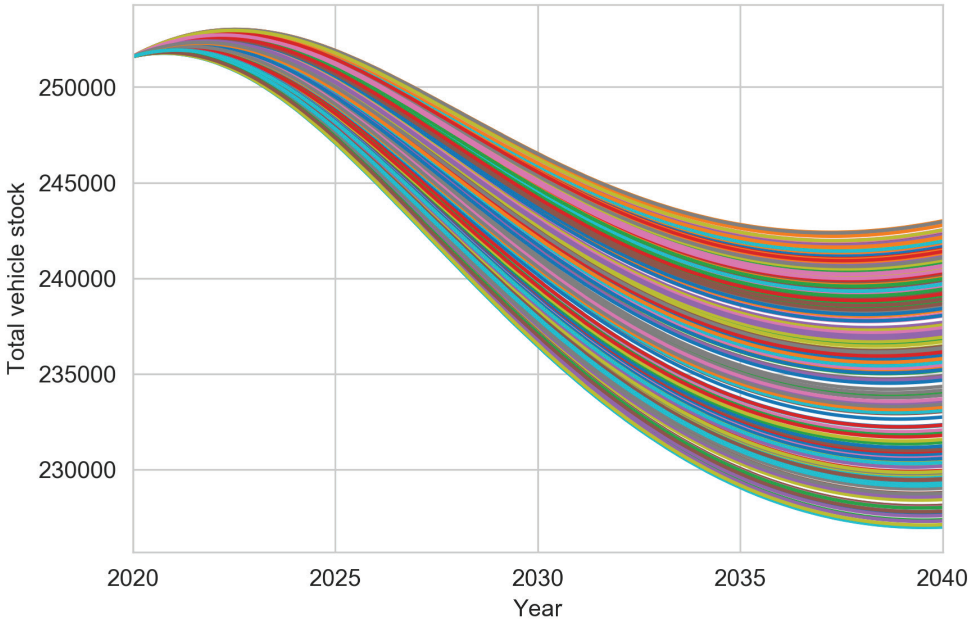

Figure 34. Total vehicle stock sensitivity to utility weight for usage cost

Sensitivity of the total vehicle stock through the simulation for parking cost (β3) is shown in Figure 35 using a random uniform distribution with a minimum of 0.01 and a maximum of 0.1. The figure illustrates this variable has a low sensitivity through the model with a final result of +/- 520 vehicles.

