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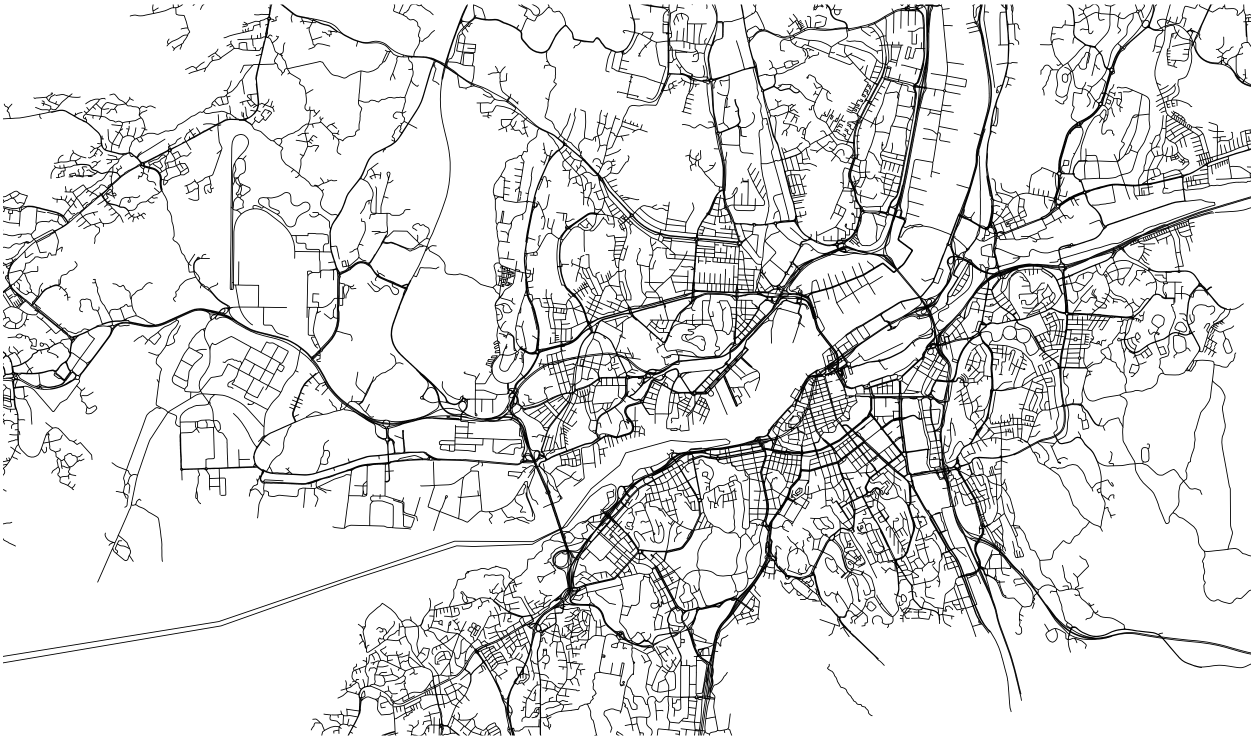

The Potential of Vehicle Automation to Enhance Sustainable Urban Development

An assessment of a technological disruption and its environmental impacts in Gothenburg

Master's thesis in Industrial Ecology

MAJA SVENDING

Department of Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

REPORT NO. XXXXXX

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In collaboration with Norconsult AB

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Cover: Gothenburg transportation network, illustration by Maja Svending.

[Tryckeriets namn]
Gothenburg, Sweden 2017

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Abstract

Autonomous vehicles are currently being developed and tested. They are no longer science fiction, but are in fact already rolling on the streets of Gothenburg. However, little is known about the different impacts of automated transportation on the city structure. This master's thesis explores how the adoption of a transportation system based on autonomous, on-demand vehicles has the potential to stimulate sustainable urban development. An in-depth review is done of the possible benefits and drawbacks of vehicle automation from different perspectives. The findings are summarized in a framework of features (see Gothenburg scenario framework p. 83) that should be included in an autonomous transportation system to ensure the most beneficial outcome and finally a list of recommendations to policy makers and planners (see Recommendation p. 89).

Key words: autonomous vehicles, autonomous drive, mobility, scenario analysis, self-driving car, sustainability transition, sustainable development, technological disruption, urban planning

Preface

This project was carried out as a Master's Thesis at the Department of Space, Earth and Environment, within the Industrial Ecology Programme at Chalmers University of Technology.

Acknowledgement

I would like to express my gratitude to the following people, without whom this thesis would not have been possible; Anna Kaczorowska - for her supervision, enthusiastic guidance and invaluable advice throughout the project. Marcus Rydbo - for initiating the project in the first place, and Carolin Folkesson for her valuable feedback throughout the process. Many thanks to Team Plan at Norconsult in Gothenburg for enduring my inquisitiveness and providing me with new perspectives. Finally, many thanks to Anna Svending for proof reading and keeping me on the right track.

Maja Svending

Gothenburg, September 2017

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AV	Autonomous vehicle (level 5, fully automated)
EV	Electric vehicle
GWP	Global warming potential
ITRL	Integrated Transport Research Lab (at KTH)
ITS	Intelligent transportation system
MaaS	Mobility as a Service
M2M	Machine to machine communication
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
SAV	Shared autonomous vehicle
TaaS	Transportation as a service
TK	Trafikkontoret (Gothenburg Traffic Planning Authority)
UCC	Urban consolidation centre
UNFCCC	UN Framework Convention on Climate Change

Contents

1 Introduction

In 2017, the Swedish government announced a goal to reduce CO_2 emissions from traffic with 70% by 2030 in comparison to the emission levels in 2010 (Dagens Nyheter, 2017). This is an ambitious target considering that the current trends indicate a steadily increasing number of vehicles in use (Statistiska Centralbyrån, 2016). The national target is also to be entirely fossil free and have net zero emissions no later than 2050. On a more regional level, the city of Gothenburg has its own environmental goals for, among other factors, air pollution, noise levels and a good built environment. Domestic transportation accounts for a third of Sweden's total greenhouse gas emissions (Naturvårdsverket, 2016a). This calls for drastic changes in the transportation sector. If the targets are to be met, a paradigm shift is necessary.

In recent years, different concepts for driverless mobility systems have been developed by researchers around the world and major car manufacturers are investing in and trying out the new technologies, e.g. Tesla's driver assistance system or Volvo's Drive Me project. Most of the technology required to develop a functioning system for autonomous transportation already exist, but cooperation between stakeholders is needed to commence a large-scale diffusion. The transition is complex as a wide range of technologies and institutions are involved in the fundamental part of a functioning, modern society that transportation constitutes, creating a lock-in in the current socio-technical regime. Despite this, a shift to driverless vehicles can happen fast, but some institutions may take longer to adopt to the new situation. One such aspect is the incorporation of autonomous transport in the way we build our cities. Urban planning is usually a medium to long term strategy on how to develop a city. Automation of the transportation system is closely entwined with the process of urban planning and city design, and include both challenges as well as opportunities. The impending effects on the urban landscape need to be considered from a triple bottom line approach; investigating social, economic and environmental consequences.

The technology is here, but there is a lack of knowledge about how autonomous vehicles can function in the city to create the best possible outcome, with positive environmental, social and economic impacts as a result. There is little understanding of how an autonomous transportation system can be integrated in the existing infrastructure and coexist or replace the present system for urban and regional mobility. In current research, it is concluded that the integration of autonomous mobility in the city structure gives many opportunities in terms of efficient area use, which makes a denser, greener and more inclusive city possible. Applying this theory on a local context, i.e. the city of Gothenburg, brings us down to some openings for additional research.

The purpose of this thesis is to assess and visualise the potential positive and negative effects of vehicle automation on the urban environment. The geographic boundary is the city of Gothenburg and the temporal horizon to be considered for future scenarios is around 2050.

Current research is mostly sponsored by either automobile and technology companies or national R&D funds. There is a general lack of a holistic perspective that yet reflects a local context. There is a lack of knowledge about what system conditions are necessary to gain the most environmental benefits out of a mobility revolution. This gap is the focus point of this report. Due to the rapid development of research within the field of autonomous transportation, the results of this report disclaim any aspects that were added to the debate after June 2017.

2 Aim

The purpose of this master's thesis is to explore how the City of Gothenburg may be affected by the adoption of autonomous vehicles and to pinpoint the challenges in facilitating a transition to an autonomous mobility system that enhances the city's sustainability. The aim is to develop a future scenario incorporating autonomous vehicles based on current research and test the scenario according to chosen criteria for sustainability. Different typologies for Gothenburg's city structure will be used as test beds to assess the local impacts and the regional scale impacts will be studied from a network perspective. The purpose is to contribute to increased understanding of how a technological paradigm shift in the transportation sector may affect Gothenburg and how it can contribute to shaping a more sustainable city, including the possibility of using efficient and smart transportation to redistribute space and create a denser, greener and more walkable city.

The results can be used by policy makers, the City Planning Authority and all stakeholders in urban planning and transportation to keep in mind the potential benefits and threats of autonomous vehicles when designing the urban landscape.

2.1 Research questions

The main question that this report attempts to answer is: What is the potential of vehicle automation to enhance sustainable urban development?

To address the problem, these focus questions must be addressed:

- What should a future system of autonomous transportation look like?
- And what would the environmental consequences of a transition to such a system be in Gothenburg?

To properly investigate, some sub-questions that should be considered are:

- What are the relevant environmental targets and current trends in Gothenburg?
- What are the possible benefits and threats inherent to the technology of autonomous vehicles?
- What are the effects on fleet size and vehicle kilometre travelled, of having a smart, free-flowing, shared, on-demand fleet instead of a conventional transportation system?
- How much space can be freed in the city, how is it distributed and what could alternative uses be?

3 Method

The method used in response to the research question consists of four main parts; background study, review of current research, analysis and results and discussion. First a background study (chapter 4) considering basis for sustainability, mobility concepts in urban planning and an introduction to autonomous vehicles. Next comes an in-depth review of relevant research projects (chapter 5) depicting different future scenarios. The scenarios are all based on the assumption that vehicles will no longer require human intervention to get from A to B, but they differ in other assumptions and have set different conditions for future development. The scenarios are analysed and compared in a PUGH matrix to find potential common elements that can be linked to a successful outcome. The assessment is done according to five impact criteria; economic, environmental, social, spatial and operational.

The PUGH matrix summarizes the different scenarios and can be used to determine which critical assumptions are associated with the most beneficial impacts. A SWOT analysis is then made to develop an overview of the inherent effects of a new mobility system. The analysis part of this thesis can be found in chapter 6. Step three of the method, the analysis, is concentrated on applying what can be learnt from the PUGH matrix onto the local context of Gothenburg and thus pinpointing the features that a beneficial scenario should include.

The last part of the method is to assess the environmental and system wide impacts of implementing the scenario and evaluating its positive or negative effects on sustainable development in relation to existing targets and trends. This part is found in chapter 7 and 8. Here the scenario is tested against predefined criteria for sustainable development within certain impact categories. To understand the development and consequences of autonomous vehicles and to define a future scenario, the original framework conditions must be known. Therefore, Multi-Layer Perspective theory (MLP) is used in chapter 4.3.4 of this report (disruptive technologies) to attain an understanding of the socio-technical system in which the transition towards sustainability must occur.

In chapter 6.4, the concept of urban typologies is used to describe and understand the local conditions for vehicle automation to generate certain effects. The typologies are used to examine and estimate how large proportion of the built environment in Gothenburg is dedicated to parking and mobility-related infrastructure. The selected sites are regarded as representative for the city and are used as local test beds for implementation of the future scenario.

Finally, the findings are concretised in a flexible framework that describes the conditions and consequences of a paradigm shift, communicating the potential of vehicle automation to enhance sustainable urban development in Gothenburg.

The methodology has been chosen as a set of tools to explore, structure and understand the impacts and effects of autonomous vehicles on sustainable development in an urban setting. The PUGH matrix is an excellent way of organising and comparing large sets of data with a mixture of quantitative and qualitative inputs. MLP theory is commonly used as a framework to define, describe and concretise a technical disruption. Scenario analysis was chosen as a way to structure an unpredictable development and explore a complex topology of different trajectories and SWOT-analysis to simplify and highlight the findings and conclusions. The methodology used in this report should not be perceived as a comprehensive and absolute way to assess and evaluate the current situation, but rather as a reflection upon some of the prevailing ideas and perspectives on vehicle automation, sustainable development and urban planning. The conclusions drawn are endemic to Gothenburg and cannot without further investigation be generalized or validated for other contexts.

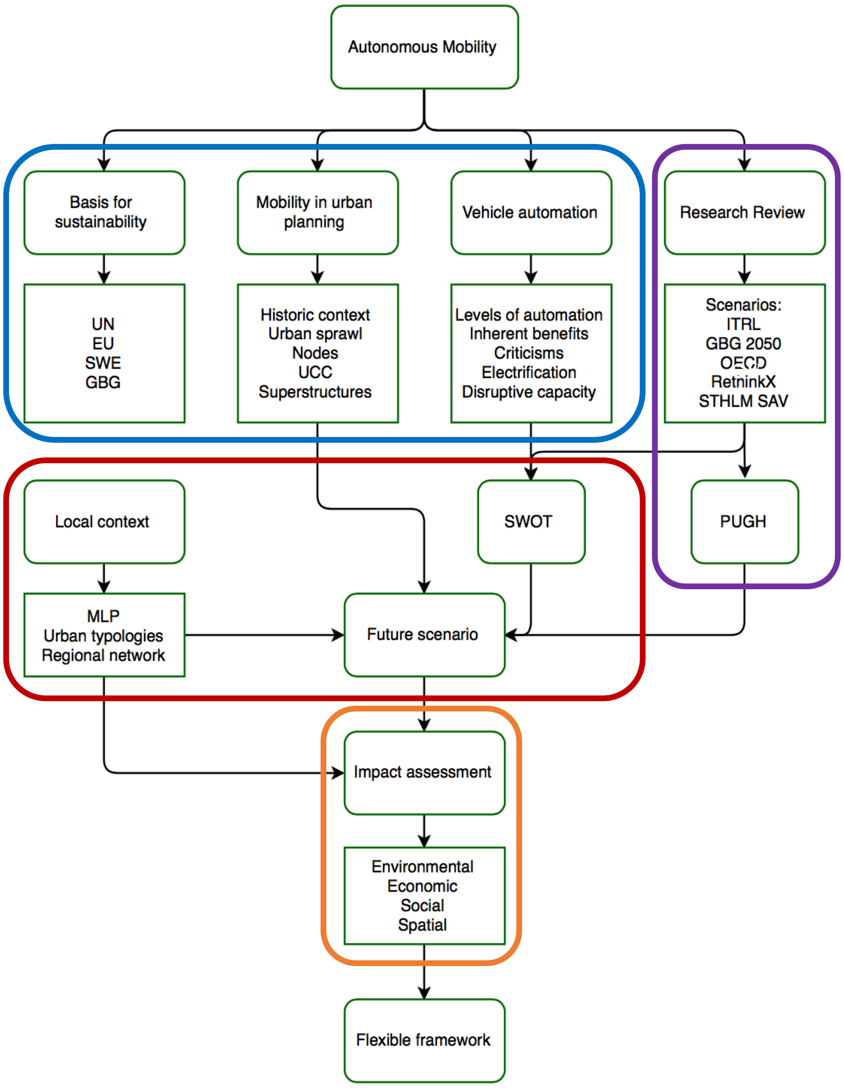

Figure 3.1 - Conceptual chart of overall process. *Illustrated by the author.*

3.1 Multi-layer perspective

MLP theory is used to understand and explain changes in society. A socio-technical system consists of all elements and conditions that society operates within. It can be described in terms of institutions, culture, policies, markets, science, technologies etc. The prevailing socio-technical regime is influenced and limited by a landscape of exogenous forces such as climate, macro-political influences and global trends. According to MLP theory, technologies and innovations are mostly developed in niches, where learning processes and new compositions can happen. Changes in the socio-technical regime can happen when landscape pressures open windows of opportunities for niche-innovations diffuse in society and reshape the existing regime (Geels and Schot, 2007).

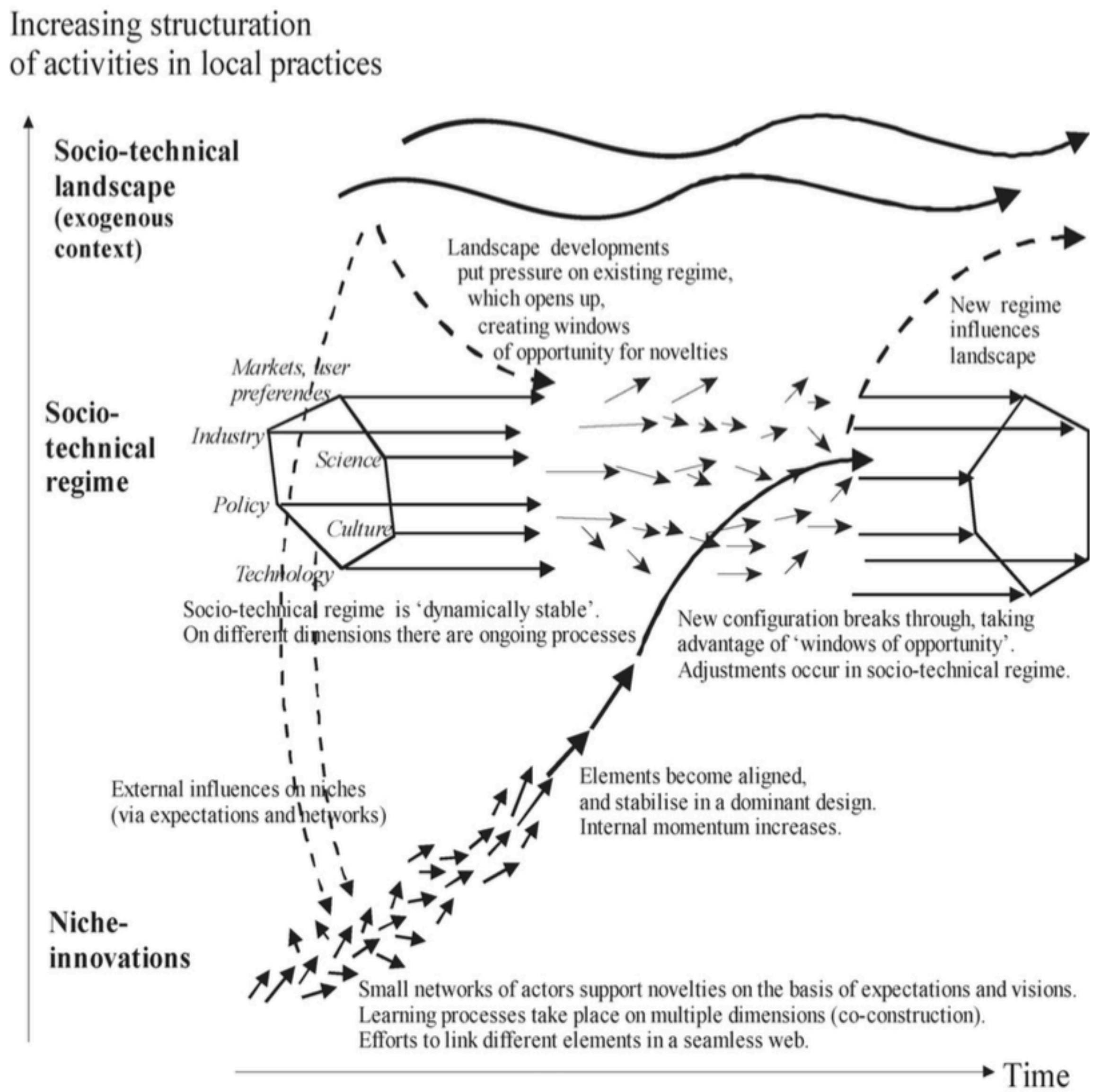

Figure 3.3 – Multi-layer perspective on transitions. *Source: https://www.researchgate.net/figure/222534486_fig1_Fig-1-Multi-level-perspective-on-transitions-adapted-from-Geels-2002-p-1263*

In this report, MLP theory is used in chapter 4.3 (Disruptive technologies) as a tool to map and understand the socio-technical system in which vehicle automation technologies may play an important role in shaping a more sustainable future and to understand the consequences of such a technological disruption.

3.2 Scenario planning

Throughout the second half of the 20th century, strategic planning could mostly be achieved by using mathematical and statistic models to extrapolate current and past trends into the future. Strategic decisions were more focused on large scale implementation of existing systems rather than creating something ground breaking. However, with the present technological advancements and evermore pressing environmental conditions setting new boundaries for development, it is harder to predict what the dominating forces of change will be shaping the world for the coming decades. In short, linear extrapolations or incremental forecasting is no longer valid in a socio-technical system full of disruptive tendencies (Trafikkontoret, 2012).

The purpose of scenario planning is not to provide unambiguous recommendations or explicit grounds for decision making, but rather a method to explore an uncertain future. Critical assumptions are spanned across two axes, allowing four different potential futures to be developed with the purpose to highlight determinative aspects. To provide a good foundation for scenario planning, external trends must be considered and strategic uncertainties must be identified. Scenario planning is a suitable tool for strategic planning for complex situations with many possible solutions. By imagining the extremes, the scenarios can be assessed and the one with most positive outcomes can be enhanced in policy making while adverse outcomes can be thwarted.

Figure 3.2 – Forecasting vs. scenario planning. *Source: Göteborgs Stad Trafikkontoret, Göteborgs trafiksituation 2050, p 4.*

Scenario planning is not used as a primary method in this report, but has been used as a tool by some of the reference projects studied in chapter 5.1 (KTH Integrated Transport Research Lab) and 5.2 (Gothenburg's Traffic Situation 2050). It is therefore important for the reader to get an introduction to the concept.

3.3 PUGH matrix

A PUGH matrix is a decision-making tool that can be used to compare concepts, scenario products or services. It is created by listing assessment criteria against the scenarios and assigning a positive, negative or neutral impact for each category in comparison to the baseline scenario (George et al., 2005) This makes the data more approachable and easy to compare. Strengths and weaknesses associated with each scenario can thus be identified and either preserved or revised to be brought into the final and optimal solution. If necessary and applicable, the criteria can be weighted by assigning numerical values corresponding to their relative importance.

This study uses PUGH matrix to compare the qualities and characteristics of different scenarios for future mobility. The scenarios that are compared are taken from different scientific studies, think tanks, workshops and reports. Key features are then identified and transferred to a future scenario within a specific context. The comprehensive PUGH matrix can be found in chapter 6.6.1.

Table 3.1 – Principle of a PUGH matrix.

Criteria	Baseline	Alternative scenarios		
Criterion 1				
Criterion 2				
Criterion 3				
Sum of positives				
Sum of negatives				
Neutrals				
Total score				

3.4 SWOT analysis

A SWOT analysis is a simple matrix that identifies the strengths, weaknesses, opportunities and threats of a system, policy, object, strategy or method etc. Strengths and weaknesses are defined as inherent positive and negative qualities, while opportunities and threats are influences by external conditions. SWOT analysis is used in chapter 6.6.2 of this report to get an overview and understanding of the qualities and effects of autonomous vehicles.

3.5 The IPAT identity

The IPAT equation can be used to express the impact of human activity on the environment. The impact of an activity or product is expressed as a function of population, affluence and technology. *Population* refers to the number of people or other kinds of users that are included in the system. The *affluence* describes the number of goods or service units per person or other user and the *technology* factor reflects the impact per good or service unit.

$$I = P \times A \times T$$

$$Impact = Population \times Affluence \times Technology$$

$$Impact = Population \times \frac{Goods\ \&\ services}{Person} \times \frac{Impact}{Goods\ \&\ services}$$

The IPAT identity is used as a qualitative tool in this report to discuss the magnitude of environmental impacts of different strategies or features included in the alternative scenarios. This analysis is done in chapter 8.1. It is also used in to determine the values of the PUGH matrix in chapter 6.6.1.

3.6 Definition of terms

AV adoption – refers to the degree of technological diffusion that autonomous vehicles has reached and is often given in percentage of the fleet (how many cars out of 100 are level 5 self-driving) or as a percentage of VKT (how much of all vehicle kilometres travelled is done by a level 5 autonomous vehicle.

Fleet – includes all vehicles that are used for transportation within a specified geographic area. *Fleet size* is the number of vehicles that are being used to provide the required level of mobility in an area.

VKT – is short for *Vehicle Kilometres Travelled* and indicates the total traffic volume within a specified geographic and temporal zone, e.g. in Gothenburg during an average week day or over the period of one year. In this report, VKT is often discussed as a relative value where 100 is the situation today.

4 Autonomous Mobility – background

A disruptive technological development such as complete vehicle automation will create ripples throughout the many layers of society and the built environment. Assessing the effects therefore requires knowledge within many different topics. The background for this thesis aims to create a holistic picture of the socio-technical circumstances around a transition of the transportation system in Gothenburg. The topics explored are; *Basis for sustainability*, *Mobility in urban planning*, *Introduction to AV* and the *Future of urban mobility*. Each section is summarized at the end, highlighting the key issues or most important knowledge to bring into the impending analysis.

To get an idea of if and how autonomous vehicles can benefit sustainable development, it is necessary to define what is meant by sustainable development and what needs to be done to achieve this. A comprehensive summary of the current relevant goals and targets is therefore a given starting point for this thesis. Chapter 4.1 explains the concept of sustainable development and lists different agendas for sustainable development with goals and targets on a global, regional and local scale, by authoritative institutions such as the UN, the EU, the Swedish government and the City of Gothenburg. The goals and targets presented are not comprehensive, but have been chosen according to their relevance to urban mobility and transportation.

An understanding of mobility and what role the car has played in shaping our modern cities is necessary to determine what the role of transportation might be in the future and how the planning of the city should relate to this potential paradigm shift. Understanding the past and what has brought us to what we have today is essential in shaping a future scenario. Section 4.2 of this report is dedicated to the historic context in which autonomous vehicles will be implemented as well as some interesting and relevant concepts for urban planning. Autonomous vehicles are another key topic for this thesis. Chapter 4.3 discusses benefits and threats inherent to the technology. Lastly, section 4.4 introduces and discusses different future scenarios for urban mobility, taken from recent and ongoing research projects.