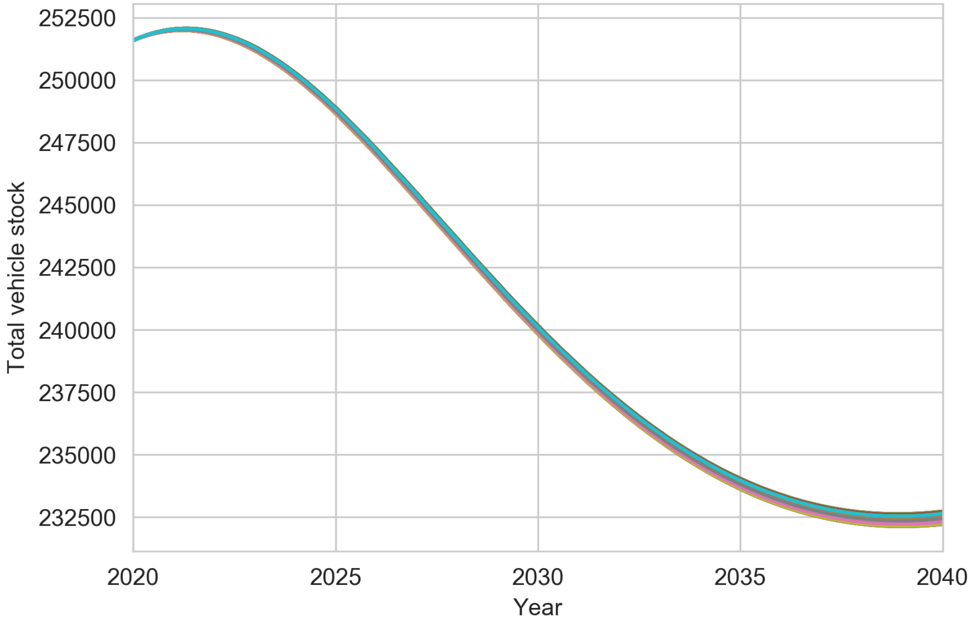

Figure 35. Total vehicle stock sensitivity to utility weight for parking cost

Sensitivity of the total vehicle stock through the simulation for environmental cost (β4) is shown in Figure 36 using a random uniform distribution with a minimum of 0.01 and a maximum of 0.1. The figure illustrates this variable has medium sensitivity through the model with a final result of +/- 3,190 vehicles.

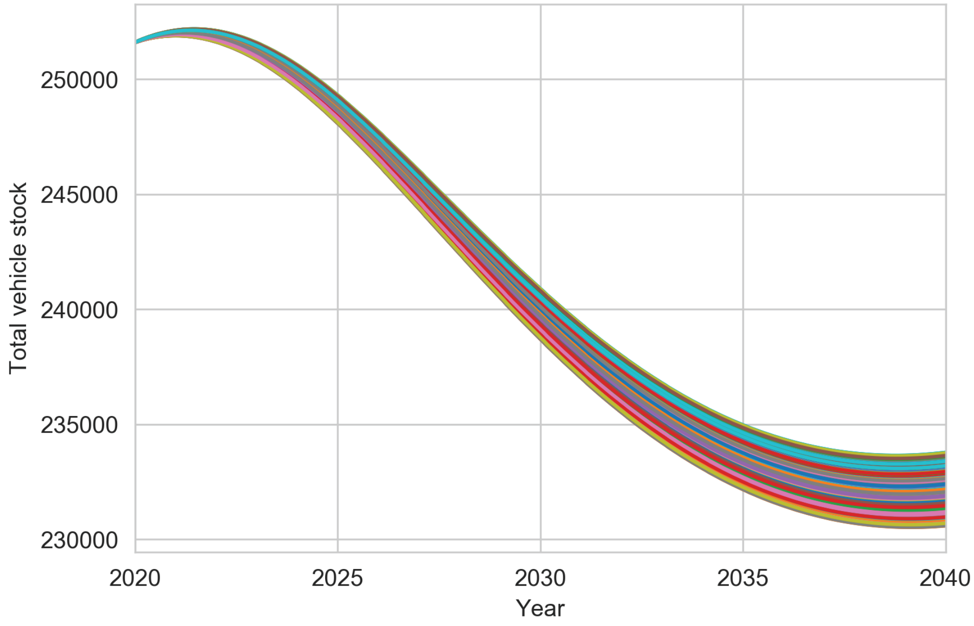

Figure 36. Total vehicle stock sensitivity to utility weight for environmental cost

B.2 Accessibility Considerations

Sensitivity of the total vehicle stock through the simulation for accessibility considerations (β5) is shown in Figure 37 using a random uniform distribution with a minimum of 0.05 and a maximum of 0.3. The figure illustrates this variable has medium sensitivity through the model with a final result of +/- 3,200 vehicles.