4.1 Basis for sustainable mobility

The modern human has been around for roughly 200 000 years (O'Neil, 2013), a relatively short time period in the context of the planet's history. We have evolved and prospered in the stable and beneficial climate of the Holocene. Planet Earth has been a good home for us, providing an abundance of energy and material resources. However, human actions have led to global climatic change and environmental degradation that is now threatening the robustness of the complex biogeochemical systems and hydrological cycles supporting our existence. We are entering a new geological era, the Anthropocene, in which humanity is the strongest single acting force on the planet. The future of our species lies in our own hands as our climate is approaching a tipping point of positive feedback loops. Our actions over the next few decades are therefore imperative in setting the future conditions for human life on this planet.

The topic of sustainability first appeared as a global agenda item in 1987 when the UN World Commission on Environment and Development was founded and issued the report "Our Common Future". The commission was led by chairman Gro Harlem Brundtland, the Norwegian prime minister at the time (UNECE, 2015). One of the most commonly used definitions of sustainable development, known as the "Brundtland definition", originates from this report.

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." – Brundtland, 1987

Sustainable development is often defined from a triple bottom line approach including social, economic and ecological aspects. These three pillars must all be met to ensure a development that fulfils the definition of sustainability. The Brundtland definition represents an anthropocentric ethical view as it only requires human needs to be fulfilled, assigning instrumental value to the ecosphere. A stricter and more ecocentric approach would be to acknowledge the intrinsic value of ecosystems and extend the definition to not only include human needs, but also the conditions necessary for biodiversity and healthy ecosystems.

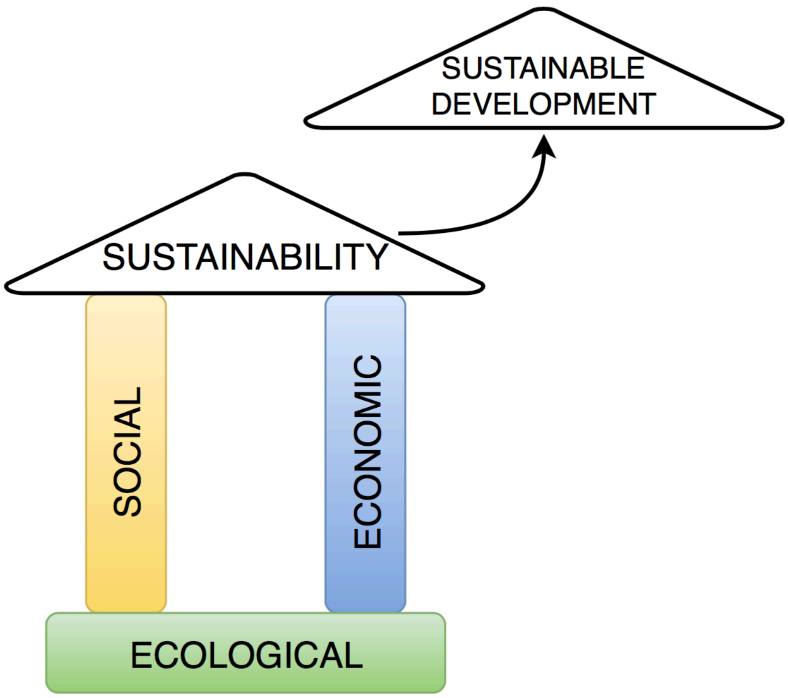

***Figure 4.1* – Three pillars of sustainable development.** *Source: the author.*

Climate change is today globally acknowledged and policies to mitigate the effects are being made on many different levels; UN, EU, national, regional and local. Ambitious targets are being set, such as limiting global warming to 1.5°C in the Paris agreement (UNFCCC, 2017). However, policies and regulations seldom have the transformative character required to meet the ambitious yet critical goals.

Researchers at the Institute of Physical Resource Theory at Chalmers have formulated four non-overlapping, socio-ecological principles for a sustainable society (Holmberg et al., 1996). The principles have been developed by applying a system perspective and focusing early in the causal chain, which makes them fundamental and applicable on all societies operating within the planetary boundaries. They are derived from the idea of sustainable development as establishing and infinitely maintaining a balanced and stable material exchange between society and nature. A sustainable society is embedded in the biogeochemical cycles and must fulfil all the below listed principles;

1. Substances extracted from the lithosphere must not systematically accumulate in the ecosphere.
2. Society-produced substances must not systematically accumulate in the ecosphere.
3. The physical conditions for production and diversity within the ecosphere must not be systematically deteriorated.
4. The use of resources must be effective and just with respect to meeting human needs worldwide.

These principles imply that intrinsic value is assigned to ecosystems as well as to human welfare and they shall be used as a basis for sustainability throughout this report.

Goals and targets for sustainable development have been set by many different institutions, both local, national and intergovernmental. On a global scale, the United Nations have taken upon themselves to strategically develop an agenda for sustainable development. The EU also has policies regarding these issues. On a national level, the Swedish government has sustainability targets that correspond to and extend beyond the UN agenda for sustainable development. Furthermore, Gothenburg has a set of local ambitions for strategic and sustainable development that are based on the national targets.

Global hectares (gha) are often used to quantify ecological footprints of people, products or activities as well as measuring the biocapacity of the Earth or specific parts of it. One global hectare is a weighted productivity of all productive land, i.e. not including deserts, the open ocean or glaciers. The Earth has a total of around 12 billion hectares of land and water that is considered biologically productive., which can be compared to the overall surface of 51 billion hectares.

The environmental Kuznets curve advocates that environmental degradation in relation to per capita income follows an upside-down U-shape, including a turning point where pollution peaks and is decoupled from economic growth. This has been true for some kinds of pollution, the most famous example being sulphur oxide emissions that were successfully regulated in the Montreal protocol. Whether this holds true for greenhouse gas emissions is widely debated and remains for the future to depict.

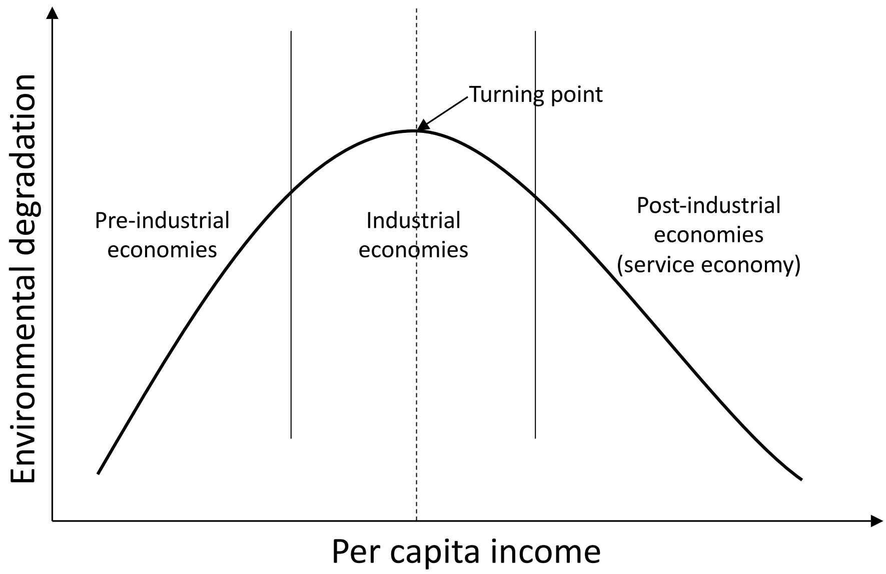

Figure 4.2 – Environmental Kuznets Curve. *Illustrated by the author.*

4.1.1 UN 2030 Agenda for Sustainable Development

In 2015, the UN general assembly agreed upon 17 sustainable development goals that should be achieved globally over the next 15 years. The implementation of the agenda officially begun on January 1st 2016 and include social, economic and ecological sustainability (United Nations, 2016a). The agenda recognises that up to 70% of the world population will be living in urban areas by 2050 and that cities possess the prime power to catalyse sustainable development. The targets that are relevant for the content of this thesis, i.e. goals that can be directly linked to transportation, are presented in more detail below.

***Figure 4.3 – UN Goals for Sustainable Development**. Transport related goals are highlighted. Source: Adapted from http://www.un.org/sustainabledevelopment/sustainable-development-goals*

4.1.1.1 Good health and wellbeing

Goal number 3 has the purpose to ensure healthy lives and promote well-being for all at all ages (United Nations, 2016b). This includes that the number of global deaths and injuries from road traffic should be halved by 2020 and the number of deaths and illnesses due to air pollution should be substantially reduced. The development on this point is diverged between high-income countries where the number of road traffic deaths has declined slowly since 2000 and low- and middle income countries, where the numbers are increasing. In addition to fatal accidents, tens of millions of people are severely injured and sometimes permanently disabled in traffic accidents each year. Children, pedestrians, elderly and cyclists are especially vulnerable ((WHO, 2017a). The global vehicle fleet is growing exponentially, having doubled since the year 2000. This makes decreasing the number of accidents an ambitious goal. Road traffic and ambient pollution due to road traffic is one of the largest contributors to premature deaths globally. AV can play a role in reducing accidents and creating cleaner urban environments.

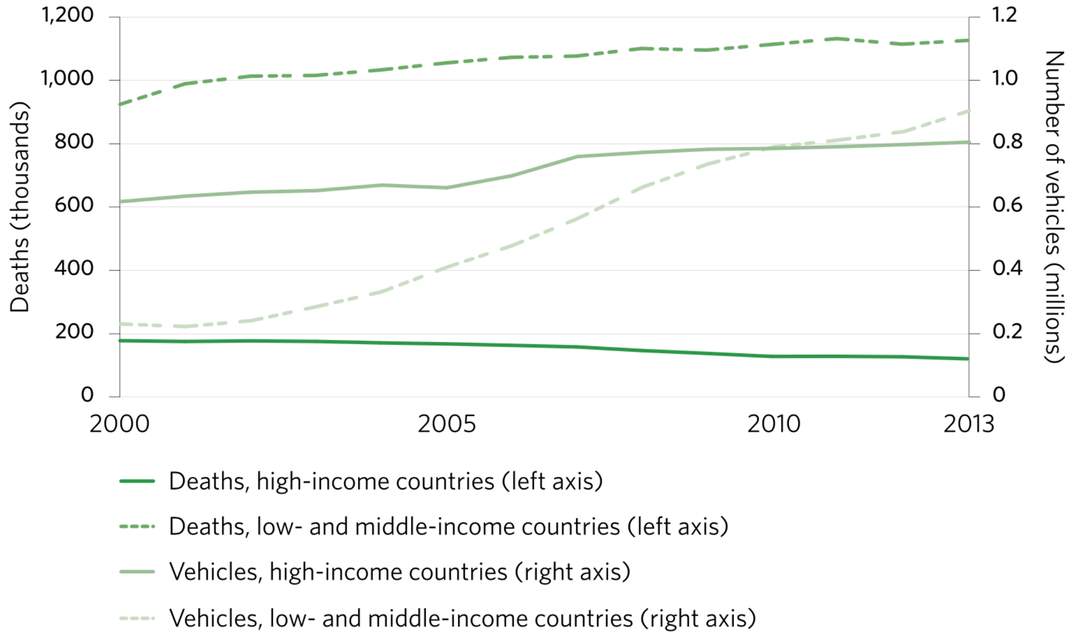

Figure 4.4 – Road traffic deaths (thousands) and vehicles (millions) in high-, low- and middle-income countries, 2000-2013. *Source: https://unstats.un.org/sdgs/report/2016/goal-03/*

4.1.1.2 Industry innovation and infrastructure

Goal 9 is about developing a sustainable and resilient infrastructure. It stresses the importance of an infrastructure with high quality, that supports human well-being as well as economic development. The focus should be to ensure equitable and affordable access for all. Infrastructure, industrialization and innovation are highlighted as three important factors (United Nations, 2016c). Infrastructure is essential in providing the fundamental physical facilities for businesses and society to develop, industrialization is a key driving force for economic growth, generating more jobs and levelling out income gaps and innovation pushes the development forward as new technologies and skills are created. Indicators and parameters such as R&D expenditures, CO_2-eq. emission per value added and manufacturing capacity are used to measure the progress in this area. Since the year 2000, energy efficient technologies and cleaner fuels have contributed to a reduction in carbon intensity of economic growth in almost all parts of the world, i.e. the emissions per value added are smaller today compared to 20 years ago. The percentage of GDP invested in R&D (research and development) is increasing worldwide, but is a lot lower in developing regions compared to developed ones and varies from 2.4% of GDP to as low as 0.3% of GDP. Energy intensity is often used to set goals for sustainable development, especially in rapidly developing nations such as China and India. However, in combination with large economic growth, more efficient energy use is not enough to achieve a decrease in net emissions and the decoupling of economic growth and energy use remains absent, especially when considering a consumption based emission accounting rather than the more common production based model.

4.1.1.3 Sustainable cities and communities

Goal 11 is focused on *Sustainable cities and communities*. By 2030, 60% of the global population is expected to live in cities (United Nations, 2016d). Cities must be inclusive, safe, resilient and sustainable. The targets under this goal include the provision of safe, affordable, accessible and sustainable transportation systems for all by 2030. Road safety should be improved by expanding public transportation and special attention should be paid to older persons, persons with disabilities and children. The adverse per capita environmental impacts of cities must be reduced and the air quality must be improved. Another target is that by 2030, all should have access to safe, inclusive and accessible green and public spaces. Additionally, inclusive and sustainable urbanization should be developed through enhanced planning and management of cities. Urban sprawl is a detriment to sustainable development as it brings a higher level of land appropriation and inefficient use of resources. The UN report defines urban sprawl as the ratio between land consumption rate and population growth rate based on a stratified sample of almost 200 cities. A ratio lower than one, meaning the cities are becoming more densely populated, was only found in a few regions such as Latin America and South and Central Asia. The global average for 2000-2015 is 1.74, compared to 1.68 for the antecedent ten-year period, an unsettling trend. Even though they are generally more sprawled to begin with, cities in developed regions are showing a more positive trend going from 2.06 to 1.93 for the same periods (UN-Habitat, 2016). Unplanned urban sprawl is closely associated with increased per capita emissions of carbon dioxide and hazardous air pollution. Other effects include rocketing prices for housing, urban segregation and increased inequality. Ambient air pollution from urban transportation and energy generation is an increasingly alarming issue, causing millions of premature deaths annually. The World Health Organization (WHO), recommends an average annual mean concentration of PM2.5 no higher than 10 $\mu g/m^3$. The global average for urban areas is a shocking 45 $\mu g/m^3$ and no region is currently achieving the recommended levels. Again, developing regions are a lot worse off than developed regions with averages of 14 and 52 $\mu g/m^3$ respectively (WHO, 2017b). Sustainable cities and communities also means that all should have access to economically obtainable housing and services. Increased efforts should be made to enhance positive economic and social exchange between urban, sub-urban and rural areas, i.e. increased focus on comprehensive and coordinated regional and national development.

4.1.1.4 Climate action

Goal 13 is dedicated to *Climate action.* The UN acknowledges that climate change is the single biggest threat to societal development, unprecedented in complexity and severity. Urgent measures are called for to mitigate climate change and its impacts but also to adapt society in response to the new climatic conditions of the Anthropocene. This includes strategies to cope with more frequent and harsher natural disasters and other climate-related hazards. Resilience is the key word here.

Despite efforts to mitigate sources, global anthropocentric CO_2 emissions have increased by around 50% since 1990 and the last decade has seen a more rapid increase than before. The average global temperature has increased around 1°C since 1880, most of which has occurred since 1975 (NASA, 2016). Transportation accounts for 14% of the global greenhouse gas emissions (US EPA, 2016). This can be compared to Sweden where almost one third of the national emissions can be traced back to domestic transportation (Naturvårdsverket, 2016a).

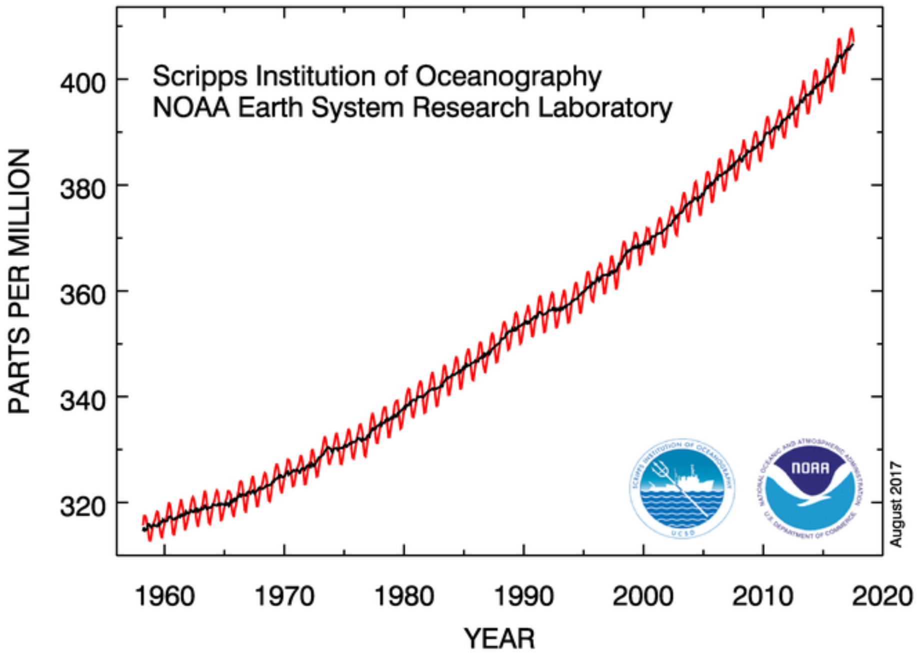

Figure 4.5 – Atmospheric CO_2 at Mauna Loa Observatory. *Source: https://www.esrl.noaa.gov/gmd/ccgg/trends/full.html*

As part of the sustainable development goals, the UN demands that climate change mitigation and adaptation must be integrated in all national strategies and planning, including the planning of urban transport and the layout of cities.

4.1.2 UN Habitat III

Habitat III refers to the United Nations Conference on Housing and Sustainable Development held in Quito, Ecuador in 2016. 167 countries were represented at the conference. The conference parties agreed on a new urban agenda; the Quito Declaration on Sustainable Cities and Human Settlements for All (Habitat III, 2016). The resulting document is an extension of the UN 2030 Agenda for Sustainable Development and includes a framework for how cities should be planned and managed to best promote sustainable urbanisation. The declaration calls for a paradigm shift in urban planning in response to inequality, poverty and climate change. It acknowledges that cities and settlements face new challenges due to unsustainable consumption and production patterns, pressure on ecosystems, decreased biodiversity, lack of equal access and freedom of mobility, pollution, natural and man-made disasters and climate change that undermine all endeavours to end poverty and attain sustainability. Due to the global and boundless character of adverse environmental impacts and cities' role as economic and social nuclei, cities have a direct impact on sustainability beyond their own urban boundaries. Urban form, building and infrastructure is one of the largest driving forces for resource and energy consumption but also constitutes one of the largest possibilities for savings and increased efficiency. Shaping urban movements, metabolism, planning and management is therefore a crucial part of improving global resilience.

"The ultimate objective of all transportation is access, not mobility." – UN Habitat, 2013

The Quito agenda discusses mobility as a central challenge for sustainable urban development. Enabling citizens to access urban functions and governmental services within a reasonable distance from their home is imperative for a functioning city. Access to public transportation is often concentrated in certain nodes within the urban topology. Balancing frequent access points against a fast transit is not easy. This creates an issue commonly referred to as the "last mile problem". There is a threshold for using public transportation as the traveller must get from the origin to the access point and then from the closes stop to the final destination. A more close-knit public transportation network can be used to counteract the effects of the last-mile problem but there are currently no satisfactory or ubiquitous solutions for bringing the passenger all the way to the destination.

The UN Habitat III report emphasises the importance of finding solutions to the last mile problem. It also urges cities to encourage non-motorized transportation and increase the non-motorized share of travel. A higher population density makes it easier to sustain a tighter network with more frequent stops and departures. UN Habitat III recommends a population of no less than 150 persons/ha (Höstmad, 2015) to enable a sustainable city design.

According to the Habitat III report, sustainable urban development requires investments and policies that support fast, reliable and affordable public transportation, renewable energy sources and efficiency in the use of water and electricity next to design and implementation of compact cities, retrofitting of buildings, increase of green areas and improved waste and recycling systems (UN Habitat III, 2016).

The design of a city's mobility system is important for these criteria from many aspects. Renewable energy resources can be promoted by using non-fossil based transportation modes, a well-planned and efficient public transportation system can decrease a city's total energy demand and create more space for green infrastructure. The transportation network is also what dictates the density or sprawl of a city. A good waste management system is also dependent on access to handle and collect waste.

4.1.3 EU

The European Union recognizes that a paradigm shift of the transportation sector lies ahead. The transition is induced by a wave of disruptive technologies and innovative business models and has a huge economic, social and environmental potential. The cost of congestion alone is currently estimated at around 1% of the global GDP (European Comission, 2016). Add to this the costs for traffic accidents, health effects from air pollution, global warming and degradation of ecosystem services to name a few. A more efficient transportation system is a much-needed development. The European Commission has issued a strategy to encourage policy making that supports a paradigm shift and in 2016 the EU called for project proposals on automated road transport.

4.1.4 Sweden

Sweden has several well-defined environmental quality goals, covering everything from healthy swamps to clean air. However, with the current trends and policies, only one out of the 16 goals is likely to be fulfilled by 2020 (Naturvårdsverket, 2016b). The national target for Sweden is to reduce overall emissions by 40% in 2020 compared to the 1990 emission levels and to achieve zero net emissions in 2045. After this, negative emissions should be attained (Miljömålsberedningen, 2016). The current rate at which emissions are being mitigated is not sufficient for meeting these targets. Another target is that emissions from the transport sector should have decreased by at least 70% in 2030 compared to 2010.

Concerning road and traffic safety, *Vision Zero* is a policy innovation for traffic safety that was presented by the Swedish Transportation Administration in 1995. The basic concept is an ethical stance that no deaths or permanent injuries should occur in traffic (Trafikverket, 2014). At the time of implementation, the vision was considered utopian and unrealistic but it has proven to be a valuable tool in the development of traffic safety. The number of deaths in traffic have been reduced significantly and is getting better every year. Sweden is now one of the safest countries in the world when it comes to fatal road accidents and the model has been adopted by many other cities and countries since (Center for Active Design, 2017). Autonomous vehicles could play an important role in taking road safety to the next level and allowing vision zero to become reality.

4.1.5 Gothenburg

The City of Gothenburg has 12 official environmental goals that were agreed upon by the city council in 2013. These include 36 sub-goals and over 200 implementation strategies on how to improve the environment and make the region more sustainable (Miljö- och klimatnämnden, 2013). There are also 13 separate strategic points for sustainable development, listed below, that were formulated by the City Planning Authority in 2009 as part of the comprehensive plan for the municipality (City Planning Authority, 2009).

1. Gothenburg’s role in a growing region
2. An attractive urban space
3. A robust community
4. More homes
5. Growth and change in retailing
6. An expanding business sector
7. Scandinavia’s Logistics Centre
8. Changing transport demands
9. Diversity and security on a human scale
10. Recreation and health for a better quality of life
11. Natural and cultural environments for increased attractiveness
12. Access to the coast
13. Special localisations

These points are all directly or indirectly linked to the topic of mobility. An expansive region needs highly efficient and functioning transportation to remain attractive. Autonomous electro-mobility has the potential to significantly improve the comfort and convenience of travelling to as well as within the city, making it easier to live and work in the area. The comprehensive plan aims to encourage a denser exploitation of land around certain strategic nodes, where public transport, residential buildings, offices and market places are highly available and connected to the rest of the city. The nodal concept assumes that public transport is used as the main means of transportation and is developed to satisfy the increasing demand of mobility. The nodes are places with higher urban density and provision of services and commodities, which makes them attractive areas for residential and commercial buildings. If implemented correctly, autonomous vehicles can support the development of a more close-knit city structure as it creates a flowing connectivity network that allows the nodes and cores to be smoothly integrated in the rest of the city structure. The nodes are also meant to decrease the pressure on the inner city as population and economic activities are sprawled across a wider section of the city.

Urban density is regarded as one of the key features of a modern and sustainable urban metropolis. The City of Gothenburg recognises this in their development strategy and the ambitions are clear. A denser city is more efficient in terms of transportation and land use, as well as an economic driving force. It also promotes a safer and more attractive built environment and provides a wider range of culture and services for its citizens. At the same time, qualities such as green areas and direct sunlight cannot be compromised. Density does not necessarily imply high-rise buildings, one of the key features is a good mix of functions. One such specific sub-goal is that grocery stores should be available within 1 km walking distance from a residence.

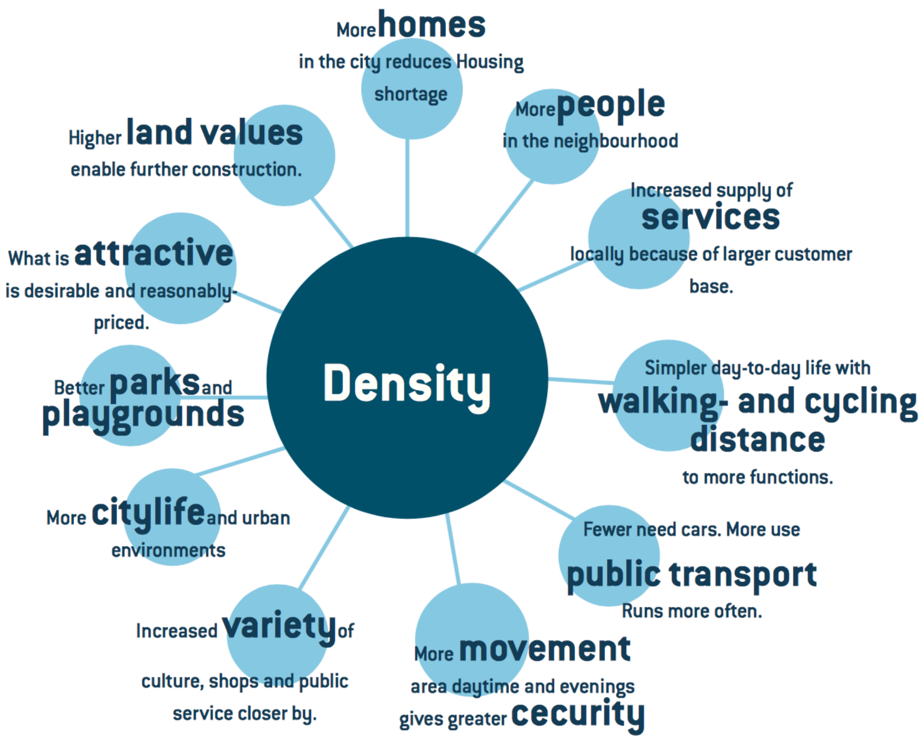

Figure 4.6 – Benefits of urban density. *Source: Development Strategy for Gothenburg 2035, City Planning Authority, 2014.*

Regarding climate change mitigation, the target is to decrease overall CO_2-emissions by 30% in 2020 compared to the 1990 levels. Goals concerning a good built environment are slightly vaguer than the emission targets as such a quality is harder to measure. According to the progress report from 2016 (Göteborgs Stad, 2016), none of the above-mentioned targets will be fully met in a timely order as a result of the existing policies. The general development is a levelling out of the measured parameters and not the necessary decline. That is, emissions and environmental degradation is still increasing, but the increase is smaller than before. The overall conclusion is that additional efforts must be made to ensure sustainable development in the region. To ensure development that supports the strategic questions the City of Gothenburg has agreed on three effect goals for travel in the city, to be reached by 2035;

- At least 35% of trips in Gothenburg are done by foot or bicycle.

- No less than 55% of all motorized travel is done by public transport.
- The travel time between two arbitrary nodes or destinations is maximum 30 minutes by car or by public transport.

Combined, these three targets implicate a doubling in travelling by foot or bicycle, a doubling of public transportation and a 25% decrease in travel by car (Trafikkontoret, 2014).

Development of the road transportation system in Gothenburg is done through a four-step principle for planning and implementation; 1) Rethink, 2) Optimize, 3) Rebuild and 4) Build new. The first step includes measures that affect the need for transportation and travel. The second is about a more efficient use of existing infrastructure and the remaining two are about physical alterations and new investments in mobility related infrastructure when existing structures are insufficient. The City of Gothenburg has three main strategies for how to achieve better urban spaces (Trafikkontoret, 2014);

- Prioritise pedestrians and cyclists and adapt the speed mainly to pedestrians.
- Rearrange the streetscape to create space where people want to be and move around
- Create a denser and more interconnected network of streets without barriers.

Effectively, this means transforming space occupied by over dimensioned infrastructure to efficient land use for a denser and greener city. Traffic routes can become city streets and street-side parking can make room for pedestrians, cyclists, greenery, goods distribution centres, seating areas or buildings. Slower traffic on the roads will make public transport more attractive. Restrictions in parking availability can be used as an effective policy instrument to discourage transportation by private vehicle. The strategy has the ambitious goal that:

"Gothenburg will become a leader in integrating the vehicle of the future into the close-knit city" – Trafikkontoret, 2014.

Autonomous vehicles are discussed as a possible development, but other than that, the question of what the vehicle of the future denotes is left to the reader's imagination.

Another strategy is the K2020, a systematic approach to creating a common ground for public transportation development in the Gothenburg Region. The framework was first adopted in 2007 with the comprehensive goal to make travel by public transport more attractive. The strategic development is concentrated to the more densely populated parts of the region; Gothenburg, Mölndal and Partille but includes the regional commuter area with up to one hour travel radius. The strategy consists of five main principles (Göteborgsregionens Kommunalförbund, 2008);

- Linking areas
- Faster journey time
- Greater frequency
- Developing the nodes
- Guaranteeing quality and service

Linking areas will be done by replacing the currently radial structure with a more close-knit network. Faster journey times is planned to be achieved by giving public transportation priority and building more separate lanes for buses and bikes. By implementing nodal development, the city hopes to make public transportation a natural and central part of urban development. Increased frequency is essentially focused along the main corridors linking nodes together. The K2020 strategy also includes what is referred to as the "Go-concept", where mobility will be developed in 6 levels, ranging from walking and biking to destinations within reasonable proximity, to airplane travel for distant locations. Customer satisfaction is assured by making the system easy to use, reliable, safe and timely.

The basic requirements for planning public transportation is *reliability*, *safety* and *accessibility*. These factors must be given priority in all contexts. The K2020 framework includes guidelines that should be followed to ensure these basic requirements, covering the topics of route network, traffic flow, interchanges and support and value creating services (Göteborgsregionens Kommunalförbund, 2008).

Figure 4.7 – 6 levels of development with the "GO-concept". *Source: https://www.grkom.se/download/18.276a42981270147ed3580006331/1359469265370/K2020+Public+transport+development+program+for+the+Göteborg+Region.pdf*

4.1.6 Summary of sustainable development goals

The different agendas for sustainable development all agree that managing urbanization in a sustainable way is a key challenge in building a resilient and environmentally sound habitat for the human species. Densification is highlighted as a desirable development in urban areas as opposed to urban sprawl. People should dictate the streetscape, not cars.

In practice the sustainable development goals imply that Gothenburg must:

- Decrease emissions from transportation with 80% by 2030 compared to 2010
- Double public transportation by 2035
- Decrease travel by car with 25% by 2035
- Double non-motorized transportation

Transportation is the single largest environmental load. It also links all aspects of the socio-technical system together, both physically and metaphorically. The connection between sustainable development and transportation is evident. Without fundamental changes in the city's mobility system, achieving any of these goals will be difficult.

Table 4.1 – Summary of relevant goals for sustainable development. *Source: By author. Based on chapter 4.1.1 to 4.1.6. See individual chapters for details and references.*

	Strategies and goals for sustainable development				
	Public spaces	Roads and infrastructure	Environment	Health and safety	Mobility
Gothenburg	Concentrate development around nodes Denser city Prioritize pedestrians and cyclists in street scape	Rethink and optimize usage before rebuilding or building new Create a denser network of streets Adapt speed to pedestrians Minimize barriers	55% of all motorized transport is done by PT in 2035 Decrease car travel with 25% by 2035 Decrease CO2 from transportation 80% by 2030, compared to 2010		Minimize the need for travel 35% of trips done by bicycle or foot 2035 Double travel by PT by 2035 Double travelling by foot and bike by 203 Max. 30 minutes travel time by car or PT
K2020		Bus lanes on all approach roads			Concentrate PT to nodes and corridors
Sweden			Decrease emissions with 40% by 2020 compared to 1990 Decrease CO2 from transportation 70% by 2030, compared to 2010 Net 0 emissions in 2045 Negative emissions after 2045	Zero traffic-related deaths or permanent injuries	
UN Habitat III	Design and implement compact cities >150 pers/ha Increase green areas		Renewable energy sources		Fast, reliable and affordable PT
UN 2030 Agenda	Ubiquitous accesses to inclusive, public green spaces by 2030 Combat urban sprawl Integrate climate change mitigation and adaptation in all planning	Enhanced resilience and climate change adaptions Equitable and affordable access Increase R&D expenditures in % of GDP	Decrease CO2 per value added Reduce per capita emissions in cities Limit global warming to 2°C	Reduce premature deaths due to air pollution Half fatal traffic incidents by 2020 PM2.5 from average 45 to < 10µg/m3	Sustainable transportation for all by 2030 Ubiquitous, safe, affordable and accessible Improve road safety by expanding PT

4.2 Road mobility in urban development

Few innovations have moulded western life as profoundly as the automobile. Ever since the 1910's when Ford started manufacturing cars that were affordable to the public (Borneskans, 2007), has the car played a major role in shaping our cities. Initially, the car was even recognized as a more environmentally friendly alternative to the horse as it didn't leave any waste on the streets. However, it didn't take too long before the downsides were acknowledged. Globally, traffic-related accidents kill over 1.25 million people every year (WHO, 2015). Another 3 million premature deaths are caused by ambient air pollution, which is closely linked to traffic (WHO, 2012). One could claim that the car is one of the deadliest inventions of all time. Despite this, most cities rely heavily on internal combustion engines for provision of personal mobility as well as freight transportation. Highways and roads are superstructures that dominate the urban landscape and are often prioritized in planning. Car-centric urban planning begun in the USA but spread to Europe within a few decades. In 1959, the Swedish government initiated "Road plan for Sweden", a policy that in practice meant that cities and roads should be adapted to suit the automobile and not vice versa (Borneskans, 2007). At a time of rapid urbanisation and economic growth, the car shaped the expansion of many Swedish cities with amplified urban sprawl as a result. The 1950's also brought the idea of the satellite city to the urban planning scene. Suburban areas and external communities were built with the aim to unburden and decentralize the growing cities. The concept was to keep housing, work and commerce within a close radius neighbourhood unit. However, in the pursuit of more housing in the 60's and 70's, the concept commonly failed to include work and commerce in the planning. This turned the satellite cities into commuter towns, with the car as the main mode of transportation.

In 1930, Le Corbusier designed the master plan of *La Ville Radieuse*, the radiant city, where he introduced the notion of zoning, i.e. the physical separation of different functions (Merin, 2013). Although the plans were never realised, Le Corbusier's holistic approach made its mark on 20th century urban planning and architecture. In Sweden, the idea of traffic separation was formally established in the SCAFT guidelines from 1968. Taking "Road Plan for Sweden" a step further, the SCAFT publication presents principles for urban planning with respect to road safety with the fundamental concept that a separation in time or space of different classes of transportation is essential to ensure safety in urban environments (The Swedish National Board of Urban Planning, 1968). A differentiation of function and characteristics within each road network should be applied to minimize conflict and obtain homogeneity in the traffic flow. In Gothenburg, following these principles throughout years of regional growth and expansion has led to many cases of over dimensioned infrastructure (Trafikkontoret, 2014). The car has shaped our cities fundamentally but around the world, this is about to change. We are approaching a paradigm shift where development plans strive away from dependency on private cars and towards denser and greener cities with public transportation, walking and biking as the main means of transportation. Separation of functions is giving way for the close-knit mixed-use city. The age of mass motoring is far from over and the road to implementation of a new regime is long and winding, but there is certainly a new direction of technological development that promises a brighter future for urban metropolises world-wide.

In the planning of public transportation in Gothenburg, there is an ongoing dichotomy in balancing travel time against frequency of stops. All destinations should be within a reasonable distance from a stop, but too many stops make travelling slower. The public mobility network in Gothenburg consists of tramlines, bus lines, and express buses. On a regional scale, commuter trains are also an important part. Gothenburg is facing various challenges in urban passenger and freight transportation. The goal is to double public transportation by 2035 (Trafikkontoret, 2014) but nodal points for public transportation, destinations and interchanges are burdened already with the current traffic volume. A doubling implies significant reallocation of space to public transportation, a more efficient use of the existing system as well as new investments in transportation infrastructure.

Congestion is another increasingly alarming challenge. In Gothenburg, drivers spend an average of 28 minutes stuck in traffic every day. That is 4 minutes more compared to 2016 and corresponds to no less than 13 working days annually (Jennervall, 2017). Although traffic volumes in central Gothenburg dropped when congestion charges were implemented in 2012, they are now increasing steadily with 1-2% per year. Some contributing factors are increased population, economic upswing and cheaper fuel costs (Arvidsson, 2016). Travel time and distances is something that directly effects the quality of life in a city. These detrimental trends are not acceptable if Gothenburg shall remain an attractive place to live in the future. Parking is another topic that continues to create an intense debate in Gothenburg. The challenge here is to balance the contemporary demand against planning ahead and not investing in infrastructure solutions that may become redundant within the next decade. Meeting the demand today, while planning for the future is a challenge that has to be addressed with long term solutions and active policy instrument.

4.2.1 Urban sprawl

The effects of autonomous vehicles on urban sprawl are widely debated with valid arguments on both sides. AV technology provides a possibility for better use of space within the city limits as parking spaces become redundant and can be transformed into other uses. Smoother traffic flows also contribute to more space efficient use of road infrastructure. These things point towards battling urban sprawl and making cities greener and denser. On the other hand, as travelling becomes more efficient and comfortable it makes commuting more attractive. This may lead to enhanced urban sprawl. The net effect depends on which of the effects that prevail over the other or the combined result may be a densification of the inner city with sprawled and less dense outskirts (Elpern-Waxman, 2016). This dichotomy highlights the importance of implementing a strong urban growth policy, parallel to transition towards a new mobility paradigm.

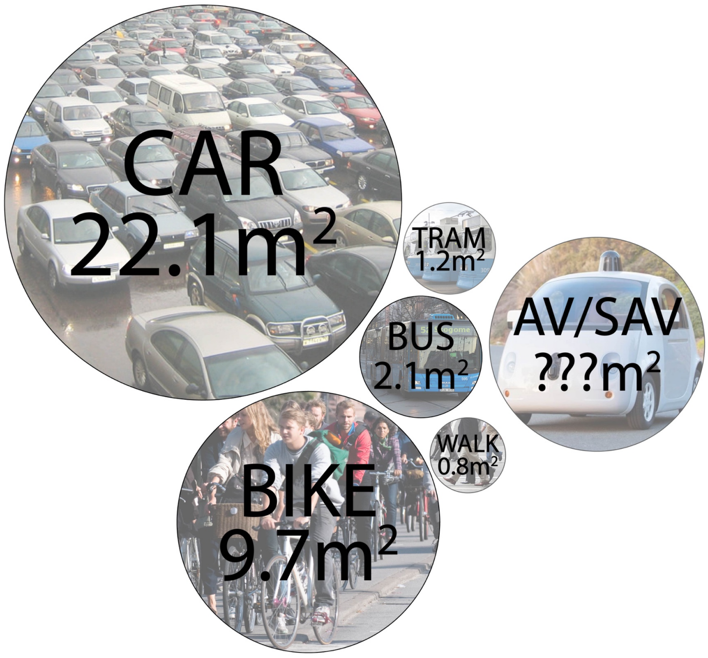

Figure 4.8 – Urban space accommodation per passenger for different modes. *Illustration by the author. Data source: Evaluating Complete Streets, Victoria Transport Policy Institute, 2015. http://www.vtpi.org/compstr.pdf.*

4.2.2 Nodes

The development plans for Gothenburg have a strong focus on nodal development, where buildings, infrastructure and services are concentrated around interconnected mobility hubs. This concept of urban development originates in a technological paradigm with long distances and limited transportation. Nodes can be an attractive part of urban development as an agglomeration of services increases the value of land and real estate in an area. It is also efficient as more people can live and work closer to public transportation access points and be better connected with the rest of the city. Urban nodes are in theory modelled as singularity, a point without any spread. It can be compared to a black hole that gathers all surrounding functions to a single, one-dimensional spot[1]. In reality however, a node does not have the characteristics of a black hole, but sprawls out over a certain area with blurred and undefined borders. Nodal expansion can bring problematic issues where both inter- as well as intra-modal transit efficiency becomes harder to achieve. One such vulnerability lies in increased distances between transportation lines within the same node, when mobility hubs become too large. This makes public transportation less attractive. A more holistic approach could be to blur and merge all nodes and edges to create a free-flowing network of services, transportation and urban functions. Nodal development requires a balance

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[1] Tvilde, D., (2017)

between the frequency and size of nodes. If the nodes in a city are too few, they tend to get larger and the pressure on a single node may turn into a stress factor for the whole system. On the other hand, if development is concentrated on too many nodes there will not be enough demand to sustain them and the whole nodal concept will fail. A resilient system cannot depend too much on a single point or edge in the network.

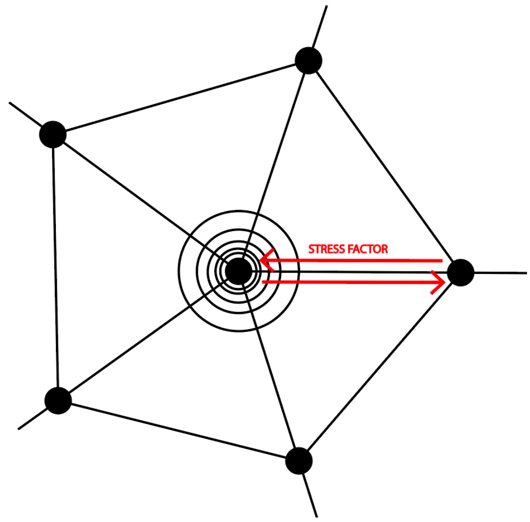


Figure 4.9 – Nodal stress. *Illustrated by the author.*

In Hong Kong, an interesting alternative to transportation nodes has been successfully implemented. Interconnections between different lines in the underground railway system are not concentrated to one station. Instead of explicit intersections, the lines run parallel to each other for a few stations where the passenger load is heavy. Depending on your direction of transit, passengers may choose to switch lines in different stations. With this system, passengers only ever have to cross the platform to find their connecting train. The "nodes" are stretched out in a controlled way to maximize efficiency instead of risking chaotic and sprawled transportation hubs. Furthermore, the trains are synced in a way that limits the transit time to under a minute.

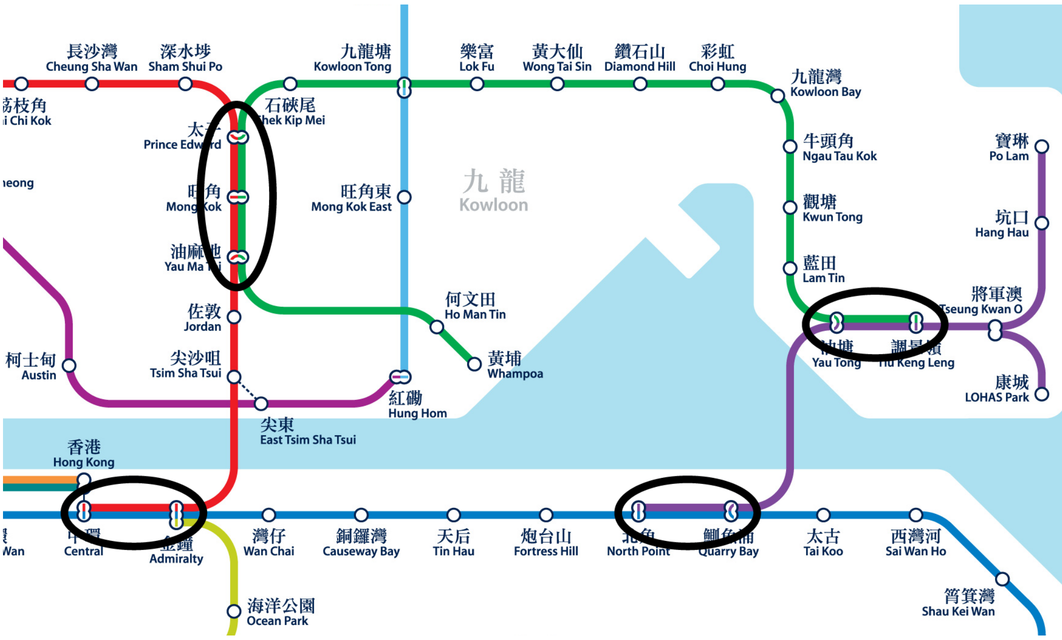
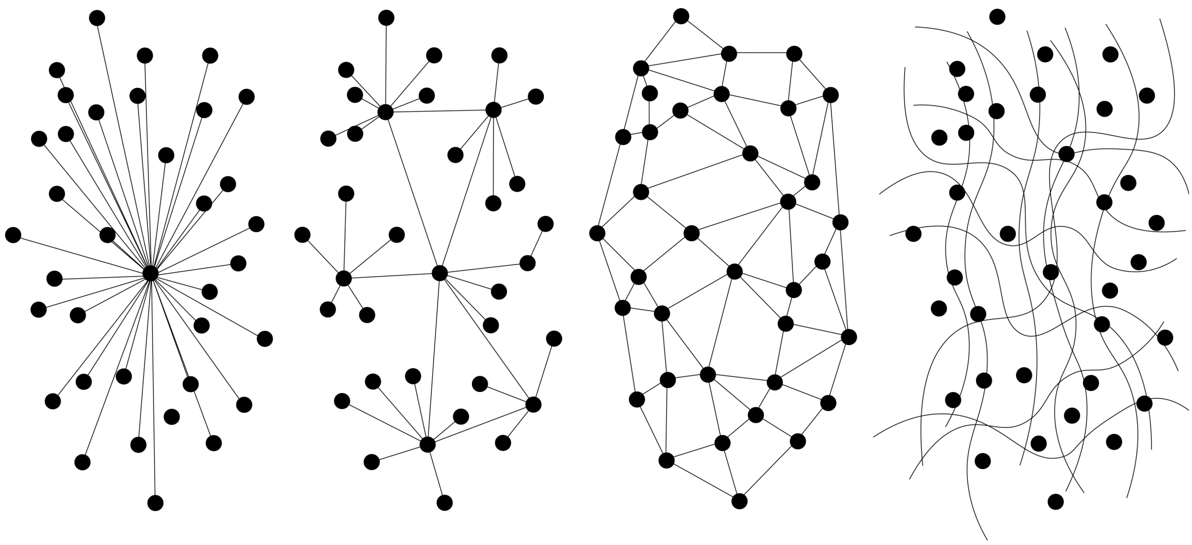


Figure 4.10 – Dispersed nodes in the Hong Kong MTR system. *Source: Adapted from http://www.mtr.com.hk/en/customer/images/services/MTR_routemap_510.jpg*

This solution may not be fully applicable on the transportation system in Gothenburg, but it shows that there are other smart solutions available. The City of Hong Kong is among the densest populated in the world, which provides unparalleled possibilities for efficient mobility solutions. Autonomous transportation systems could question the nodal concept as a free-flowing and flexible network does not necessarily rely on large transportation hubs for interchange. Instead of a polycentric structure, the development plan could aim for a fully distributed network, at least within the densely-populated city centre.



a) Centralized *b) Decentralized/polycentric* *c) Distributed* *e) Free flowing*

Figure 4.11 – Centralized, decentralized, distributed and free flowing networks. *Illustrated by the author.*

4.2.3 Urban consolidation centres

Urban consolidation centres (UCC) are a way to decrease heavy freight traffic in city centres or other densely populated areas. In contrast to the traditional model where heavy trucks are used to deliver goods from suburban depots to sale points, micro consolidation centres can be used for redistribution of goods close to the final destinations and letting light weight electric vehicles, tricycles or other non-polluting transportation modes distribute the goods within reasonable proximity of the UCC. Heavy freight trucks are rarely used to their full capacity and operating a large, half-empty truck in areas where street space is already congested is neither energy nor space efficient. By using the micro-centres as intermodal logistic facilities to consolidate deliveries, this can be avoided.

The model has been tested and approved in several different metropolitan areas around Europe. One study (Browne et al., 2011) was done in London, where the reduction in freight traffic, due to implementation of UCC, and its environmental impact was assessed. The experiment used an UCC in combination with electrically assisted cargo tricycles and electric vans and the results from the study show that the total distance travelled decreased by 20% and the average CO_2-eq. emissions per parcel dropped by 54%. The cost of delivery did not change significantly between the two systems as some components increased the cost while others reduced the overall cost.

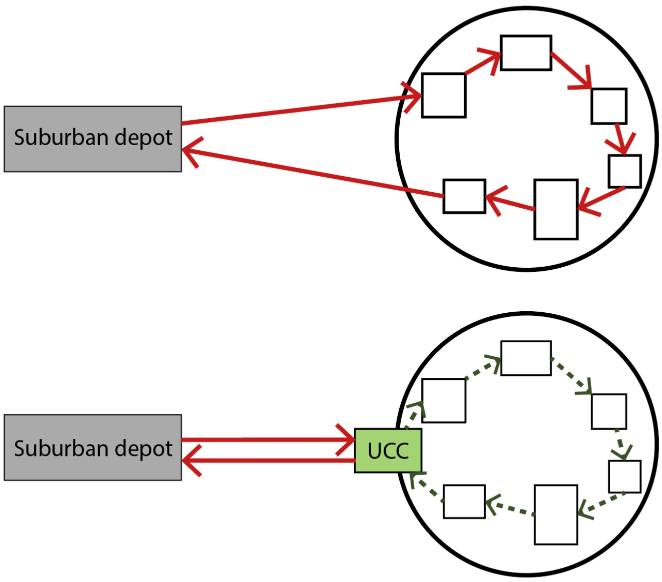


Figure 4.12 – Conceptual illustration of urban consolidation centre. *Illustrated by the author.*

UCCs are an attractive feature to combine with mobility automation as freed up kerbside space due to reduction in parking demand can be used for building strategically located consolidation centres. Furthermore, automation technology can be used to reduce the cost of man hours within the freight delivery system, which is one of the few factors that has a negative effect on the economics of the system.

4.2.4 Superstructures

Infrastructure connects different parts of a city and allows us to move from one place to another. However, it also creates barriers. When looked at in fragments, infrastructure allows movement in one dimension only, creating a barrier in the other two dimensions.

Superblocks is a step towards minimizing the barrier effect of infrastructure and reclaiming the streets. The concept has been introduced in Barcelona with the aim to "return the city streets to the people". Superblocks are zones the size of around 9-12 blocks where traffic is restricted to residents only and speed is limited to pedestrian tempo (Garfield, 2017). The idea is to create pedestrian-friendly, green, clean and safe areas in the city where the citizens' needs are in focus. Within the superblock, speed is limited to 10 km/h and vehicle access is only granted to residents in the area, emergency vehicles and loading/unloading under special circumstances. Street level parking is not permitted within the superblock. One of the strengths inherent to the superblock model is that it can be implemented directly on the existing structure without having to make any physical interventions other than reorganizing the streetscape to accommodate alternative mobility routes.