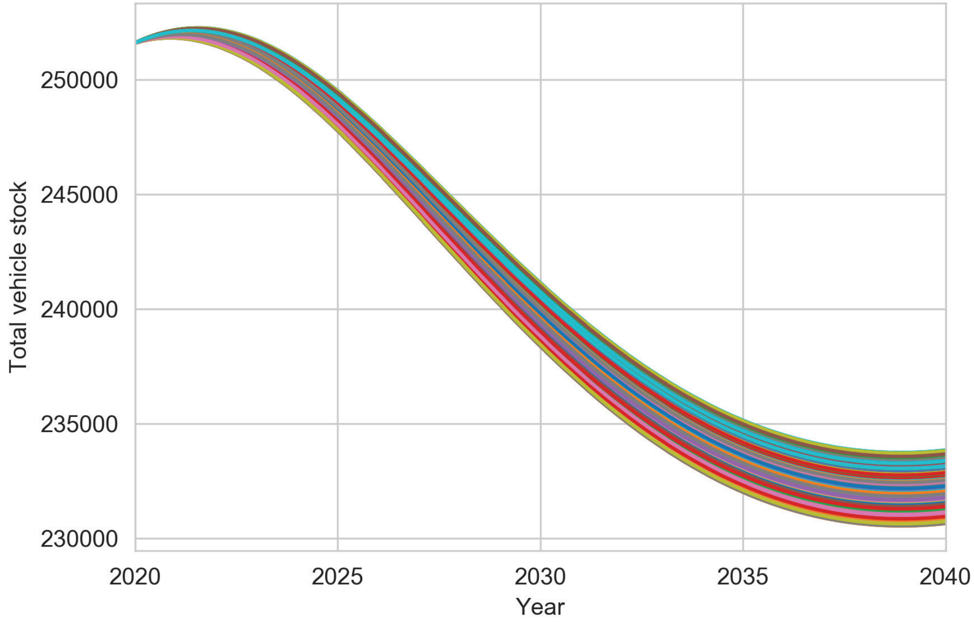

Figure 37. Total vehicle stock sensitivity to utility weight for accessibility

B.3 Ownership Sensitivity

Sensitivity of the total vehicle stock through the simulation for ownership sensitivity (β6) is shown in Figure 38 using a random uniform distribution with a minimum of 0.05 and a maximum of 0.3. The figure illustrates this variable has high sensitivity through the model with a final result of +/- 15,400 vehicles.

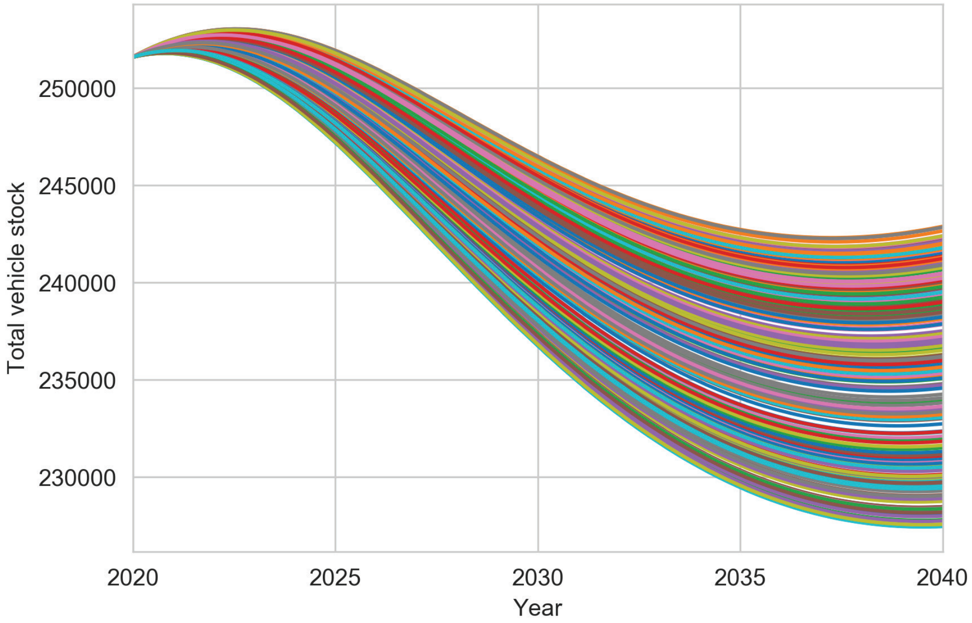

Figure 38. Total vehicle stock sensitivity to utility weight for ownership sensitivity

B.4 Platform Attributes

Sensitivity of the total vehicle stock through the simulation for platform scope attributes (β7) is shown in Figure 39 using a random uniform distribution with a minimum of 0.05 and a maximum of 0.3. The figure illustrates this variable has medium sensitivity through the model with a final result of +/- 2,980 vehicles.