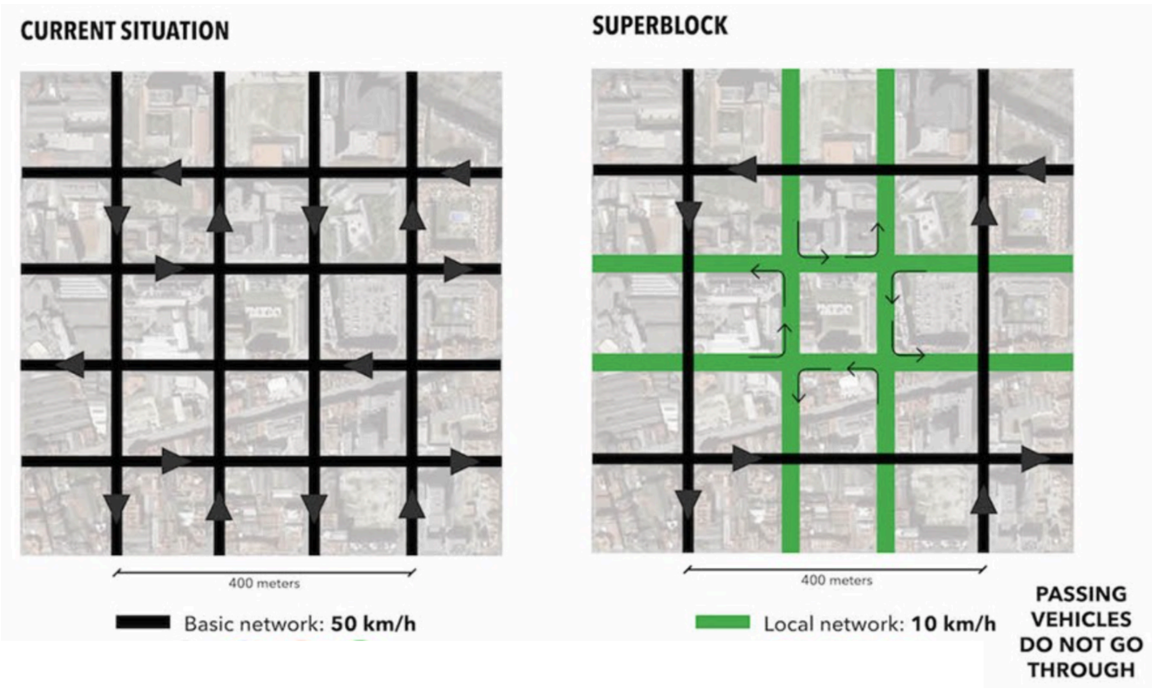


Figure 4.13 – Road hierarchy in a Superblock model. *Source: http://inhabitat.com/how-barcelonas-pedestrian-friendly-superblocks-reduce-pollution-and-return-streets-to-the-people/*

The first step of further implementation in Barcelona was done in September 2016 (O'Sullivan, 2017) and has been met with both praise and pessimism. Confining higher-speed motorized traffic to outer routes creates a safer and more inclusive street scape. It also decreases the overall traffic in the city, with positive consequences for air quality and greenhouse gas emissions.

The expected effects are a decrease of overall traffic by at least 20% as well as freeing up 60% of street space. Space that has been occupied by cars will be redistributed and turned into “citizen spaces” (Bausells, 2016). Another positive outcome is significant decrease of noise pollution. The new mobility concept is planned to be extended on a larger scale across the city by 2018 (O’Sullivan, 2017).

However, the concept of superblocks is not a new feature in Barcelonan city planning. The very first one was created in the Gràcia district back in 1993. A study done by the city’s urban planning team reported that walking and cycling in the area had increased 10% and 30% respectively in 2016, compared to 2007. The overall traffic volume had decreased with 26% and on the internal streets, driving had decreased by 40% for the same time period (Garfield, 2017). Most of the critique against the superblocks in Barcelona consists of complaints that driving from A to B now requires long detours and that external routes get more congested (O’Sullivan, 2017). Accessibility for residents has also been an issue.

In combination with vehicle automation, the benefits of superblocks can be achieved while minimizing the drawbacks. The city can be programmed to prioritize motorized transportation on external routes while the streetscape within the superblocks is dedicated to green infrastructure, soft mobility, social spaces and other functions. Multi-modal sharing of space is possible with AV technology, but modal separation is still necessary for high-speed transportation.

4.3 Disruptive technologies – MLP

Like all technologies, autonomous vehicles are being developed within an existing system of opportunities and limitations, a socio-technical regime. A transition is a change from one socio-technical system to another. To understand transitions, it is important to have a good idea of the structure of the current system. Geels and Schot (2007) have developed a descriptive framework for describing technological diffusion and change in a socio-technical context.

Different transition pathways are described using a multi-level perspective with three levels with increased structuration of activities in local practices; niche-innovations, socio-technical regime and socio-technical landscape. See chapter 3.2 of this report for an introduction to multi-layer perspective theory. Landscape developments, i.e. changes in the exogenous context, can put pressure on the existing regime and thus open opportunities for change. The landscape is generally stable and has an inherent inertia to change, but long-term trends and fluctuations can be observed. The meso-level, the socio-technical regime itself, can be described as dynamically stable and has many different ongoing processes in its multiple dimensions. It is continuously adapted due to influences in form of niche-innovations and landscape pressures. The niche level consists of many small networks of visionary actors that support and develop novelties based on their expectations as well as external influences. Sporadically, dominant designs emerge within a niche where it gains internal momentum and can be injected into the socio-technical regime when a window of opportunity appears, thus creating a new configuration in the socio-technical system (Geels and Schot, 2007).

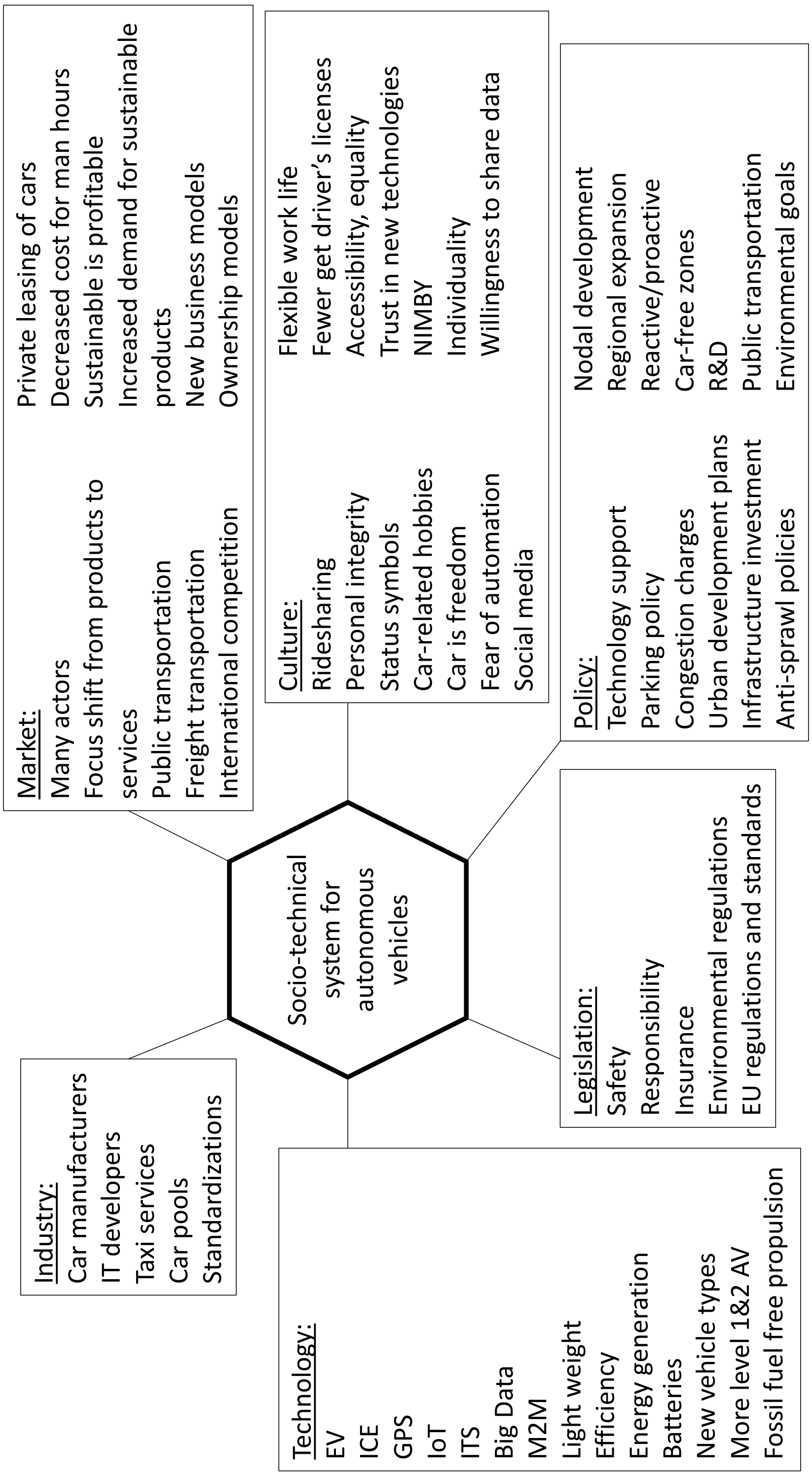


Figure 4.18 – Socio-technical system for vehicle automation.

Vehicle automation has been step-wise developed by different actors in a few different niches for the past few decades. Landscape pressures to transition to a more sustainable transportation system can create a window of opportunity for autonomous vehicles to be a part of the new paradigm.

A leverage point is somewhere in a complex system where a small change in one thing can result in a large shift of the whole system. In "Leverage points: Paces to intervene in a system" (Meadows, 1999), Meadows argues that a system's goals, structures, rules, behaviours and parameters arise from paradigm and that system wide changes can be instigated by concentrating measures on leverage points.

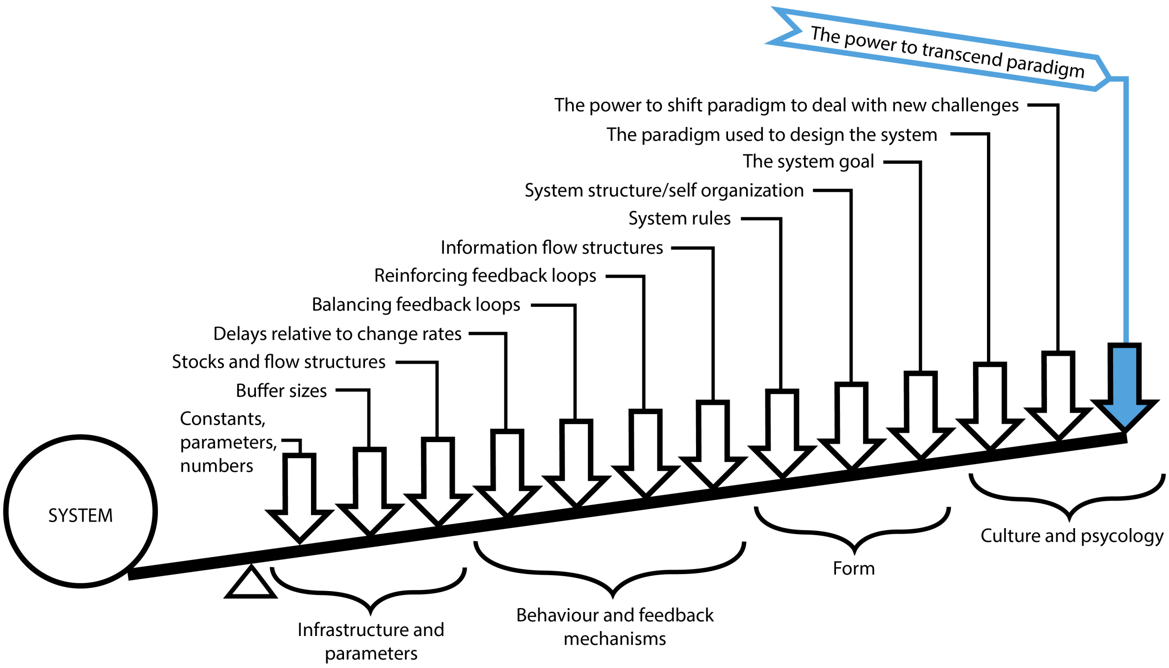


Figure 4.19 – 12 points to intervene in a system. *Source: Adapted from "Leverage Points, places to intervene in a system" by Donella Meadows.*

Changing norms and behaviour, instead of relying on end-of-pipe solutions, is a much more powerful way to intervene in a system. Technology and human behaviour has a two-way relationship in which we shape technology, but technology also has the power to shape human life, sometimes in unexpected and unprecedented ways. A disruptive technology can have fundamental impacts on culture and social norms. If a technology is powerful enough to change the culture and psychology of the system, it can catalyse a paradigmatic transition. The leverage point theory can be applied on the current mobility regime and its socio-technical system. The system can be changed by making adjustments to the infrastructure and physical parameters. Stocks and flows, i.e. fleet sizes and traffic work, can change the scale and dimensions of the system, but not the system itself. System behaviour can also be affected by implementing policy instruments such as congestion charges, subsidised public transportation, fuel taxes or emission standards. However, for the mobility revolution necessary for a sustainable society in the stricter sense, the very paradigm that our system arises from must be reshaped. From a macro-level perspective, the transportation system is a leverage point to induce change in the entire urban system. The possibility to have mobility solutions as a leverage point for societal change and a transition towards sustainability is both enticing and realistic.

For a more tangible approach to systematic change, the prevailing solutions can be regarded as a result of public policy and consumer choice (MIT, 2017). Vehicles, technology, new modalities, fuels and infrastructure is continuously shaped and reshaped by an indefinite number of decisions made by consumers and policy makers.

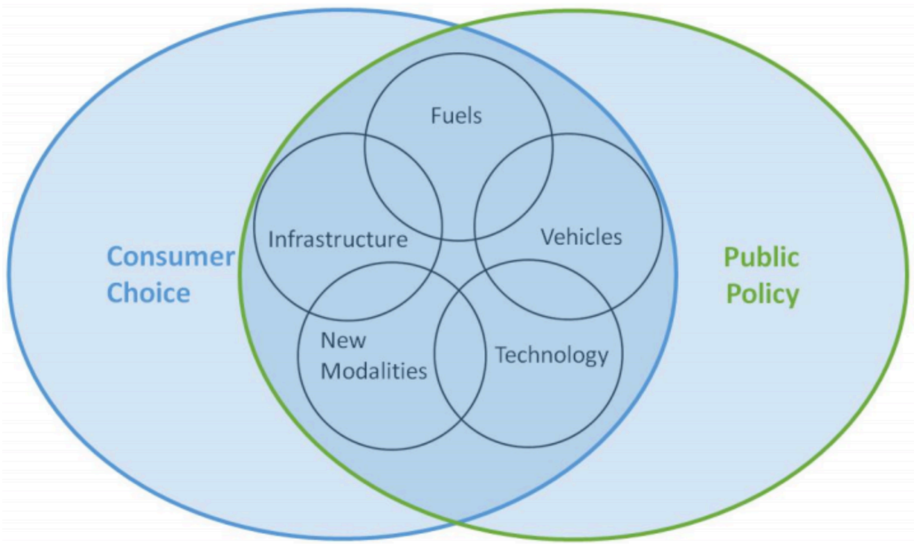


Figure 4.20 – Mobility of the future. *Source: MIT Energy Initiative, examining future changes in the transportation sector. http://energy.mit.edu/research/mobility-future-study/*

4.4 Autonomous vehicles

The autonomous vehicle represents the biggest technological leap for personal mobility and freight transportation since the invention of the car itself. AV adoption has the potential to bring about a technological paradigm shift with implications that will permeate through the many layers of society. All aspects of the current socio-technical regime will be influenced and the very landscape of urbanism will change. Autonomous transportation technology has emerged stepwise as a combination of different technologies. The task of driving has gradually been transferred from the human driver to a computer, from only assisting in specific situations, to full automation. Driver assistance systems, such as adaptive cruise control and lane keeping support, may require the driver to take over at any time, meaning the driver must stay constantly focused and monitor the situation. Automated driving on the other hand, will enable the driver to become a passive passenger without any responsibilities. Such a vehicle would not even need a steering wheel or seats viewing the road. The former driver is free to focus entirely on other tasks such as being productive, consuming media or communicating. The fully automated vehicle not only allows passengers to ride along without intervention, but can also relocate itself when empty of passengers. This presents many possibilities, one being that kerb-side parking spaces and parking on valuable land is rendered obsolete.

Some of the major opportunities for self-driving vehicles are presented by the possibility of a new system for car-sharing. Blurring the lines between private car ownership and public transportation, SAVs (shared autonomous vehicles) resemble a taxi service, with the distinction that there is no driver and the car may stop to pick up or drop of other people along the way. In the scenario, an app can be used to summon an AV that would arrive to pick you up within minutes. By entering a destination and number of passengers, a smart system could optimize the route and vehicle type to deliver you directly to your destination. With such a system, the need for privately owned cars would be minimal in urban areas, leading to a substantial decrease in number of vehicles. Different types of services could be provided for transportation of larger items, longer distance travel, urgent trips etc. Research shows that 10% of today's fleet would be sufficient to provide the same level of mobility. Additionally, there would be no need for on-street parking and only 20% the amount of off-street parking would be required (OECD, 2015).

A "smart" city can imply many things, for example a vision of high technology information systems, such as the Internet of Things (IoT) and Big Data, integrated in a city's many dimensions to enable a secure and efficient management of its assets. A city's assets include elements such as energy generation and storage, waste management, health care, law enforcement, education, transportation systems and many more. Digitalization can be a solution to many of the contemporary urban challenges. Autonomous transportation is in many ways dependent on large streams of Big Data to ensure the system maximum efficiency and convenience.

A SAV system could be modelled to complement a public transportation system and provide an affordable and more sustainable solution to the *last-mile problem* as well as connecting areas in the city that suffer from unreasonably inconvenient pathways of public transit using the current transportation network. The potential benefits of autonomous vehicles are many and include both social, economic and environmental effects, but there are also threats. The extent of many of these effects is directly dependent on what type of ownership model or shared mobility system becomes dominant. The potential scenarios range from clean and space-efficient transportation to increased congestion and more traffic due to private AVs driving around empty.

Vehicle to vehicle and vehicle to infrastructure communication enables AVs to minimize reaction delays and the traffic will thus flow more smoothly. AVs can follow very closely behind each other, optimizing the use of road space and increasing the roads overall capacity, which leads to decreased risk for congestion. Human driver behaviour in congested situations is typically characterized by a sharp stop-and-go effect, where vehicles accelerate and decelerate erratically due to fluctuation in the traffic flow. This is very disadvantageous for fuel consumption and emissions. AVs can be programmed to run at the engine's sweet spot for a large portion of the trip and traffic can flow at a constant speed with very few interruptions and thus substantially reduce congestion during heavy traffic (Barth et al., 2014). Accidents is another common cause for congestion that could eventually be eliminated as even more advanced automation technologies are developed. AVs have a clear advantage over conventional cars when it comes to fuel consumption as they continuously use the most efficient driving and routing. The energy performance can also benefit from platooning, i.e. a reduction in aerodynamic drag forces due to vehicles following very closely behind each other. The ability of vehicles to communicate with each other in real time makes it possible for AVs to drive very close to each other without risking collision. Platooning has mostly been focused on trucks and heavy vehicles as the effect of drag forces is generally larger there, but substantial energy gains can also be achieved for smaller vehicles. Research shows that 10-15% energy savings can be achieved by keeping a constant distance of 4 m between vehicles (Browand et al., 2004). A potential decrease in number of vehicles due to increased sharing is another strong argument for AVs capability to reduce traffic congestion.

Cars are built to withstand impacts and extreme crash forces to protect its passengers. A safer construction generally means heavier and larger and it needs more materials to be built as well as more fuel to be propelled forward. Soft mobility is often used to referrer to non-motorized transportation, such as walking and biking in the planning of cities. With AVs, the concept of soft mobility could potentially be expanded to include motorized vehicles. This provides a possibility to decrease the embodied energy of the transportation fleet as fewer vehicles are needed and a much lighter construction can be used as the risk for crashing borders to non-existent. Which would result in a much smaller use of materials and energy to produce and sustain a fleet.

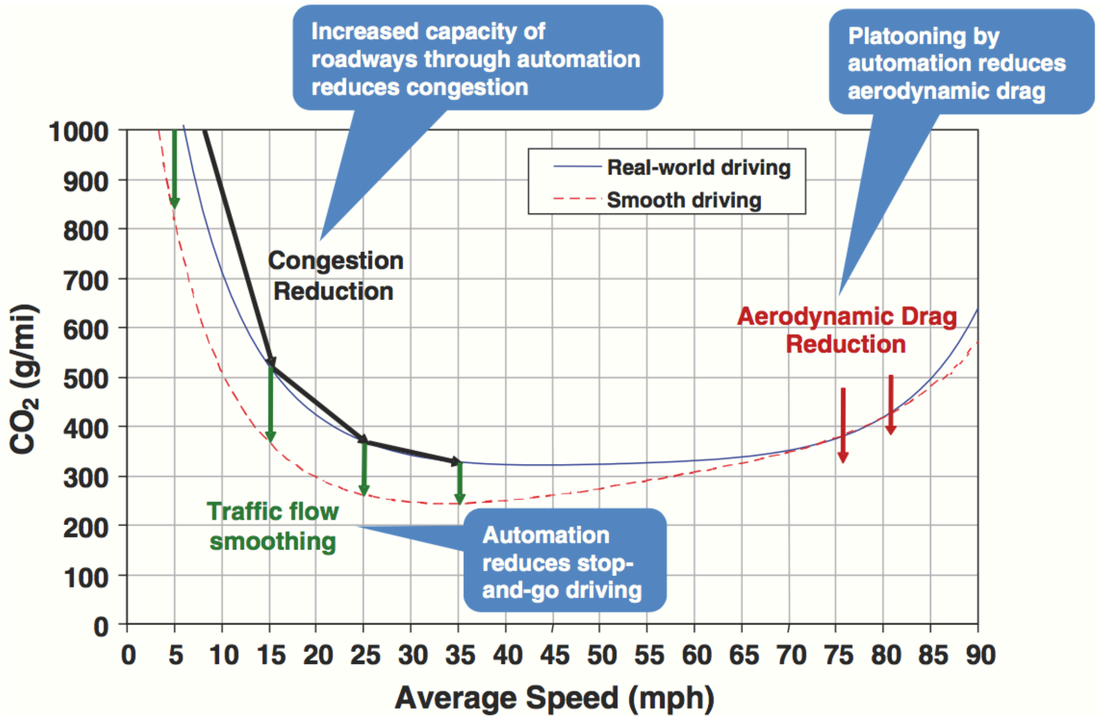


Figure 4.14 – Real world carbon dioxide impacts of traffic congestion. *Source: (Barth et al., 2014), http://umtri.umich.edu/content/2014.EnergyWS.Barth.pdf*

The technology of autonomous vehicles presents many opportunities for improved land use efficiency in urban areas. One aspect is a significant decrease in parking. Today, cars are parked for 95% of the time (Barter, 2013). An SAV system could provide a much more efficient use of vehicles and parking would be reduced to loading and overnight storage. Parking could be secluded to less attractive areas where vehicles could be packed closely together as no one would have to get in or out from the car where it is parked. Autonomous parking would also allow vehicles to navigate into a tight spot without needing a lot of space for manoeuvring or risk scratching.

Different studies show different potentials in reduced space for parking as the modelling depends on different assumptions, but the following points are widely agreed upon (KTH ITRL, 2017)(Arbib and Seba, 2017)(OECD, 2015)(Trafikkontoret, 2012);

- Reduced number of vehicles
- Smaller distance between vehicles in movement
- No need for street-side parking
- Reduced need for off-street parking

A more in-depth discussion about these effects can be found in chapter 5 of this report.

The potential of autonomous vehicles to contribute to a more close-knit city structure is high as it means transport-related infrastructure will take much up much less space in the city. However, there is also a risk that AVs will increase urban sprawl as travelling longer distances is faster and more convenient. As commuting becomes more attractive, regional expansion increases.

Figure 4.15 – Google self-driving vehicle. *Source: https://fortunedotcom.files.wordpress.com/2016/06/dri07_d.jpg*

Figure 4.16 – Autonomous last-mile delivery vehicle. *Source: https://www.disruptordaily.com/nuros -friendly-looking-autonomous-delivery-van-garners-92-million-series-funding/*

Figure 4.17 – Uber self-driving car. *Source: https://qzprod.files.wordpress.com/2016/09/uber-self-driving-car.jpeg*

Figure 4.18 – Autonomous mini bus. *Source:https://f.nordiskemedier.dk/24qy38mz5kylvgdb.jpg*

4.4.1 Levels of automation

In the automobile industry and research community, five definition levels are used to refer to the level of automation of a vehicle. In this report, the abbreviation AV is used to indicated level five autonomous vehicles. Level 1 and 2 automation has been around for a long time in form of cruise control options and other assisting features while level 5 has been developed recently. The levels are presented in more detail in the following table.

Table 4.2 – SAE levels of automation. *Source: Copyright SAE International and J3061, 2014. https://www.sae.org/misc/pdfs/automated_driving.pdf*

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

4.4.2 Criticisms of autonomous cars

The hopes for mobility automation and all the potential benefits it brings are high, but there are also critical voices in the debate. One aspect is safety. Are autonomous vehicles as safe as they claim to be? Insurance policies and legislation must be updated in response to the technological development. This raises ethical issues such as who is responsible if someone is hit by an AV or how should AVs be programmed to respond in situations where an accident is inevitable but a choice can be made. For example, must AVs be programmed to choose between hitting a child or running into a bus? Should the AV prioritize the safety of the passenger, i.e. the paying customer, or that of pedestrians? Autonomous vehicles create a unique situation in which the value of life has to weighted and translated into algorithms.

The Swedish Data Inspection Authority recently expressed its doubts regarding new legislations concerning vehicle automation. AV technology gathers huge amount of data to navigate and communicate with other vehicles, users and infrastructure elements. The recording of sound and collection of visual material is very sensitive and must be handled in a way that does not threaten the personal integrity of users or anyone else (Datainspektionen, 2016). It must be legally specified exactly what kind of data can be stored and who gets access to it. The selling of personal data for marketing or other commercial purposes should be prohibited. Job losses is another issue that has been raised in the AV debate. Many jobs within the transportation sector will become obsolete when drivers are no longer needed.

Most of the critique is based on technicalities that can be solved, at least hypothetically. However, there is one aspect that is inherent to the technology itself and that seems to be a major source of distress among critics, namely; taking away the joy of driving. The former Volvo CEO P G Gyllenhammar said in an interview that (translated from Swedish by the author, Ahlström, 2017);

> *"The joy of driving disappears. The sadness about it is that the car becomes a necessity, which it is not always today, it can also be a bit joyful." – P G Gyllenhammar.*

Furthermore, AV operation in shared city spaces is technically challenging and there are some issues that need to be addressed. In areas with a lot of pedestrians, AVs risk getting stuck in as they are programmed to stop whenever a person is approaching. While AV technology in theory has the potential to be 100% safe, it is hard to translate these ambitions into reality. Proving the safety of an autonomous vehicle is challenging (VA, 2016).

4.4.3 Electrification

Electrification of the transportation network is often seen as a solution to emissions of greenhouse gases, nitrous oxides and particle matter in cities. This may be true from a local perspective, but from a holistic view, it is not that simple. Fossil fuels are refined in a process that produces different fractions of oil products. The different products are separated through a distillation process in which crude oil is heated to different degrees, separating more volatile compounds first. Products include, in order or boiling point; sulphur, LPG and butanes, naphtha, kerosene and jet fuel, diesel oil, gas oil, petroleum coke and asphalt (Australian Institute of Petroleum, 2015). Gasoline is blended from different fractions but the key thing here is that jet fuel, diesel and gasoline are produced in the same process, making it impossible to produce one without getting the others. If the trends for air travel don't change dramatically or find another fuel for propelling aircrafts, gasoline will be produced and used for other purposes, thus causing the same level of CO_2-emissions as before, only emitted elsewhere (DI, 2017). To reach peak oil sooner rather than later, the demands for all types of fossil fuels must decrease. Large amounts of diesel and gasoline will not be left non-combusted as by-products to jet fuel. For economic reasons, if there is a production of gasoline there will also be combustion.

The city of Gothenburg has the goal to have an annual production of 500 GWh renewable electricity in 2030 (Miljö- och klimatnämnden, 2013). Assuming one full charge per 24 hours and a battery capacity of 30 kWh, that would be enough to sustain 45,600 vehicles. However, this estimation also assumes that the cars are used more efficiently than today as a full charge is rarely used up in one day. The average car in Sweden in 2017 only runs around 14 150 km/year (Trafikanalys, 2017). With an energy consumption of 10-15 kWh/ 100 km, which is normal for an electric vehicle with the current technology, the 500 GWh would be enough to support over 200 000 vehicles.

4.5 Local context

The impacts of vehicle automation depend on the local context. Different cities have different potentials to incorporate autonomous vehicles in the urban structure and make it a natural part of the city's transportation system. Chapter 4.4 of this explores macro-structural characteristics in Gothenburg that may influence the way that AV should be integrated in the city to ensure the most advantageous outcome.

On a regional scale, Gothenburg is the central hub for western Sweden with surrounding towns. Gothenburg also has a central location in Scandinavia, connecting Stockholm, Copenhagen and Oslo. Intercity highways and railways have the characteristics of regional superstructures. Regional expansion is a central part of Gothenburg's development plan and the city plays a key role for the job market in the whole of western Sweden.

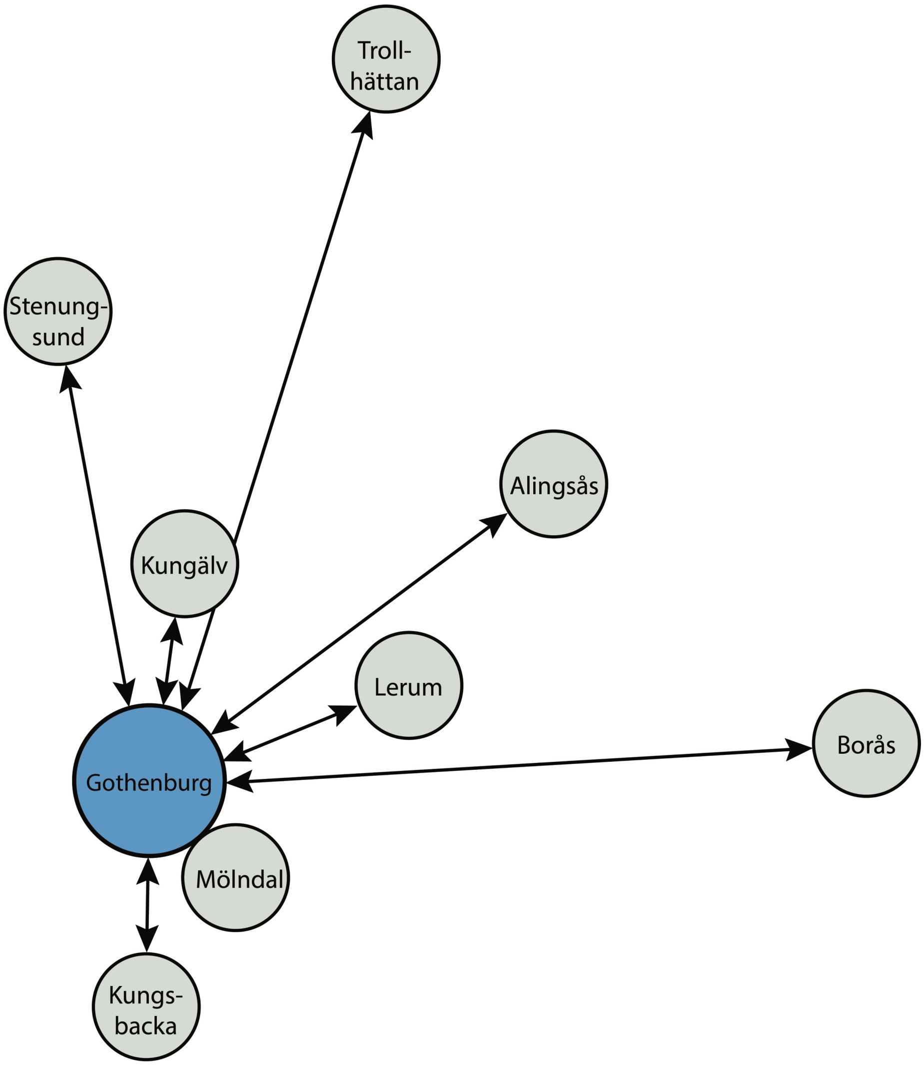


Figure 4.21 – Regional structure of Gothenburg. *Illustrated by the author.*

Cities are physically composed of three fundamental elements; buildings, streets and spaced in-between. Space can be private, semi-private, semi-public or public, but there are also areas that are difficult to define, with unclear purposes and functions (Stadsbyggnadskontoret Göteborgs Stad, 2008). Private space is intended for the use of one household. Semi-private space can be used by two or more households, for example a shared yard, while semi-public spaces are in theory open to all but located within a block and is generally meant for residents in the area. Public space is open and accessible to all. Some examples of public spaces are parks, streets, squares and playgrounds (Stadsbyggnadskontoret Göteborgs Stad, 2008).

There are currently over 180 000 private cars in Gothenburg and 226 000 parking spaces, not including privately owned parking. Without taking into consideration the areas needed to access each parking spot, this corresponds to around 2 900 000 m^2, or the equivalent of just over 400 soccer fields. A more detailed analysis of some of the different types of city structures present in Gothenburg is done in chapter 6.4 of this report.

There are often multiple layers of transportation networks in a city. Ground level corridors are complemented by elevated roads, railways or underground systems. In Gothenburg, transportation is very much concentrated on ground level where trams, buses and cars operate in shared and sometimes separated spaces. New infrastructure development is costly and the environmental impact is rarely compensated through higher efficiency or change of transportation mode. Although AV could also be run on other network types, autonomous vehicles can easily be implemented and run on the existing transportation infrastructure in Gothenburg and enable a more efficient use of existing structures.

Figure 4.22 – Network for road transportation in Gothenburg. *Illustrated by the author.*

The Gothenburg city structure is intentionally developed around nodes with high concentration of buildings and services and good access to different transportation modes. The development program currently in force highlights a number of new areas as potential future nodes for transportation and commerce. Figure 4.23 shows existing and potential nodes within the city of Gothenburg with a decentralized network.

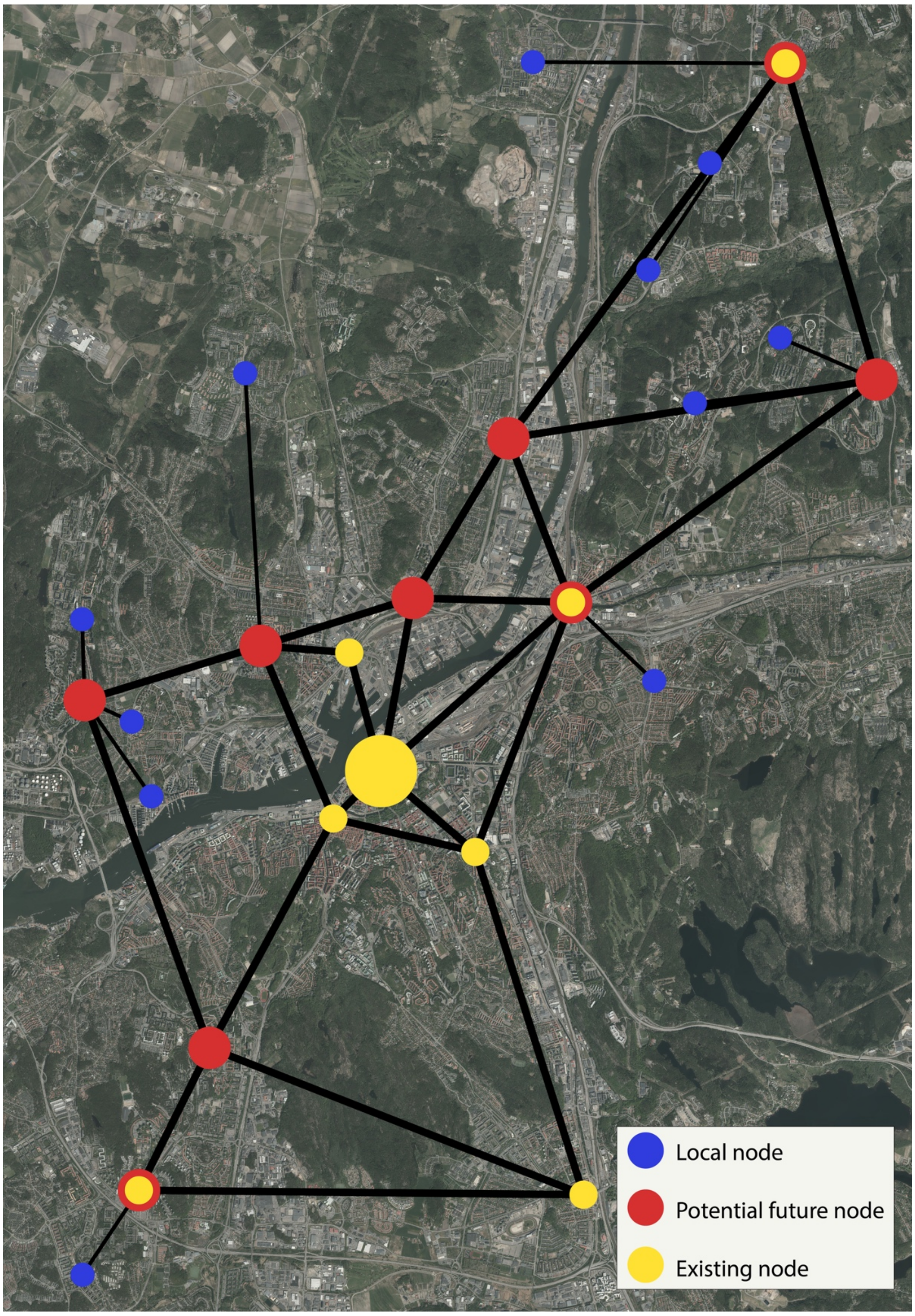


Figure 4.23 – Conceptual model of nodal structure for road transportation in Gothenburg. *Existing, potential and local nodes in a polycentric network, according to Traffic Strategy for a Close-Knit City, City of Gothenburg 2014, illustrated by the author.*

5 Future Scenarios – review of current research

During the last year, Swedish newspapers and magazines have been scattered with articles debating and monitoring the development of self-driving cars and what this can possibly mean for the close future. The discourse generally has a positive attitude characterized by excitement and high hopes for what is referred to as a the most revolutionary development in transportation technology since the dawn of the car itself. As the established automobile capital of Sweden, Gothenburg is at the cutting edge when it comes to testing and integrating autonomous vehicles in the city. There are high and well-formulated ambitions from both politics and industry and they are reflected in media where parking norms and development strategies are being debated enthusiastically by experts and politicians.

Section 5.1 to 5.4 of this report introduces and discusses environmental, social, economic, spatial and operational aspects of different studies and scenario analyses that have been done on the impacts of vehicle automation on urban mobility in the future. The studies have been conducted by a range of different institutions such as universities, planning authorities or think tanks and have been elected through a systematic but subjective process with the aim to highlight interesting aspects of current state-of-the-art research rather than providing a comprehensive representation of the academic landscape.

5.1 ITRL project

The Integrated Transportation Research Lab (ITRL) held a seminar at KTH on March 9th 2017, where a study on future mobility in Sweden was presented and discussed. All information in chapter 5.1 of this report is based on the author's own observations from the seminar and personal reflections thereof. ITRL has, in collaboration with Cairo Futures developed four future scenarios for where self-driving vehicles may take us, in this report henceforth referred to as ITRL1, ITRL2, ITRL3 and ITRL4.

The scenarios are based on two strategic uncertainties and a number of developments that were considered certain enough by the expert panel and to be included in all scenarios. The material was collected in a workshop setting, with discussions with 40 experts from different institutions in academia and industry. After each of the three workshops, an analysis team compiled the material to base the next workshop on. The group listed several, according to the expert panel, certain developments and then singled out two strategic uncertainties. The time frame of the project was set to 2030 and the geographic boundary to Sweden (KTH ITRL, 2017).

According to the expert panel, ITS (intelligent transportation systems) will be developed and used throughout society within the next ten years. Everything will be 100% connected, social media will have a large influence on society and work life will be more flexible and boundless compared to the situation today. Urbanization is a prevailing trend, as is regional expansion, that will be amplified due to increased connectivity, specialized recruitment, urban escapism and concentration of economic forces. Urbanization will bring a more competitive situation for street and city room and higher land prices that will trigger a more efficient use of valuable urban land, especially central areas. Another trend is that young people in cities tend to get their driver's licences later and later or not at all. Older people also keep their licences longer. This shift in the average driver can have consequences for demand and requirements concerning safety, accessibility and ease of orientation in different traffic situations. The panel also concludes that the trust in new technologies is generally high and that people in cities tend to be fast adopters (KTH ITRL, 2017).

Within the next decade or so, the market situation will shift its focus from product oriented consumption to services and solutions, as time becomes an increasingly scarce resource and sustainability targets are augmented. The landscape of services may be intermittently messy, with many new actors and business models, among which sustainability as a prerequisite for profitability plays an important part. Mobility as a service will emerge from new technologies and business models and may either compete or merge with public transportation, depending on political decisions and policies for implementation. There is a clear political and corporative ambition for Sweden to be a testbed for alternative mobility solutions as the international landscape gets more and more competitive and countries don't want to be left behind.

Other external trends that have been observed are increased fossil free propulsion, electrification of the transportation sector, more frequent and pertinent effects of EU standardization and regulations and a wider range of new vehicle types, including light-weight EVs and different levels and versions of AV such as pods of different sizes. Automation is believed to decrease the cost for man hours within the transportation sector, for passengers as well as freight. Furthermore, it will make feeder buses as a compliment to public transportation a realistic and feasible solution of the last-mile-problem which will boost the attractiveness of public transportation and increase accessibility for underserved groups.

Other than the above listed trends, two strategic uncertainties were singled out as significant for what consequences these future developments may bring to an urban area in Sweden;

1) Proactive or reactive urban planning and policy making

2) A breakthrough in sharing economy

Combining the extremes of the two strategic uncertainties creates the basis for the four different scenarios that were described in the study. The scenarios were named in accordance with their respective characteristics as displayed in the following diagram.

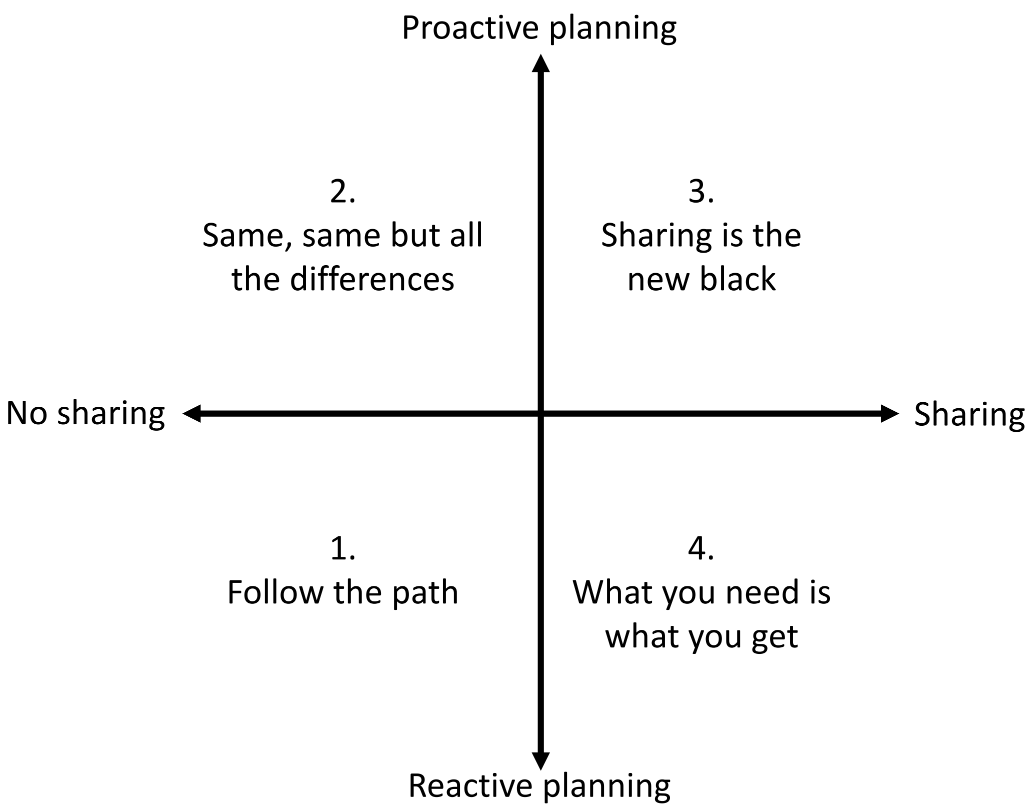


Figure 5.1 – ITRL strategic uncertainties and resulting scenarios. *Source: The author's observations at the ITRL seminar at KTH on 9 March 2017.*

5.1.1 Scenario ITRL 1 – Follow the path

The first scenario is called *Follow the path* and is characterized by a future where sharing economy has had no or little breakthrough and planners and policy makers have a reactive approach to new technologies. The privately-owned car is the normative mobility solution, but the technology is more advanced and automated driving can be activated on demand. However, a lack of clear political ambitions and guidelines has created an uncertain situation, which has slowed down the development of fossil free alternatives. The development is market driven and there are as many different solutions as there are actors. Alternative fuels are still being explored and tested. There is a resistance among the population for sharing personal and big data and the little sharing that occurs is done with caution to protect private integrity and avoid cyber-attacks. High-tech solutions have made life slightly cooler and more convenient, but overall, society is not that different form today. Ubiquitous and equal mobility is yet to be developed and some residential areas are more beneficial to live in from a mobility perspective than others. Polarization and segregation remains a tangible problem.

5.1.2 Scenario ITRL 2 – Same, same but all the differences

In the second scenario, *Same, same but all the differences*, sharing economy is not commonly practiced, but policy makers and planners have been proactive in adapting society to technological paradigm shifts, including the mobility sector. Electrification is the chosen driveline for transportation and has prevailed over other alternative fuels. This means industry and research has been concentrated on improving battery performance and constructing more efficient EV. Strong regulative policies have become more accepted and there are congestion charges and large car-free zones in cities. Parking availability has been limited to a minimum as a means to promote public transportation. Consumption patterns are similar to today, but it is easier for consumers to make more sustainable choices. There is a resistance against sharing of personal and big data. The market for light-weight, private electric vehicles is flourishing, as it is a cheap and convenient way to move around. Even though the system on a whole is not vastly different from what we have today, automation is making travelling more convenient, cheaper and efficient. Mobility has become more equal as automation has increased accessibility to previously underserved groups. Public transportation is well developed, but is still competing with privately owned vehicles for different target groups.

5.1.3 Scenario ITRL 3 – Sharing is the new black

In the third scenario, *Sharing is the new black*, proactive policy making in combination with a breakthrough of shared economy, has shaped a new urbanity. Public transportation is equal and available for everyone. Designated commercial actors are well integrated with the public system. Citizens trust the government and other institutions with their data, which makes the system more efficient. Although, it comes with the price that "big brother sees you". A sharing culture and high-tech solutions have transformed society. The lines between public and private transportation are blurred, and mobility is sold as a service from private and public actors. New transportation modes have been developed such as smaller pods for 2-4 persons and larger pods, 10-15 persons. These modes function as feeder systems for mass transit, efficiently solving the last-mile-problem and cutting the need for private means of transportation.

5.1.4 Scenario ITRL 4 – What you need is what you get

The fourth scenario assumes a breakthrough in sharing economy, but policy making and planning remains reactive. The result is *What you need is what you get*, a rather messy situation with countless of actors competing on the market. Sharing data is a little scary, but it is accepted anyway since the benefits are so desirable. Vehicle automation has come a long way, but a lack of infrastructure support makes it difficult to reap all the benefits. There is little need for private car ownership as services are connected and mobility is integrated in the overall experience, i.e. "a free ride to the mall". Autonomous vehicles have permeated the system and is a natural part of life. Sharing is done as it is a cheaper option for the consumers. Medium sized AVs are a common means of transportation, creating a flexible and close-knit mobility grid in densely populated areas. Large corporations have a lot of power in this scenario and the services are concentrated where the purchasing power is strong. This has augmented the gaps in society and rural areas are often left behind (KTH ITRL, 2017).

5.1.5 Comment on ITRL scenarios

The total size the fleet and the vehicle kilometre travelled (VKT) also differs between the scenarios. As does the degree of technological penetration, i.e. the ratio between AVs and non-AVs. Sharing increases the market breakthrough of AVs. The total vehicle fleet required to deliver mobility solutions is also lower in the scenarios that include a high level of sharing. The total vehicle kilometre travelled (VKT) is also lower when sharing is present in the transportation model. Sharing also results in more miles per vehicle which means a faster turn over time for the more efficient vehicles in use. *Follow the path* is the scenario that has the smallest impact on mobility consumption trends and has a larger fleet and higher VKT compared to the other scenarios (KTH ITRL, 2017).

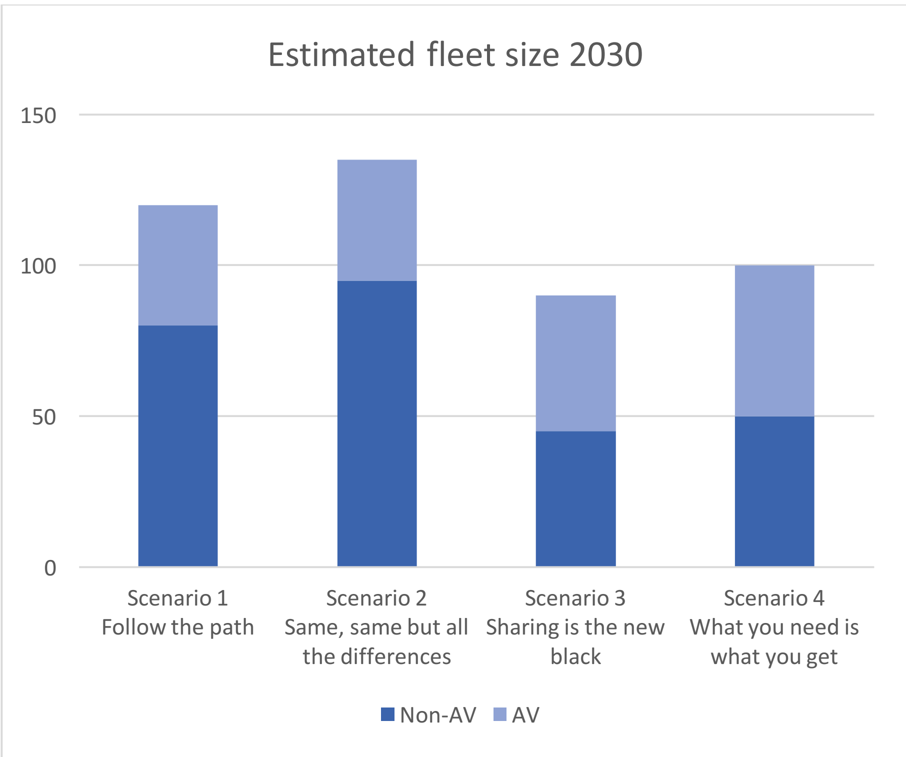


Figure 5.2 – Estimated fleet size. *Source: The author's observations at the ITRL seminar at KTH on 9 March 2017.*

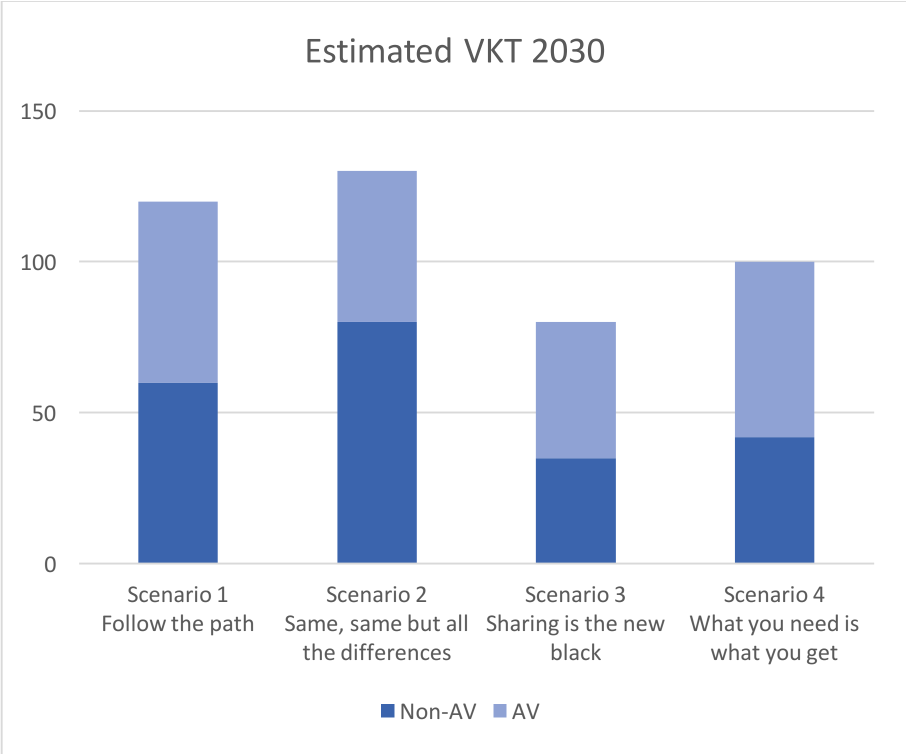


Figure 5.3 – Estimated VKT. *Source: The author's observations at the ITRL seminar at KTH on 9 March 2017.*

The four scenarios have different inherent qualities in terms of sustainability. As the author of this report, it is my personal reflection that proactive planning and a high degree of sharing, constitute conditions that enhance the ability of individuals to make more sustainable choices in their everyday life. Proactive planning and sharing economy, as opposed to reactive planning and private economy, can be considered desirable components in developing a sustainable society.