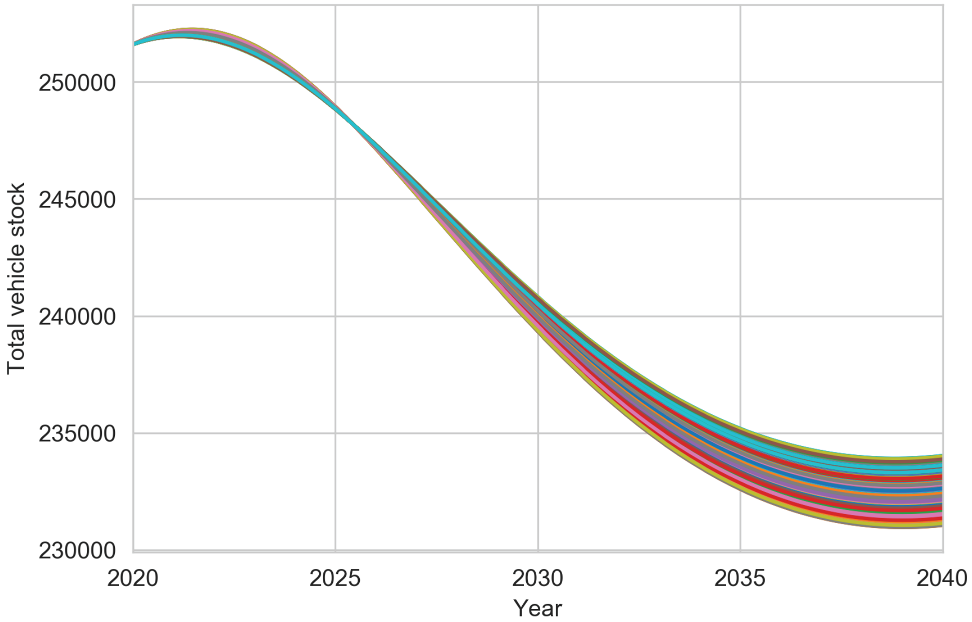

Figure 39. Total vehicle stock sensitivity to utility weight for platform scope

Sensitivity of the total vehicle stock through the simulation for platform range (β8) is shown in Figure 40 using a random uniform distribution with a minimum of 0.05 and a maximum of 0.3 The figure illustrates this variable has low sensitivity through the model with a final result of +/- 405 vehicles.

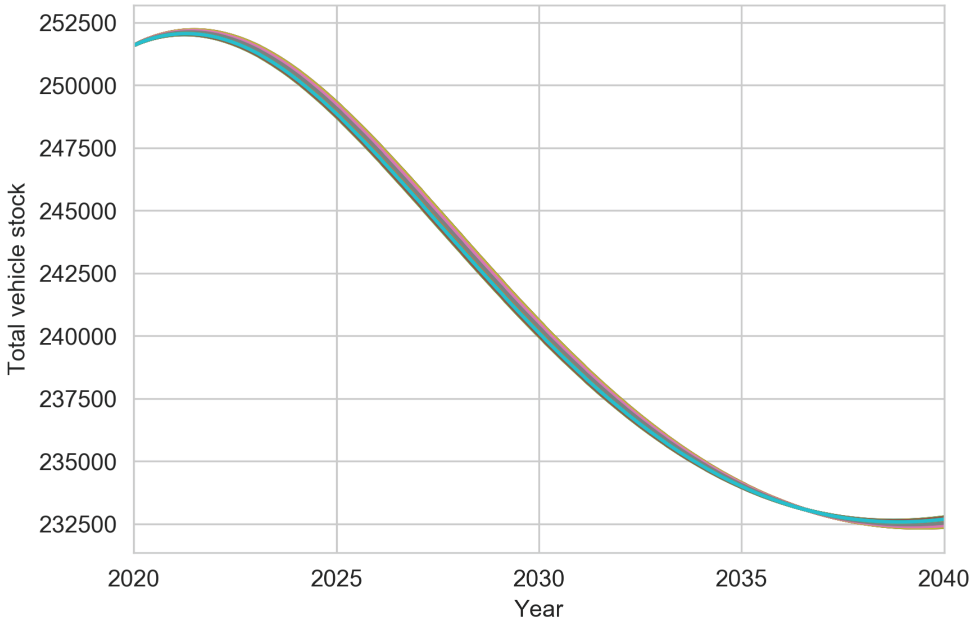

Figure 40. Total vehicle stock sensitivity to utility weight for EV range

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