Proactive planning is difficult if there are uncertainties about the technological trajectories. Infrastructure developments demand a long-term perspective and certainties regarding the transportation system. If electric vehicles are the future, infrastructure must be built accordingly with charging stations and standardizations that make travelling longer distances possible. If on the other hand fuel cells or biogas turn out to be the winning design, an entirely different system is required. These kinds of developments and adaptations are large scale and very expensive. Therefore, monetary, energy and material investments are avoided as long as there are uncertainties regarding their future value. The incorporated value in all current transportation-related infrastructure is huge, thus creating an inherent inertia to change. It is easier for decision makers to continue building on the same system, as the economic benefits are more certain within a well-known system. For proactive planning to be possible, we must rely on the competence of current research to predict the best options for the future and shape the projects of today to satisfy the needs of tomorrow.

Proactive planning and policy making can accelerate the technological development as resources and knowledge is focused. Balancing technological variety and excellence is a difficult task. It is also a political and democratic issue; should politics actively dictate winners and losers in the development of new technologies by creating policies that support what is believed to be the best choice for the commons or should the invisible hand of market forces pick the dominant solutions? Perhaps the results will eventually be the same, but the resource intensity, time perspective and transition pathway might be different. The four ITRL scenarios suggest that it is easier to reap the benefits of vehicle automation if the planning is proactive. This means actively shaping infrastructure, policies and legislation to support a diffusion of AVs and can be done through infrastructure investments, parking policies, R&D grants, monetary policy instruments and information campaigns inter alia. These decisions are becoming increasingly important in a time where actions to mitigate climate change can no longer be delayed.

An important question to consider when discussing the future of mobility is which will be the dominant drive line. Electrification of the transportation sector is one possible outcome, but some argue that this will only be an intermediate step towards something completely different (KTH ITRL, 2017). Self-driving vehicles do not implicate electric engines but naturally, the high-tech navigation system benefits from electrification as the major technical components of a car go from mechanical to electric. Efficiency is one of the key elements of a sustainable transportation system both in terms of efficient vehicles but also usage and logistics. However, these conditions might change in the future if renewable energy is produced in abundance. Perhaps then, material resources will be what is setting the boundaries for feasibility and sustainability.

Reality is multi-dimensional and most likely the future will be a combination of these scenarios. However, the scenarios are important to keep in mind when actively and democratically shaping the future that we want. Different stakeholders will favour different scenarios as the demand and market situation varies and there are different winners and losers in all scenarios.

5.2 Gothenburg's traffic situation 2050

In 2012, as part of the process of creating a new traffic strategy for Gothenburg, the local Traffic Planning Authority made a scenario analysis of the traffic situation in 2050. The purpose was to use scenario planning as a discussion platform and support the process of creating the new traffic strategy. The subsequent report (Trafikkontoret, 2012) displays four different future scenarios for dominant transportation modes and societal megatrends towards 2050. The scenarios are derived from a range of assumed or observed external trends combined with two strategic uncertainties;

1) Economic growth

2) Breakthrough of alternative mobility options

Similar to the ITRL study, the Traffic Planning Authority has acknowledged certain tangible megatrends in their report, i.e. tendencies that were used as a common foundation in the shaping of the different scenarios. They establish the fact that travelling within as well as across borders to the Gothenburg region continues to increase. The region will continue to expand and regional cities will be interconnected nodes in the unceasing urbanization. Other aspects taken into consideration are trends such as increased individualization and increased economic disparity throughout society. They also note an alteration in the economic dependency ratio, where fewer people are believed to work and support more fellow citizens in the future. Although the power of monetary capital is persistently dominant, there is an ongoing socio-technical paradigm shift from an industrial and consumption driven economy to a service and knowledge-based corporative culture. New financing and business models for public investment are emerging within this new culture. Furthermore, the report acknowledges that we no longer have a choice than to accept that climate change and other environmental challenges will dictate the conditions for growth and development in the future. This includes a limited availability of energy, material resources and water. The subsequent scenarios are characterized by difference in economic growth and the level of adoption of alternative transportation modes in accordance with figure 5.4.

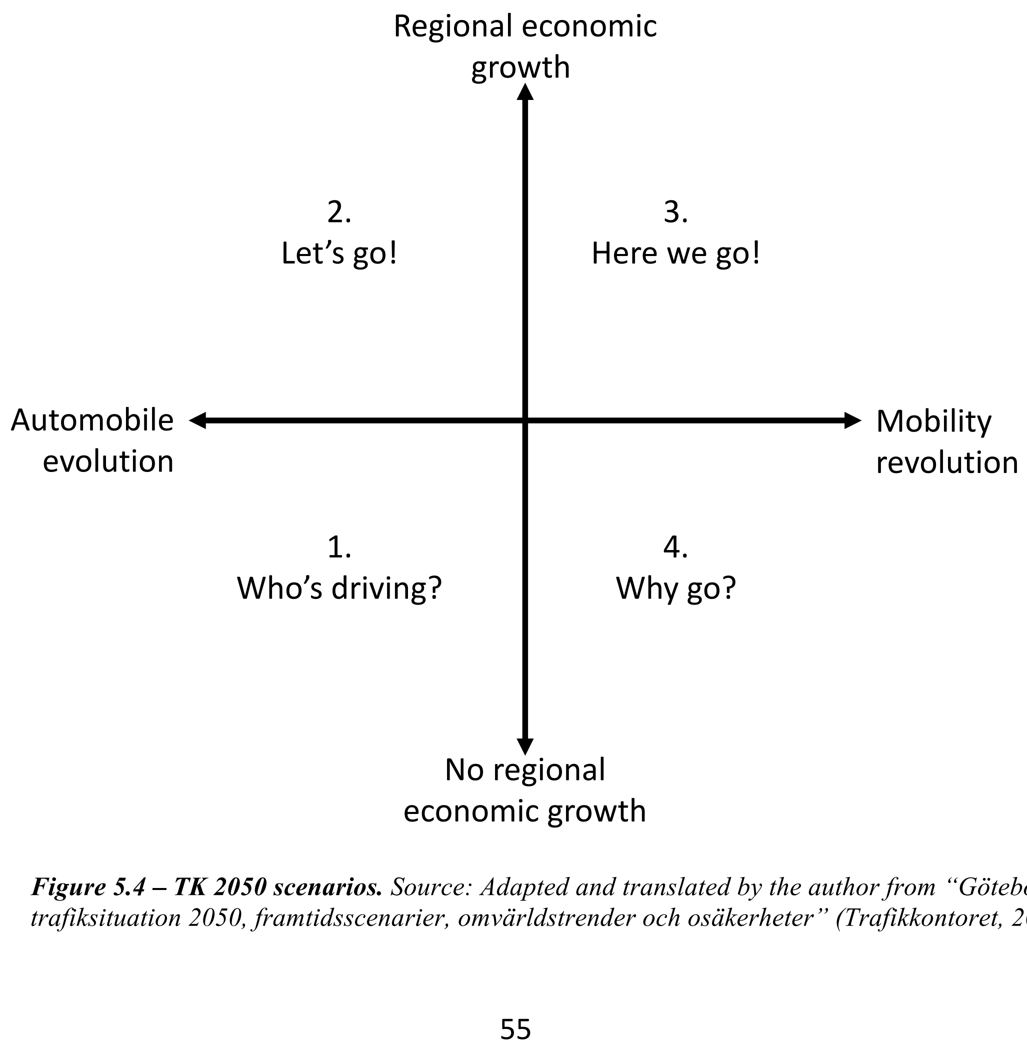


Figure 5.4 – TK 2050 scenarios. *Source: Adapted and translated by the author from "Göteborgs trafiksituation 2050, framtidsscenarier, omvärldstrender och osäkerheter" (Trafikkontoret, 2012).*

5.2.1 Scenario TK 1 – Who's driving?

The first scenario, "Who's driving?", is based on no economic growth in the region in combination with an evolution of existing mobility options, rather than disruptive new technologies. The car is the main transportation mode in this scenario and the city is becoming increasingly sprawled. However, the lack of economic growth has led to a stagnation of travelling in the region and ridesharing is more common as it is an efficient way to reduce the economic cost of travelling. Not everyone can afford a car, which has caused increased segregation and polarization in society. Regional expansion is regarded as a solution to unemployment. In this scenario, the development goals set in K2020 and the local environmental goals are not within reach (Trafikkontoret, 2012). The strategic development plan for a more attractive and accessible city is also not accomplished. Although the technology is available for AV, the market breakthrough is limited as it is not seen as a prioritized investment. Innovative ownership models and systems for ride- and car-sharing are lacking and most people can't afford to buy their own AV. The main challenge for policymakers is to strengthen a development strategy that is visionary but at the same time respect the prevailing conditions for change. New investments must be balanced against maintenance of infrastructure to support travelling within the expanding region. Engineers are challenged with making efficient use of current structures and the public are faced with the task to minimize travel expenses by reducing or rationalizing their travel.

5.2.2 Scenario TK 2 – Let's go!

The second scenario, "Let's go!", is depicted by economic growth and a more conservative automobile evolution. The scenario is characterized by increased travel and individualization of transportation modes. Large infrastructure investments are being made. Consumers and producers are both pushing the development of more efficient and smarter vehicles. Urban sprawl and regional expansion is the dominating trend and development is governed by accessibility by car.

5.2.3 Scenario TK 3 – Here we go

"Here we go!" is a scenario characterized by economic growth as well as progressive development of alternative mobility options. The demand for travel is high but a clear, common goal and strategy has achieved a shift in the way we travel. Public transport is considered a convenient and pleasant way to get from A to B and the status is high due to investments in new multi-modal systems. The city structure is dense and has been proactively developed with transit-oriented nodes and arteries. The competition for building space within proximity of the nodes is high. In this scenario, the environmental goals for Gothenburg have been achieved (Trafikkontoret, 2012).

5.2.4 Scenario TK 4 – Why go?

The fourth scenario is portrayed by a breakthrough of alternative mobility despite no or little economic growth in the region and is called "Why go?". In this scenario, politicians and citizens are on the clear that alternative mobility options are needed, i.e. a car-based society is not an option anymore. Large scale infrastructure investments are not possible due to the economic circumstances. Local initiatives are therefore the main driver for development. Bike pools and other types of collaborations are popping up all over the city. Work is preferably within walking distance from home and travelling is only done when necessary. The inner journey is considered more important than going away for the holidays (Trafikkontoret, 2012).

5.2.5 Comment on TK scenarios

The Traffic Planning Authority's report (Trafikkontoret, 2012) concludes some key issues that are all the scenarios have in common;

- The city needs a holistic view when planning as urban growth and development is closely entwined with the transportation system
- Public transportation should be concentrated in strategically placed nodes
- Invest in bicycles and/or two-wheelers as a mode of transportation
- Ensure active political governing and use of policy instruments.

The scenarios are also differentiated by several factors that have been identified and need to be treated differently in correspondence to the strategic uncertainties, including;

- Magnitude of automobile related infrastructure investments
- Alternative public transportation systems
- The density of the built environment around nodes and arteries
- The initiatives and knowledge of citizen and market forces.

The report regards technical development as an inevitable external trend, where manufacturers and market mechanisms continuously evolve the technological paradigm. The uncertainty lies in what values and ideas we let the course of development be dictated by.

The transition towards sustainability calls for fundamental changes in the socio-technical system. A scenario that is built on extrapolations of existing trajectories does not satisfy this demand for change. The TK scenario analysis is conservative in its assumption that economic growth is a prerequisite for technological development. The stricter definition of sustainability implies that positive development and wellbeing must be decoupled from monetary and material growth.

5.3 OECD scenarios

The International Transport Forum (ITF) is an intergovernmental organisation and part of the OECD. In 2015, the ITF compiled a report "Urban Mobility System Upgrade – how self-driving cars could change city traffic" , with the purpose to summarize the current findings in research on how shared self-driving cars can change city traffic. The report uses two different concepts for vehicle automation and mobility as a service; "TaxiBots" and "AutoVot". TaxiBots are based upon a ride-sharing system where autonomous vehicles can be shared between different passengers travelling on the same route. AutoVots on the other hand only assume car-sharing and will pick-up and drop-off single passengers sequentially. The study examines a mid-sized European city and explores four different scenarios; two with 100% implementation of AVs, i.e. all trips motorized trips are replaced by AutoVots or TaxiBots and two with 50% implementation. Total number of vehicles required, volume of travel and space allocation for parking are considered on two different time scales; peak hour effect and 24-hour average effect (OECD, 2015). The report concludes that, in an ideal scenario based on highly efficient public transportation complemented by TaxiBots, 10% of the cars can provide almost the same mobility as the current system. Even in the scenario that resulted in the smallest impact, AutoVots without high-capacity public transport, 20% of the vehicles would be sufficient to satisfy the city's mobility needs. This effect is accompanied by reduced needs for parking, freeing up large areas in the city previously occupied by cars.

5.3.1 Scenario OECD 1 – TaxiBot 100

This scenario features a TaxiBot system with 100% implementation. That is, car- and ride sharing is used to minimize the number of vehicles needed to provide a sufficient level of mobility. The TaxiBot system is complemented by a high efficiency public transportation system for mass transit. The system covers 100% of mobility provision within the city limits. Compared to the baseline, applying these conditions on the model city resulted in 9% more traffic volume during peak hour, 6% more during the week and only 10.4% of the fleet size necessary to provide the same level of mobility (OECD, 2015).

5.3.2 Scenario OECD 2 – AutoVot 100

The AutoVot 100 scenario does not include ridesharing. The AVs are programmed to pick up and deliver one passenger or a company at a time and then move on to service the next customer. The scenario also assumes that a high capacity public transportation network is in place and that the system is implemented to 100%. The fleet size required in this scenario is 16.8% of the baseline fleet. The traffic volume increases 55 % during rush hour and 44% overall during weekdays (OECD, 2015).

5.3.3 Scenario OECD 3 – TaxiBot 50

This scenario assumes partial implementation where autonomous vehicles provide 50% of for all motorized transportation. The scenario uses a TaxiBot model where ridesharing is used to a maximum. High capacity public transportation and private vehicles are also used in the city. The simulation showed that this would result in 78% of the original fleet size and 130 % of the base line traffic volume during week days. Rush hour traffic would increase with 36% (OECD, 2015).

5.3.4 Scenario OECD 4 – AutoVot 50

The OECD 4 scenario is based on an AutoVot system with partial implementation. 50% of all motorized trips are done with autonomous vehicles and the rest is provided with private cars. There is also a high capacity public transportation system in use. No ride sharing is done. The scenario has a smaller effect on the fleet size and requires 82% of the original fleet to provide the same level of mobility. The traffic volume increases to 151% and 156% of the baseline during weekdays and peak hour respectively.

5.3.5 Comment on OECD scenarios

The most profound impacts were found in the scenario where SAVs were fully implemented and combined with an expanded and efficient public transportation system, we can assume-The result was 10% the number of vehicles, zero on-street parking and 20% of off-street parking (OECD, 2015).

All simulations tested in the OECD report resulted in increased overall traffic volume. The smallest increase was seen in the TaxiBot100 scenario where the total VKT increased with 8 %. The largest change was a doubling in overall traffic volume as a result of 100 % AutoVot implementation without any public transportation. Partial implementation was generally less successful than full implementation in terms of fleet size and traffic volume. Systems that were accompanied with high capacity public transportation also showed better effects in regards to environmental impact (OECD, 2015). All four above presented OECD scenarios result in a substantially decreased fleet size as well as an increase in overall traffic volume.

5.4 Scenario RethinkX

RethinkX is an American independent think tank that specializes on technological disruptions. They analyse and forecast the speed, scope and scale of technology-driven development and its implications across various socio-technical sectors. They identify choices that can or must be made to enhance or avoid certain trajectories (Arbib and Seba, 2017). The report “Rethinking Transportation 2020-2030 – The Disruption of Transportation and the Collapse of the Internal-Combustion Vehicle and Oil Industries” was issued by RethinkX in May 2017 with James Arbib and Tony Seba as the main authors. Arbib and Seba argue that the transportation sector is on the verge of one of the fastest and most consequential disruptions in history.

The main driving force for the upcoming mobility revolution is economics. According to RethinkX, the average American family will be able to decrease travel cost by over $5,600 per year, adding a trillion dollars to other possible consumer spendings (Arbib and Seba, 2017). These figures have been estimated by hypothetically implementing a TaaS (transportation as a service) system, where owning a private vehicle is no longer a necessity. As RethinkX is based in the USA, the study has been done with American conditions as a baseline, i.e. a society in which much of the population is heavily dependent on internal combustion engine automobility. However, some of the conclusions made in the report can with care be extended to an international context and applied on Gothenburg. It is noteworthy that the study, despite its futuristic and visionary outcome, only used existing technology in its assumptions. The large-scale implications of a technological paradigm shift are not dependent on the technology itself, but a result of how the system is shaped around the new technology.

Furthermore, RethinkX explores the potential of transportation to be financed by advertising, data monetization, entertainment or product sales instead of the conventional ticket-price where the mobility consumers pay the price for transportation. These possibilities become clearer as private and public transportation merge. Companies may sponsor transportation to sale points or services are provided as a holistic concept where transportation is included. The role of public transportation authorities will change from owning and managing mobility assets, to managing and coordinating actors to ensure quality, equality and ubiquitous access at a low cost (Arbib and Seba, 2017). Cost saving will be the main reason for consumers to adopt the alternative transportation model and will be an incentive to overcome obstacles such as distrust in technology, joy of driving, bounded rationality and inertia to change. Nonetheless, rural areas will be less prone to adoption as costs and waiting times can be expected to be less attractive in less densely populated areas. Adopting mobility as a service does not require any initial investment or lock-in from the consumer and is therefore more attractive for early adopters in the transition stage. Adoption is predicted to follow the standard exponential s curve, that is used to explain technological diffusion in society for any given innovation, as presented in figure 5.5.

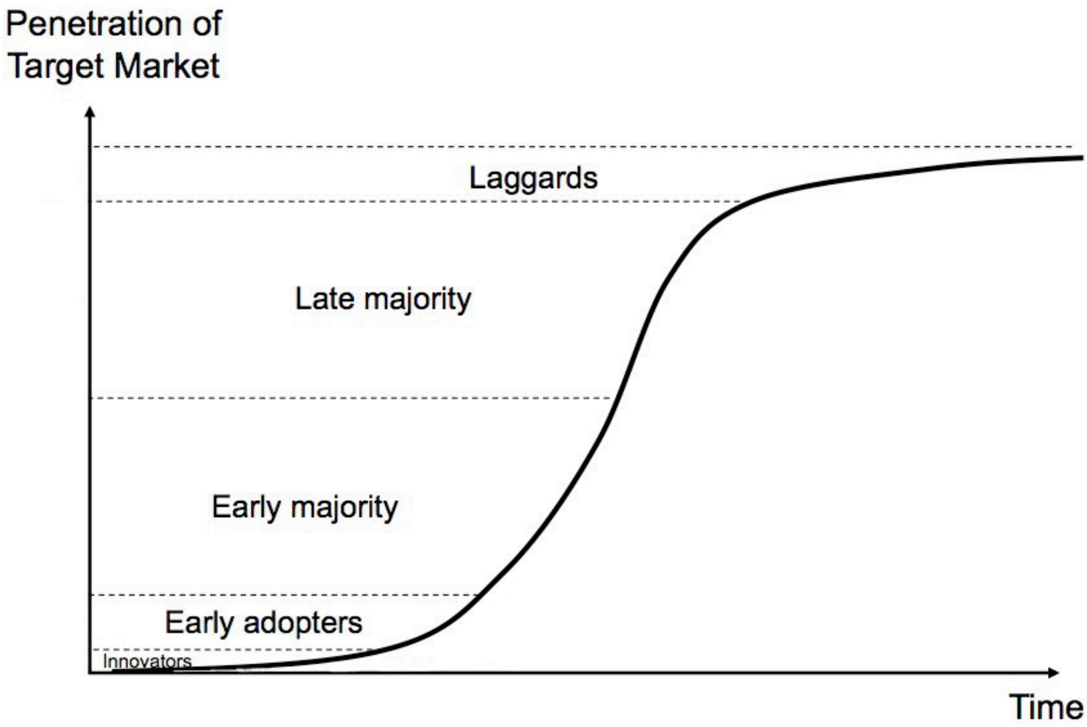


Figure 5.5 – S-curve for technological diffusion. *Source: http://www.business-planning-for-managers.com/main-courses/marketing-sales/marketing/the-adoption-curve/*

Other than increased monetary efficiency, the main findings of the report include a higher vehicle utilization rate, i.e. each car will be used at least 10 times more than a private car is today, meaning fewer cars are required for providing the same level of mobility. Over 80% of the vehicles operated on American roads today will be redundant by 2030 and annual car productions will drop by 70% (Arbib and Seba, 2017). This will have system wide impacts on the value-chains of automobile and oil industries. RethinkX predicts a peak in oil demand at around 100 million barrels per day in 2020 and then a gradual decrease over the subsequent 10 years down to 70 million barrels per day, which will be 40 million barrels less per day compared to the business as usual scenario in 2030. The demand driven collapse in oil price will make a large portion of shale oil and gas as well as off-shore and other costlier extraction methods fall under the line of commercial viability. According to RethinkX, the TaaS disruption will substantially decrease, or even put an end to ambient air pollution in cities.

The ReThinkX study shows that a technology-driven disruption of the oil industry is possible. The combination of electric vehicles and car- and ride-sharing lead to a permanent collapse in oil prices as early as 2021. With a peak oil in 2021, the challenge to battle global warming remains, but the chances to keep the warming below the 2°C target increase. The SAV disruption will have a huge influence on the automotive and oil value chains. Full adoption will result in a 70% drop in annual car manufacturing numbers from 2020 to 2030. During the same period, the overall oil demand will decrease with around 30%, going from

100 to 70 million barrels per day (Arbib and Seba, 2017). According to Arbib and Seba., oil prices may begin to plummet as early as soon as 2021. As a result, oil fields with high extraction costs, such as those in the artic or other less accessible areas, will no longer be feasible.

5.5 Scenario Stockholm SAV

Another study was done in 2014 as a master's thesis at the Department of Industrial Ecology at the Royal Institute of Technology (KTH) in Stockholm. Software was used to model six different scenarios based on shared autonomous vehicles mobility solutions (Rigole, 2014). The study assumes a free flowing, level 5 autonomous fleet that transports travellers on-demand in the Stockholm metropolitan area. The temporal horizon is set to 2030. Six different scenarios were developed using 0%, 30% or 50% allowed maximum increase in travel time, a starting time window of 0, 10 or 15 minutes and finally optimizing for as little empty mileage as possible or minimized parking time (Rigole, 2014). Scenario 1 and 2 do not allow for any increase in travel time, which implies no ride sharing as stopping to pick up co-travellers always results in extra travel time. The remaining scenarios allow a buffer time to stop and pick up other passenger, thus making ridesharing possible.

Table 5.1 – Scenarios considered in the Stockholm SAV study. *Source: Adapted from "Study of shared autonomous vehicles based mobility solution on Stockholm", Rigole (2014).*

Scenario STHLM:	1	2	3	4	5	6
Max. increase in travel time [%]	0	0	30	30	50	50
Max. waiting time [min]	0	0	10	10	15	15
Optimized for	Empty mileage	Parking time	Empty mileage	Parking time	Empty mileage	Parking time

The study concludes that an autonomous vehicle can replace 14 private cars. This means that only 7.1% of the current fleet size is necessary to provide the necessary level of mobility. This would save up a lot of space in the city that can be used for other purposes. Scenarios 1,2 and 4 resulted in increased overall mileage, while the other scenarios managed to cut mileage by up to 24 %. The most profound impact was found for scenario 5.

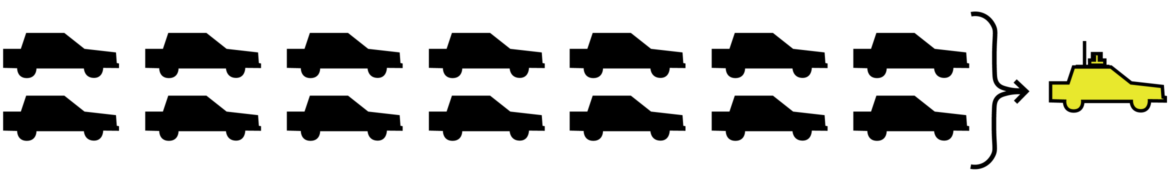


Figure 5.6 – 14 cars can be replaced by 1 AV. *Source: Adapted from "Study of shared autonomous vehicles based mobility solution on Stockholm", Rigole (2014).*

6 Analysis

The analysis chapter of this report consists of four sections. First, the scenarios presented in sections 5.1 to 5.5 are assessed according to 5 criteria; 1) operational, 2) economic, 3) environmental, 4) spatial and 5) social, that have been summarized in a scenario-criteria table. The table is constructed using a PUGH matrix model to enable a comparison and evaluation of the different scenarios. The PUGH matrix helps to identify common features that can be linked to a successful outcome and indicate what descriptive features can be associated with positive environmental impacts. A further explanation of the PUGH matrix method can be found in section 3.4 of this report.

The second part is a SWOT analysis that summarizes inherent strengths and weaknesses as well as opportunities and threats of an autonomous transportation based mobility system. The objective in ms environmental impact of possible features and outcomes linked to autonomous vehicle implementation. The SWOT analysis is used to get a quick overview of potential outcomes and highlight which features should be incorporated or avoided in the future scenario for Gothenburg. The third part of the analysis contains a vision for a sustainable future and pinpoints contemporary challenges alongside the desirable outcome. The scenario for Gothenburg is based upon the vision and the SWOT analysis and supported by the conclusions drawn from the PUGH matrix. The last part of the analysis is a zoom in on the local context where Gothenburg is represented by three different urban typologies. The purpose is to allow the different features from the scenarios in the PUGH matrix to be adapted and tested according to local qualities.

6.1 PUGH matrix

The impacts of vehicle automation are system-wide and uncertain. Based on the background chapter of this study, certain criteria have been chosen to describe and evaluate the effects of autonomous vehicles on urban sustainability. The criteria, against which the scenarios will be tested in the PUGH matrix, are described in the sections below. The criteria must be suitable for assessment on a local and regional scale and should reflect the sustainable development goals to enable an evaluation of the scenario in relation to existing goals and targets.

All data and information used in the PUGH matrix is taken directly from the reports presented in sections 5.1 to 5.5. Numeric data is taken as stated in the source while, although the author has in some cases taken the liberty to translate actual numbers to relative and vice versa by using the baseline scenario for Gothenburg. The qualitative information is the authors direct interpretation of the original sources. Criteria that are not included in the source documents have been marked with n/a (not available).

6.1.1 Criteria description

The environmental criterion includes the effects on emissions from traffic and the level of decarbonisation of the transportation sector as well as assumed amount of internal combustion engines still being in use. Predicted impacts on peak oil and the potential of achieving climate goals and local environmental targets are also noted where available. Lower VKT is directly connected to smaller environmental impact, regardless the drive line technology.

The economic aspect is treated as an efficiency in terms of how large a fleet is needed to provide a certain level of mobility and to what cost. In this way, the material capital and efficient use of assets is taken into consideration. Where available, the assumed economic growth is also noted. However, economic growth is not marked as positive or negative feature as it is often associated with higher energy and material consumption and it is debated whether higher economic growth is positive from an environmental perspective. A decoupling of economic growth and energy consumption is possible through an implementation of circular economy and a redefinition of growth, but this question is left beyond the scope of this report.

The operational criterion is used to express effects that are directly dependent on how the system used to provide mobility is organised, considering parameters such as business model, AV adoption and how well the system runs. Effects on congestion is noted under this criterion as it depends on how the traffic volume is distributed by organising movement in time and space.

The spatial criterion is interesting from many aspects. The key here is how the scenario influences the demand for parking space. The effects on the city structure is mentioned as a result of parking demand and the prevailing mode of transportation. When possible, effects on urban sprawl are also discussed under this criterion.

Social effects include to what extent transportation is equally available for everyone, despite where you live, your economic situation, age, gender or disabilities. The term *underserved groups* is used to refer to people that have less access in the current mobility system as a result of socio-economic aspects, disabilities or other disadvantages.

The PUGH matrix is colour coded to indicate negative or positive impacts according to the IPAT identity. Green cells represent positive consequences from a sustainability point of view and red cells indicate negative impacts. The bottom rows summarize the number of positive and negative impacts and gives the evaluated scenario an overall score.

Table 6.1 – PUGH matrix part 1

Criteria		Baseline	KTH ITRL				Trafikkontoret Göteborg				RethinkX
			ITRL 1	ITRL 2	ITRL 3	ITRL 4	TK1	TK2	TK3	TK4	
Descriptive	Location specifics	Gbg	Sweden				City of Göteborg				USA
	Method		Scenario analysis, workshops with expert panel				Scenario analysis				Seba framework
	Study done in		2016-17				2014				2017
	Temporal horizon	2017	2030				2050				2030
	Critical assumptions		Reactive planning, no sharing	Proactive planning, no sharing	Proactive planning, sharing	Reactive planning, sharing	No economic growth, automobile evolution	Economic growth, automobile evolution	Economic growth, mobility revolution, disruptive tech.	No economic growth, mobility revolution thanks to local initiatives	Highly disruptive technological development
1. Operational	AV adoption (% of vehicles)	0	33	30	50	50	Low	High	High		60
	AV adoption (in % of VKT)	0	50	38	56	58	n/a				95
	Ride-sharing (in % of trips)	Close to 0	0	0	Very high	High	Increasing	Very low	High	High	n/a
	VKT (relative)	100	120	80	130	100	<100	>>100	>100, although digital solutions and deliveries brings it down	<100	n/a
	Public transportation share	28*	~	High, but competing with private	New modes, e.g. pods and feeder buses. Blurred lines	Higher, private actors, TaaS	~	Low, individual travel preferred	High, high status, multi-modal	High share of motorized travel, but low overall	Low, unless TaaS is part of PT
	Privarte car share	46*	High	Low, high charges and strict parking policies	Very low	Low	Still high	Very high	Low	Very low, car/bike pools more common	Low
	Effects on congestion	Frequent congestion on certain routes during rush hour	More congestion due to VKT↑ and bad planning	Lower VKT and level 5 efficient use of road space and traffic flow	No congestion	Less congestion, better flow (AV)	Regional commute routes congested during rush hour, less in city centre	High levels of congestion as private car is main mode of transportation	PT more space efficient, nodes more congested	Most travel is done by foot, bicyle or PT. Low/no congestion	Reduced by smaller fleet and efficient driving
2. Economic	Fleet size	184000	220800	165600	248400	184000	~, lower per capita	High level of car ownership	n/a	Very low	33120
	Relative fleet size	100	120	135	90	100	~100	>>100	<100	<<100	18
	Cost of transportation		n/a	Cheaper	Cheaper	Included in services	Depends on fuel prices	High	Cheap and expensive options available	Cheaper mode chosen over convenience	Saving $5,600/year (>60%) for average family, potentially free
	VKT/vehicle		1.00	1.69	0.69	1.00	n/a				n/a
	Economic growth	4.1%	n/a				Low/negative	Normal/high	Normal/high	Low/negative	Collapse of oil and car industries

n/a Unknown, not applicable or not available

~ No significant change compared to baseline

Net negative impact on sustainable development

Net positive impact on sustainable development

Table 6.2 – PUGH matrix part 1 continued

Criteria		Baseline	KTH ITRL				Trafikkontoret Göteborg				RethinkX
			ITRL 1	ITRL 2	ITRL 3	ITRL 4	TK1	TK2	TK3	TK4	
3. Environmental	EV/other decarbonized (%)	1	Low, still being tested	Very high, light-weight EV, pods	High	n/a	Very low	High	High	Slow increase as expensive investment	60
	ICE (% of fleet)	99	~	Low	Low	n/a	High, aging fleet	Low	Phasing out	Slowly phasing out	40
	Emissions from traffic		High	Depends on electricity production	Low	n/a	Still high, targets not met	Better due to advanced tech./EV	Lower as PT more efficent/new tech.	Low thanks to VKT	90% reduction compared to BAU
	Peak oil prediction		After 2030	Before 2030	Before 2030	n/a	n/a				2020
	Climate targets achieved		No	Better chances	Yes	Better chances	Almost	No	Yes	Yes	Better chances
	Local SDG achieved	no	No	Yes	Yes	No	Almost	Almost	Yes	Yes	Better chances
4. Spatial	Parking demand	226000	Self-parking more space efficient	Low availability to promote PT	Very low	Lower, AV, car-charing	~	Very high	~	Low	Low in rural, very low in urban areas
	Relative parking demand	100	~	<100	<<100	<100	n/a	>>100	n/a	<100	<<100
	City structure		~, some areas more connected than others	Car free zones	Denser and greener	Close-knit grid, rural/suburban areas left behind	Less dense, cheaper land developed	Concentration around highway intersections	Strong growth in nodes and arteries	Local developement, polycentric	"Land bonanza"
	Effects on urban sprawl		~	Decreased sprawl, less parking denser city	No sprawl	n/a	n/a	High rate of urban sprawl and regional expansion	Low sprawl, new features added to existing structures	No sprawl	n/a
5. Social	Equality and wellbeing		New tech. make life more comfortable, but not for everyone	Improved	Ubiquitous mobility, high wellbeing	Augmented gaps	Car enhances segregation, strong polarization	Limited polarization, wide gap between extremes	Low polarization, high wellbeing	Local life, low polarization	Improved mobility, consumer income gains
	Accessibility	Underserved groups and areas	Nonubiquitary	Better thanks to AV	Better geographic mobility distribution	Market driven	Low for underserved groups, little/no investment	Limited for underserved groups and economically weak	Geographically and socially improved	Low	Improved for inderserved groups and economically weak
Positive (green)			1	12	16	7	3	4	12	14	10
Negative (red)			-12	-3	-1	-2	-8	-12	-1	-2	-1
Neutral (white) or n/a			11	8	6	14	13	8	11	7	12
Total			-11	9	15	5	-5	-8	11	12	9

n/a Unknown, not applicable or not available
~ No significant change compared to baseline
Net negative impact on sustainable development
Net positive impact on sustainable development
Scenario with most net positive impact

Table 6.3 – PUGH matrix part 2

Criteria		OECD Urban mobility system upgrade				KTH STHLM SAV					
		TaxiBot100	AutoVot100	TaxiBot50	AutoVot50	STHLM1	STHLM2	STHLM3	STHLM4	STHLM5	STHLM6
Descriptive	Location specifics	Mid-sized European city (Lisbon)				Stockholm Metropolitan					
	Method	Software simulation				Software simulation					
	Study done in	2015				2024					
	Temporal horizon	2050				2030					
	Critical assumptions	100% AV, ride-sharing, high capacity PT	100% AV, car-sharing, high capacity PT	50% AV, ride-sharing, high capacity PT	50% AV, car-sharing, high capacity PT	Optimized for minimum empty mileage	Optimized for minimum parking time	Accept 30% increase in travel time, 10 min waiting. Optimized empty mileage	Accept 30% increase in travel time, 10 min waiting. Optimized parking time	Accept 50% increase in travel time, 15 min waiting. Optimized empty mileage	accept 50% increase in travel time, 15 min waiting. Optimized parking time
1. Operational	AV adoption (% of vehicles)	100	100	50	50	100	100	100	100	100	100
	AV adoption (in % of VKT)	100	100	n/a	n/a	100	100	100	100	100	100
	Ride-sharing (in % of trips)	High	0	High	0	0	0	>0	>0	High	High
	VKT (relative)	106	144	130	151	124	172	89	115	76	97
	Public transportation share	22	22	22	22	Not specified. Likely to increase as SAV is a solution to last-mile problem.					
	Privarte car share	0	0	50	50	0					
	Effects on congestion	65% fewer vehicles during peak hour, but 9% increase in peak hour VKT	43% fewer vehicles during peak hour, but 55% increase in peak hour VKT	9% fewer vehicles during peak hour and 36% increase in peak hour VKT	3.4% more vehicles during peak hour and 56% increase in peak hour VKT	Increased congestion	High increase in congestion	Decresed congestion as less VKT and much smaller fleet	Slightly increased congestion	Substantial decrease in congestion	Very slight decrease in congestion
2. Economic	Fleet size	19136	30912	143888	150880	14904	15824	9936	11040	9016	9752
	Relative fleet size	10	17	78	82	8.1	8.6	5.4	6.0	4.9	5.3
	Cost of transportation	Up to 90% cost reduction for SAV compared to conventional private car.				Cheaper as cost for vehicle is shared, parking fees eliminated, lower insurance cost and no cost for driver.					
	VKT/vehicle	n/a				n/a					
	Economic growth	n/a				n/a					

n/a Unknown, not applicable or not available — Net negative impact on sustainable development

~ No significant change compared to baseline — Net positive impact on sustainable development

Table 6.4 – PUGH matrix part 2 continued

Criteria		OECD Urban mobility system upgrade				KTH STHLM SAV					
		TaxiBot100	AutoVot100	TaxiBot50	AutoVot50	STHLM1	STHLM2	STHLM3	STHLM4	STHLM5	STHLM6
3. Environmental	EV/other decarbonized (%)	Assumed 100% EV with 30 min recharge time every 175 km means 2% larger fleet is required.				GWP_{100} 80% less for EV compared to ICE, using Swedish electricity mix.					
	ICE (% of fleet)	n/a				n/a					
	Emissions from traffic	Directly correlated to increase in VKT. Can be mitigated through EV adoption.				124	172	89	115	76	97
	Peak oil prediction	n/a				Depending on EV adoption					
	Climate targets achieved	n/a				n/a					
	Local SDG achieved										
4. Spatial	Parking demand	Zero need for on-street parking freeing up 20% of kerb-to-kerb street space, 80% of off-street parking redundant				Up to 95% reduction in parking demand thanks to smaller fleet and much higher useage per vehicle.					
	Relative parking demand	6	11	76	79	n/a	n/a	5	5	n/a	n/a
	City structure	Freed up parking space can be used for new houses, green areas, UCC etc.				n/a					
	Effects on urban sprawl	n/a				n/a					
5. Social	Equality and wellbeing	Improved accessibility for underserved groups. Door-to-door communication and solution to last-mile problem. Increased mobility for suburban areas.				Equal access for everyone dispite driving abilities.					
	Accessibility	Travel time down 13%, waiting time down 86%	Travel time down 38%, waiting time down 89%	Travel time down 7%, waiting time down 85%	Travel time down 31%, waiting time down 87%	Increased access for underserved groups		Slightly longer travel time		Much longer travel time, slower overall mobility system,	
Positive (green)		12	11	9	9	8	8	12	9	11	10
Negative (red)		-2	-2	-4	-4	-3	-3	-1	-4	-1	-1
Neutral (0)		9	10	9	10	13	13	11	11	12	13
Total		10	9	5	5	5	5	11	5	10	9

n/a Unknown, not applicable or not available

~ No significant change compared to baseline

Net negative impact on sustainable development

Net positive impact on sustainable development

6.2 SWOT analysis

The following SWOT analysis was made with the objective to ….and is based on the scenarios discussed in chapter 5 of this paper. It summarizes the inherent strengths and weaknesses as well as the potential opportunities and threats that autonomous vehicle technology brings to the future city. The effects include environmental, social, economic aspects as well as systemic changes. The analysis should not be seen as a comprehensive assessment of AV technology, but rather as a way to summarize findings that have hitherto been discussed in this report.

Table 6.5 – SWOT analysis.

Strengths	**Weaknesses**
Reduced parking pressure Energy efficient driving Efficient routing Faster fleet regeneration spurs technological development New types of vehicles, adapted to specific needs and situations Ride- and car-sharing easier to administrate Door-to-door transportation Smaller fleet to deliver the same mobility Reallocation of urban space from less parking Travelling more comfortable and attractive	Bounded rationality inherent to the idea of car ownership and freedom of mobility Personal integrity issues with big data sharing Lack of ability of the public sector to invest in new technologies Lack of skilled work force AV technology currently means low speed and over-cautious driving Uncertain technological development Fear of investing in the "wrong" technology Vulnerable transition period Negative public health consequences with door-to-door transportation
Opportunities	**Threats**
Decreased traffic volume Integrated streetscape Greener cities and better possibilities for ecosystem services Enhanced walkability and bike-friendliness Reframing public perception of public transportation Enhanced equality and urban integration Solution to last-mile problem Feeder services to public transportation Additional public transportation services with higher frequencies, on-demand, extended hours and lower cost Chance for electrification or other decarbonisation of transportation Social inclusion and increased mobility for underserved groups Mobility as a service Modal integration and seamless transit Urban densification, less sprawl	Lack of public acceptance Increased traffic volume due to "empty mileage" Increased traffic volume as travelling and congestion becomes more bearable Reactive planning Privatisation of urban mobility, reduced influence of public authorities Loss of jobs in transport sector Personal safety issues related to ride-sharing Stratification of the transportation sector Increased urban sprawl Partial implementation gives tricky traffic situation Increased urban sprawl

6.3 Future vision for an AV-based mobility system

By envisioning the qualities of a future scenario for Gothenburg in 2050, the concept of autonomous mobility can be hypothetically tested and evaluated according to the basis for sustainable urban development defined in the background chapter of this report. Identified contemporary challenges and lock-ins that are hindering sustainable development are presented in table 6.1, which is based on conclusions and findings made in this report alongside the vision for a future with enhanced urban sustainability.

Table 6.1 – Contemporary challenges and future vision for a sustainable mobility.

	Contemporary challenges	**Future vision**
Environmental	Emissions from traffic Noise pollution Ecosystem services threatened Air pollution Fossil fuel dependency	Carbon neutral Green infrastructure Clean air Silent transportation 100 % renewable
Economic	High energy demand High material consumption Inefficient use of assets High cost of parking	Cheap, ubiquitous transport Efficient use of material assets Sharing economy Circular economy
Social	Physical and socio-economic segregation Gender inequalities in accessibility Modal gender inequality Unequal access for underserved groups	Universal access Public transport the most convenient Public transportation higher status Affordability Active and pedestrian-oriented streetscape Urban agglomeration Shared public spaces
Spatial	Parking takes up a lot of space Motorized vehicles dominate Over-dimensioned structures not used efficiently Urban sprawl Increased competition for land Mobility, not activity Overloaded nodes	High walkability Dense and close-knit structure Coherent green network for ecosystem services Urban consolidation Priority for pedestrians and cyclists Clear distinction between separated networks and areas with modal integration Superstructures in designated areas
Operational	Congestion Private vs public services Overloaded nodes Centralized Uneven distribution in time and space Uneven efficiency in time and space	Efficient use of assets Vehicles to share Mobility as a service Merge of public and private transportation Close-knit network Free flowing, flexible system UCC in dense areas with commerce Possibility of integrated freight transport

6.4 Use of existing space – urban typologies

Gothenburg consists to a large extent of a few standard urban structures, originating from different epochs of planning and architecture. By investigating features such as mobility opportunities, freight transportation, car dependency and the distribution and availability of parking spaces for each of the typologies, the local effects of AV implementation can be more easily assessed than when looking at the city as a whole. The urban typologies presented in section 6.3.1 to 6.3.3 of this report were chosen from a book published by the Urban Planning Authority of the City of Gothenburg; "Stadsbyggnadskvaliteter Gothenburg" (Stadsbyggnadskontoret Göteborgs Stad, 2008), and include *traditional block structure*, *traffic-separated high-rise* and *residential garden city*.

Space distribution within each typology was analysed to get an idea of how much space is dedicated to transportation and mobility related functions.

Table 6.2 – Analysis of urban typologies.

Parameter	*Vasastaden*	*Frölunda*	*Utby*
*Area [km^2]**	0.08	0.10	0.29
Population density [pers/km^2]	18663	12140	2366
*Population (2016)**	1493	1214	686
*Nr. of households**	916	800	226
*Registered cars**	324	267	313
Cars/capita	0.22	0.22	0.46
Cars/household	0.35	0.33	1.38
e (total floor/land area)	1.0-2.3	0.8-1.4	0.1-0.3
*Parking spaces***	396	627	~460
Type	Kerbside	Off-street (124 in garage)	On property /on-street
Parking/household	0.40	0.78	2.21
*Estimated parking area [m^2]***	4166	19476	6900

*Sources: *) http://statistikdatabas.goteborg.se/pxweb/sv/Delområden%20%20Befolkning-Bostäder-Arbete-Inkomster-Utbildning/?rxid=f22dffa3-5a53-4949-b05d-381ba86a8e52. **) Area estimated by measuring dimensions on a dwg map of Gothenburg. Parking spaces manually counted using satellite pictures from google.maps.com.*

To simplify, the typological urban structures were stripped down to roads, buildings, parking spaces and spaces in-between. Figures 6.5 and 6.7 show the distribution of parking spaces (grey areas) in the example areas of Vasastaden and Västra Frölunda.

6.4.1 Traditional block structure

This typology constitutes a traditional block structure and is, in this report, represented by Vasastaden in central Gothenburg. Most of the inner city of Gothenburg is made up of closed blocks with semi-private courtyards and direct access to the street. The street structure is coherent and has a wide mix of functions. The ground levels of buildings are mostly dedicated to shops, restaurants and other commercial or public services. The lines between public and private space are distinct and very little space has an undefined function. Every square meter is predetermined and described in the zoning plan. The buildings are generally 3-8 stories high, creating an exploitation value varying from 1.0 to 2.3 (Stadsbyggnadskontoret Göteborgs Stad, 2008).

Figure 6.4 – Traditional block structure in Vasastaden. *Source: Adapted from Maps, Vasastaden, Gothenburg, Version 2.0 (1983.24.9.30.35) Copyright © 2012-2016 Apple Inc.*

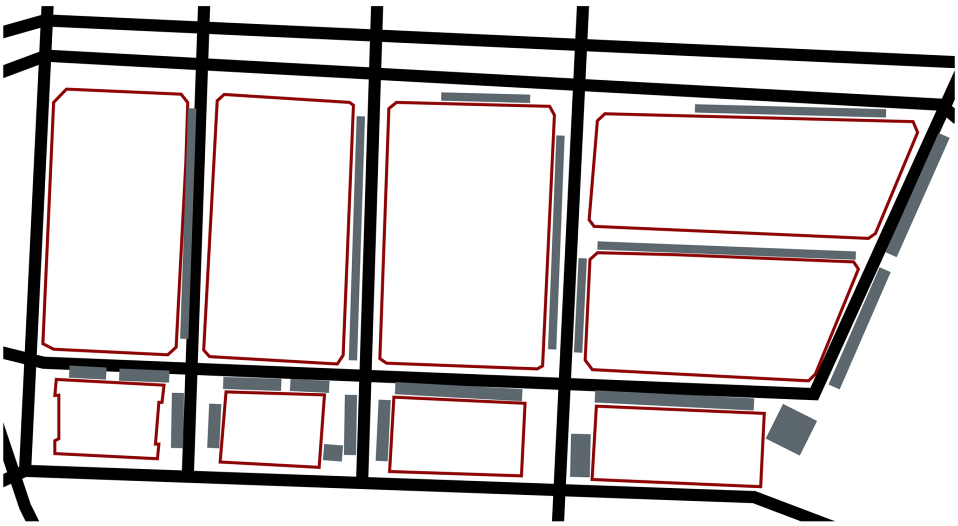


Figure 6.5 – Distribution of parking area in a traditional block structure (Vasastaden). *Parking is marked in grey.*

Most parking is located on the street, or in underground car parks. The population density is high and the area also attracts a lot of people who reside elsewhere. It is a popular daytime and night time destination, weekends as well as weekdays. This part of the city is characterized by pre-modernistic buildings and small-scale property divisions, which enhances the diversity and flexibility of the area. Space is equally distributed between semi-private and public areas, with only a very small amount of private, semi-public or undefined spaces. The street grid is orthogonal and has a repetitive layout.

Implementing a superstructure concept such as the one described in chapter 4.2.4 of this report, is beneficial in an area with a well-defined block structure as it is easy to determine which streets should be incorporated in the super-network and which should be part of the local network. The typology shows a lack of direct access to green public spaces and could benefit from a more diverse and inclusive use of the streetscape.

Urban consolidation centres could play a role in areas with traditional block structure that have more businesses, shops and other commercial functions. Redundant street-side parking spaces can then be used for building micro centres for logistics and distribution of goods in within the superblock. Even in strictly residential areas with this urban structure, consolidations could serve a function for parcel deliveries as online commerce becomes increasingly popular.

Developing transportation nodes within a traditional block structure can be challenging as there is little space that is not predefined. However, the basis for public transportation and different transportation options is large as the demand for mobility is high in densely populated areas. When developing nodes within this typology, it is essential to control the nodal expansion and have a close-knit network of access points around the node, that partially relieves the node of some of the load and counteracts nodal stress. Additionally, feeder pods could be a way to unburden local nodes and make regional and long-distance mass transit a more attractive option.

6.4.2 Traffic separated high rise

This type of urban structure is characterized by larger scale buildings, 6-12 stories, with direct access to the street or public or semi-public green areas. The sample used in this study is taken from Frölunda in western Gothenburg. The street and building structure is segmented and there is a clear distinction between spaces for infrastructure, residence and recreation. Due to noise regulations, parking is often used as a barrier to create distance between the buildings and roads with heavier traffic. The lines between private and public areas are blurred and there is a large proportion of semi-public and undefined spaces. The typology has a general lack of well-defined public spaces. The function is mostly residential, but in some cases, there are possibilities for commercial premises at ground level. The exploitation value for these kinds of areas typically lies between 0.8 and 1.4 (Stadsbyggnadskontoret Göteborgs Stad, 2008).

Figure 6.6 – Traffic separated high rise in Frölunda. *Source: Västra Frölunda, Gothenburg, Maps, Version 2.0 (1983.24.9.30.35) Copyright © 2012-2016 Apple Inc.*

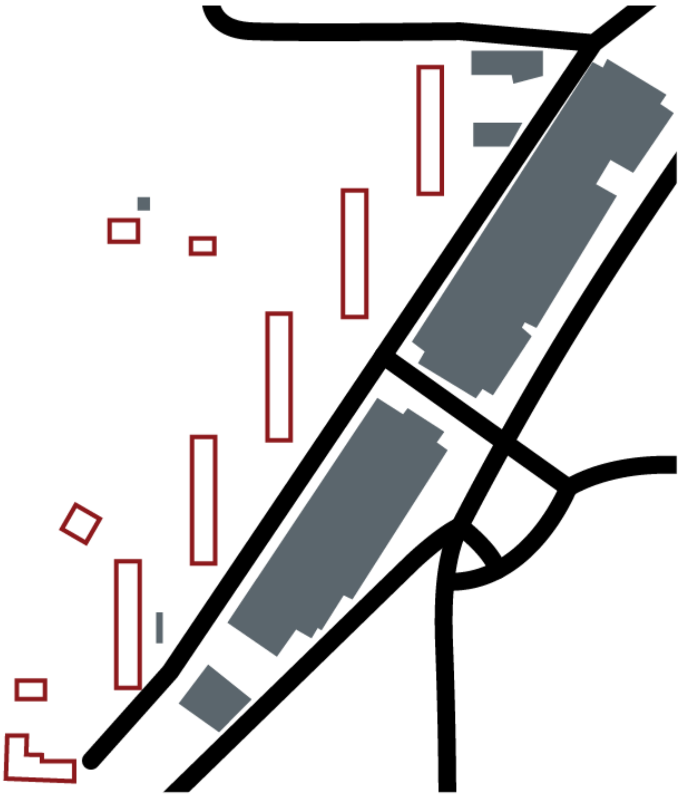


Figure 6.7 – Distribution of parking area in a traffic separated high rise structure (Frölunda). *Parking is marked in grey and buildings outlined in red,*

The large spaces used for separated parking areas in this type of structure makes further development of the area very attractive. Space freed up from redundant parking is concentrated in a way that makes it possible to build rather large-scale new structures without interfering too much with the surrounding buildings and infrastructure. The concept of traffic separation has led to a kind of superblock already, where motorized vehicles are secluded to certain areas. Superblock implementation is perhaps less obvious in this more open structure compared to the traditional block structure but nonetheless effective. While turning parking into housing and densifying the area the possibility for local businesses to advance is enhanced. Micro consolidation centres could therefore also be part of the development plan of such an area.

With a lower exploitation value and lower population density, the distance to transportation is generally longer. The frequency of departures is also lower and modal options are limited. To complement the mass transit network with an AV feeder pod system could therefore be very beneficial and make public transportation more attractive for residents in the area.

6.4.3 Residential garden city

This type of built environment consists of small dethatched and/or semi-dethatched houses organised in a regular or irregular grid structure and is commonly found along the outskirts of central Gothenburg. This study uses Utby, a residential area in just east of central Gothenburg, as a typical example of a residential garden city type of settlement. Each house is usually meant for one family and comes with its own garden. These residential areas have been built in the outskirts of Gothenburg from the 19th century onwards (Stadsbyggnadskontoret Göteborgs Stad, 2008).

*Figure 6.8 – **Residential garden city in Utby.*** *Source: Vasastaden, Gothenburg, Maps, Version 2.0 (1983.24.9.30.35) Copyright © 2012-2016 Apple Inc.*

The houses are accessed from the street or from the garden and there is a very clear distinction between private and public areas. There is essentially no semi-public or semi-private and very few undefined spaces. The population density is lower and car ownership is a lot higher here than in other areas. This kind of urban structure contains no or little commerce and services are located elsewhere. It is a strictly residential area except for the occasional kindergartens, primary schools or recreational grounds. The exploitation value lies somewhere between 0.1 and 0.3 (Stadsbyggnadskontoret Göteborgs Stad, 2008).

The road network within this typology is of very local character and implementation of superblocks may therefore not have a significant impact on the neighbourhood. The challenge here lies not in reducing the traffic within the typology, but in changing the transportation norm for getting to and from the area. Car ownership per household is four times as high in the residential garden city compared to the other two typologies explored within the scope of this report. AV feeder pods for local nodes and mass transit access can be a beneficial feature to incorporate in this type of structure.

7 Results

Chapters 7 and 8 of this report aims to readdress and answer the research questions presented in chapter 2; what is the potential of vehicle automation to enhance sustainable urban development?

- What could a future system of autonomous transportation look like in Gothenburg?
- And what could the environmental consequences of a transition to such a system be?

Findings from the PUGH matrix and the consequential scenario for Gothenburg are presented and later discussed under the topic of each impact category to shape a framework for enhancing positive environmental impacts form AV implementation.

7.1 Correlating factors

The most significant factors, when looking at environmental impact and disregarding the propulsion technology, are fleet size and VKT. Table 7.1 below shows a zoom in of the comprehensive PUGH matrix, highlighting the correlation between assumed AV adoption, VKT and required fleet size.

Table 7.1 – AV adoption, VKT and fleet size correlation. *Source: See table 5.2 and 5.3.*

Scenario	*AV adoption (% of vehicles)*	*VKT (relative)*	*Fleet size (relative)*
Baseline	0	100	100
ITRL 1	33	120	120
ITRL 2	50	80	90
ITRL 3	30	130	135
ITRL 4	50	100	100
TaxiBot100	100	106.4	10.4
AutoVot100	100	144.3	16.8
TaxiBot50	50	129.8	78.2
AutoVot50	50	150.9	82.0
USA TaaS	60	n/a	17.8
STHLM1	100	124.4	8.1
STHLM2	100	171.6	8.6
STHLM3	100	88.8	5.4
STHLM4	100	114.6	6.0
STHLM5	100	76.0	4.9
STHLM6	100	96.7	5.3

A linear correlation (R^2= 0.97718) was found when plotting the assumed AV adoption against the corresponding fleet sizes for the different studies discussed in sections 5.1 to 5.6 of this report. However, no similar correlation could be found when plotting AV adoption against the relative VKT. This means that, according to the scenarios included in the study, it is likely that fewer vehicles will be needed once AV technology is adopted, but the total traffic volume will not necessarily decrease. The traffic volume is directly linked to environmental impact. Thus, further measures are required to ensure that the overall traffic volume does not increase when autonomous transportation is adopted in a city.

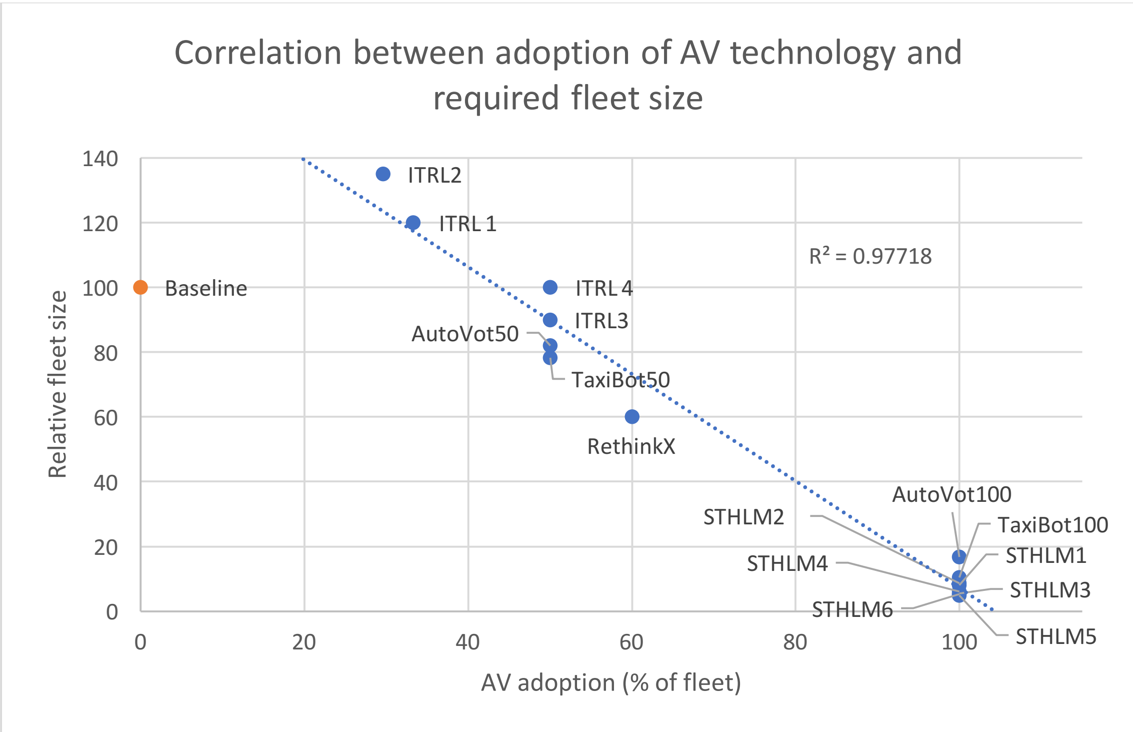


Figure 7.1 – Correlation between AV adoption and relative fleet size.

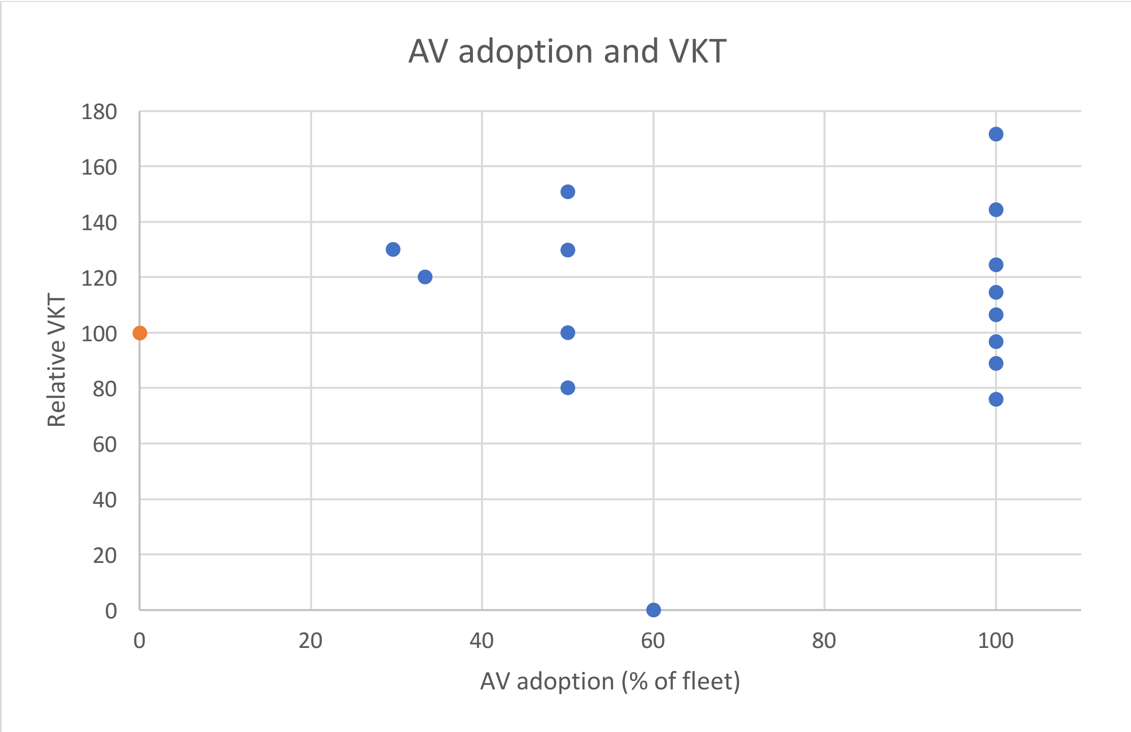


Figure 7.2 – AV adoption and relative traffic volume.

The overall traffic volume is prone to increasing when implementing an AV based mobility system.

7.2 Energy demand

Energy consumption is another effective indicator on environmental impact. It is linked to the traffic volume in combination with the propulsion technology used in the vehicle. In the IPAT identity, VKT/person would be the affluence, i.e. the level of mobility, and technology would be kWh/km or CO_2/km due to the type of engine in the car. The potential change in energy demand for mobility purposes is presented in figure 7.3.

Figure 7.3 shows that everything from a substantial decrease in energy demand to a distressing increase is possible depending on the form of implementation. However, with a decarbonisation of the propulsion technology, it is likely that the conditions for environmental sustainability will improve, despite a slight increase in overall travelling.

Due to adoption of autonomous vehicles, the overall energy demand for urban transportation can be increased as transportation becomes more attractive and available to a larger group. Depending on the model of implementation this effect can increase the total traffic volume. As safety can still be ensured, the high technology system also has the potential to allow higher speeds when travelling on roads designated to AVs only. This may become another source to increased energy demand.

There are also many factors that will contribute to smaller energy requirements. Less time looking for parking and efficient routing contribute to minimizing the overall traffic volume. Platooning, efficient driving and lighter vehicles decreases the fuel consumption per kilometre. Note that electrification or other decarbonisation is not considered here, but only effects that are inherent to AV technology. If it is assumed that all these effects are present to their fullest extent, the net effect is close to zero.

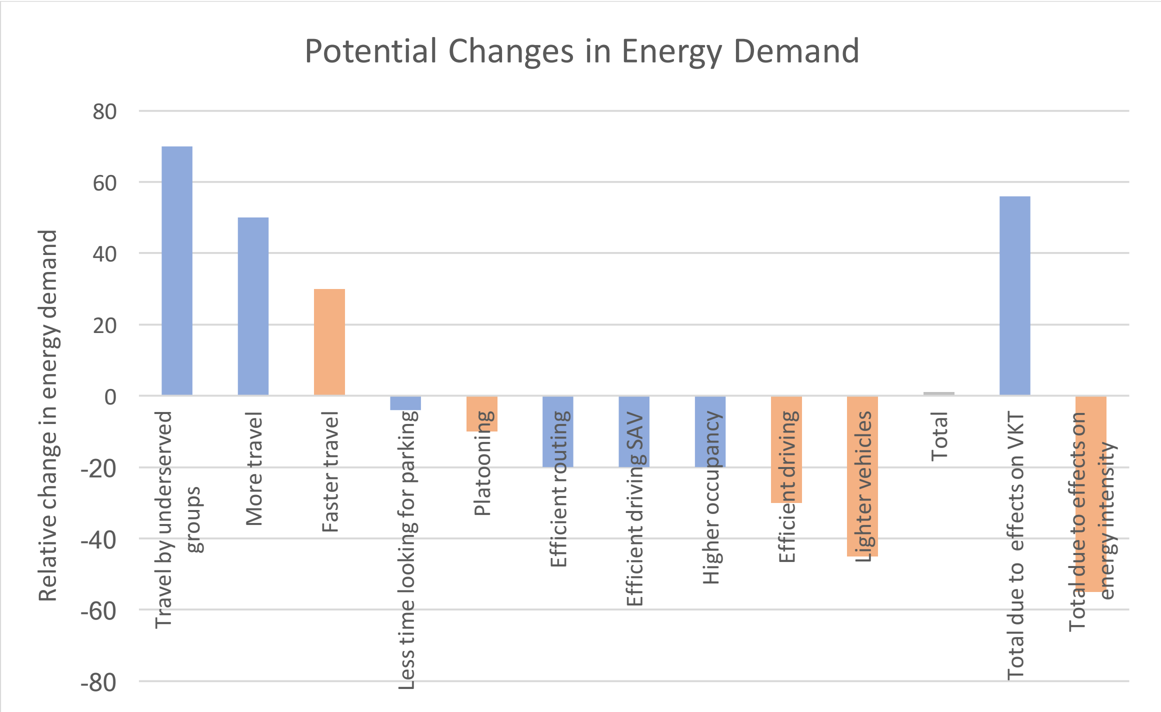


***Figure 7.3 – Potential changes in energy demand due to AV adoption**. Source: graph based on data from (Brown et al., 2013).*

7.3 Strategic uncertainties

There are certain factors that have significant influence on the development of autonomous vehicles and their effect on urban development from a sustainability perspective. The shaping of the future follows different trajectories, depending on the outcome of strategic uncertainties. External macro-trends set the constraints for the extremes while policies and choices affecting strategic uncertainties represent different opportunities for development trajectories to become reality. The scenarios introduced in chapter 5 have been constructed using different assumptions for external trends as well as strategic choices. This section of the report presents which trends and strategies are relevant, should be discarded or enhanced to shape a beneficial, future scenario established around the local context of Gothenburg.

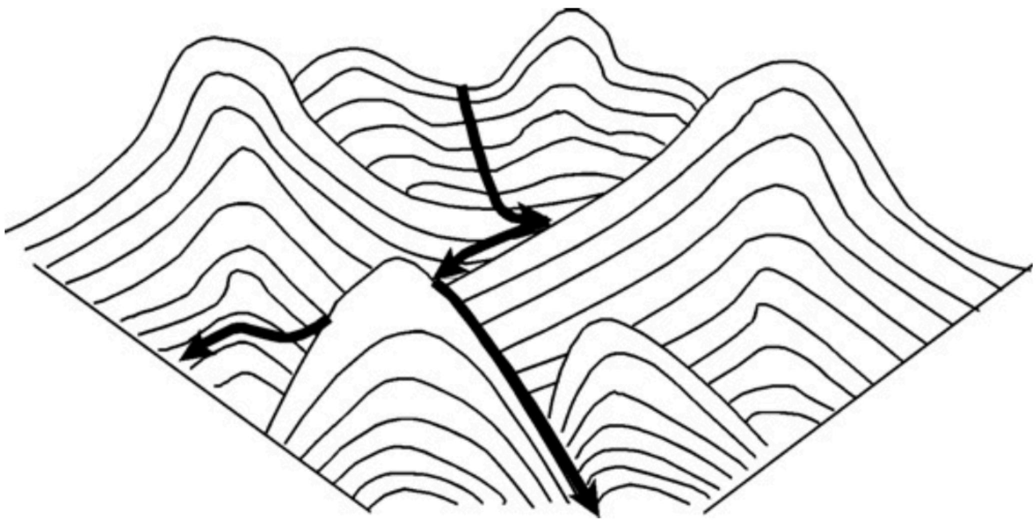


Figure 7.4 – Topography of development trajectories. *Source: Sahal, 1985, p. 79. https://www.researchgate.net/figure/222534486_fig3_Fig-3-Topography-of-development-trajectories-Sahal-1985-p-79*

A breakthrough of sharing and circular economy would have a huge impact on all aspects of society, including mobility and urban planning. The consumption based paradigm today would be replaced by less buying and more renting, sharing, repairing and reusing. Local communities would get an enhanced role in this future.

The future traffic volume and fleet size depends directly on people's willingness to adopt car- and/or ride-sharing in everyday life. A high degree of sharing could dramatically decrease the traffic flows and spatial requirements for mobility related infrastructure. Autonomous vehicles can result in anything from a 90% decrease to a 100% increase of today's traffic volume, depending on adoption mode and travel patterns. This brings huge discrepancies to the environmental, social and economic consequences. There are currently different systems for ride-sharing, both informal and private as well as more regional or community based solutions. Although ridesharing is encouraged, the breakthrough has proven limited. Part of the charm with owning your own car is the freedom to come and go as you wish without having to adapt to others' claims in space or time. Ride-sharing requires communication and planning and is therefore less attractive. By transferring these responsibilities to an automatic, computerised system, ride-sharing can become more attractive and the economic and environmental benefits might be a strong enough incentive to share a ride. Car-sharing is often seen as less controversial as it does not include the personal safety or integrity issues associated with ride-sharing. Vehicle automation makes car-sharing easier and more convenient as no pre-travel interaction with the fellow passengers is required. The economic advantages are also clear.

Proactive versus reactive planning is another strategically significant aspect of future urban development, especially when it comes to mobility development and technological paradigm shifts.

The possibilities for decarbonisation can be synergised with the technological development connected to vehicle automation. Electrification is especially beneficial for AVs as they already operate with a highly advanced electronic system.

Strategically important uncertainties include:

- Breakthrough of sharing economy
- Proactive or reactive planning
- Electrification or other decarbonisation of the transportation sector
- Rate of urbanisation and competition for land in urban areas
- Energy availability and price
- Economic growth
- Public attitude towards autonomous mobility

The capacity of vehicle automation to have a positive impact on sustainable urban and regional development is highly dependent on the model of implementation

7.4 Gothenburg scenario framework

The ideal scenario features a close integration of mobility networks for public, private and cargo transportation. One of the key factors in creating a beneficial scenario is proactive planning and active policies that steer the development in a desirable direction. Vehicle automation can only make a significant contribution to sustainable development if it increases ride- and car-sharing. The public transportation system with trams, buses and commuter trains constitutes the core of urban mobility. It is enhanced by a highly efficient and flexible network of shared autonomous vehicles (SAV). A SAV system can handle passenger transportation as well as freight and deliveries. The combined system allows for maximum efficiency while preserving the flexibility of a free-flowing and autonomous system. Within the city limits, AV adoption must be 100% to create the most beneficial situation. A software system with a mobile app can be used to summon vehicles and calculate the best route and mode for each individual passenger.

The findings made throughout this report can be summarized in a list of features that can be considered beneficial in enhancing urban sustainability while implementing a transportation system based on autonomous vehicles.

- AV is an integrated part of public transportation.
- TaxiBots/SAV rather than AutoVots.
- Network feeding pods to support public transit.
- Micro-UCC on former parking areas where appropriate.
- Superblock structure with priority for motorized vehicles only on certain routes.
- Most roads are pedestrian-oriented shared spaces.
- Separate bike lanes for quick and safe access.
- Reallocation of parking space to coherent green infrastructure for ecosystem services and enhanced wellbeing throughout the city.
- Integration of networks under strict conditions, i.e. defining spaces according to pedestrian, intermodal sharing or AV priority.
- Flexible design of parking spaces and transport-related infrastructure.
- Integrate system for goods deliveries in urban planning with AV operation.
- Decarbonisation of transportation and energy sector.

8 Discussion

In regard to the sustainability goals summarized in table 4.1, the impacts of vehicle automation have the potential to push the development along the desired trajectory. A green future is possible only if policy makers and planners take responsibility and support a sustainable urban transportation system. The scenario for Gothenburg contains a number of different features that can enhance the sustainability of the city. Transportation is only a part of a city's carbon footprint and environmental load but the paradigm shift can bring beneficial system wide changes.

8.1 Impacts on sustainability

The impacts of the scenario for Gothenburg for each of the categories used in the PUGH matrix (section 6.1) are further discussed and evaluated in this section of the report. The possible environmental, economic, social, spatial and operational effects are reviewed in the reflection of the local context of Gothenburg. The urban typologies presented in chapter 6.4 are used as test beds for the overall impact assessment, this becomes especially prominent in section 8.1.4 that is dedicated to spatial impacts.

8.1.1 Economic impacts

The economic impacts of a transition towards autonomous mobility have not been thoroughly investigated within the scope of this thesis. All transportation related industry will be reshaped to serve the new market and transportation as a service brings a whole new kind of market with huge potential for new business models as well as great value for the public realm. In terms of efficiency, vehicle automation provides possibilities for better use of existing assets. Investments in infrastructure, industry and business models that support the old paradigm create a lock-in that makes the transition less appealing.

For the individual, AV technology presents an unprecedented opportunity to cut transportation costs by embracing car and ride sharing. This creates a number positive effect when money previously spent on fossil based mobility can instead be used for sustainable consumption that enhances the personal wellbeing. Cheaper ubiquitous transportation options can also contribute to decreased economic disparity throughout society.

8.1.2 Social impacts

Personal safety is a concern that arises as ride-sharing becomes a normative way of transportation. A system to ensure safety is necessary and must be balanced against personal integrity issues. There is also a possibility of negative health impacts due to convenient door-to-door communication.

Positive effects include increased accessibility for underserved groups and chances of more equal mobility options for different groups in society. Decreased travel time and more productive travel time can be seen as a positive effect on social sustainability as people get more time to spend on activities that increase the personal wellbeing.

8.1.3 Environmental impacts

Decreasing motorized transportation is a challenge regardless the mode use to provide the mobility. Why it is essential to decarbonize the system and build the city in a way that minimizes the need for transportation. Problems with greenhouse gas emissions and air pollution cannot be solved by vehicle automation technology in itself. As technology is improved the CO_2 emissions per value added can be effectively decreased.

Fleet size and VKT are essential factors as they have a direct impact on emissions as well as space requirements. As shown in figure 7.1, the required fleet size is directly dependent on the level of AV adoption. Traffic volume is likely to increase drastically unless ride-sharing is deployed. The traffic volume is represented by the affluence term in the IPAT equation, and has a linear correlation with the impact of traffic on the environment. According to these results, it is essential to have a rapid transition and cover all transportation with full automation in order to achieve the maximum efficiency in the system. AV implementation does not solve any environmental problems on its own but must be accompanied by ride-sharing as the normative complement to public mass transit as well as a decarbonisation of the dominating driveline technology.

Space can be regarded as one of the most fundamental resources in a city and the competition for space in proximity of dense human and economic capital is increasing worldwide as the rate of urbanisation is picking up. As a historic heritage, cities are often surrounded by prime crop land. This means expanding city limits often eats away land that could otherwise be used for food production. The ecological value of land must be considered whenever making changes to the urban environment. The fleet size represents embodied energy with an inherent carbon debt as well as consequences due to spatial requirements. The area claim per passenger is therefore an important aspect in shaping the mobility system of the future. Vehicle automation can allow a reallocation of space to ecosystem services to create a green infrastructure throughout the city. AVs can help to form a denser city by making parking spaces redundant and creating a more space efficient mobility flow. The area appropriation per passenger may decrease with ridesharing and vehicle types better adapted to the actual needs of the passengers. AVs can also be programmed to prioritize pedestrians and other soft mobility modes in designated streetscapes. As of urban sprawl, the effects depend on the chosen system of implementation, whereas measures must be taken to consider this aspect in all decisions made concerning mobility in the region. The use of roads and infrastructure can be remodelled to reassess the use of over dimensioned structures as well as minimizing barriers in the city. AVs also present an enhanced opportunity to concentrate public transportation to nodes and corridors as an efficient and economically viable feeder system can complement the public mass transit.

Sprawling cities lead to the appropriation of more land for urban development. Due to the historic context of urbanisation, land around cities is often productive and farmable. The environmental impacts of land use transformation can be adverse. Replacing green areas with hard surfaces affects the local climate, resilience, storm water capacity, biodiversity and provision of ecosystem services. When developing a new area, the ecological value of land and of a global hectare must always be considered and the consequences thoroughly investigated.

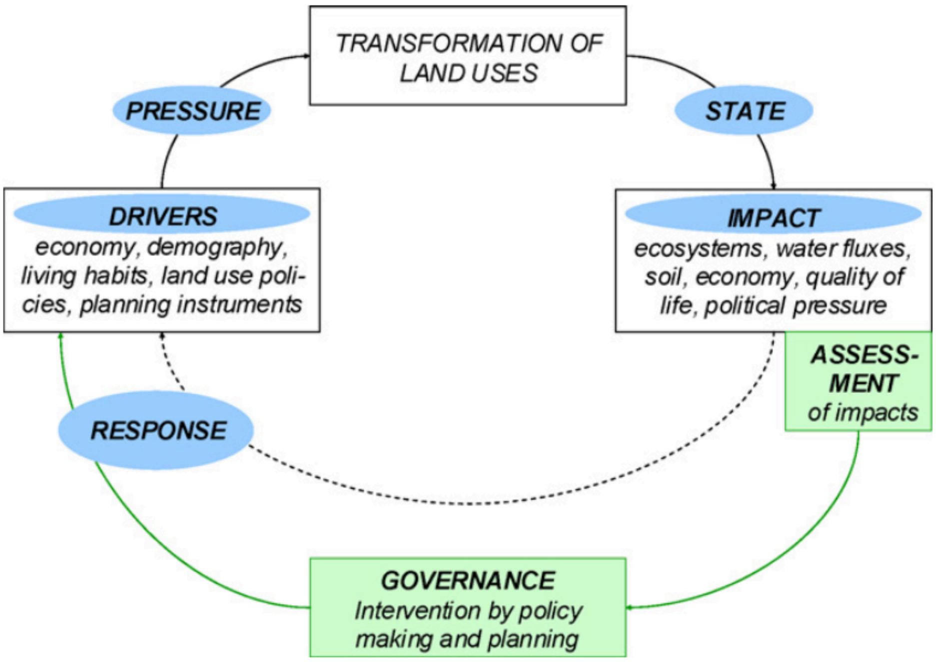


*Figure 8.1 – **Transformation of land uses.** Source: https://www.researchgate.net/publication/223688006_Environmental_impact_assessment_of_urban_land_use_transitions-A_context-sensitive_approach*

8.1.3.1 Traditional block structure

The most obvious visual change in parts of Gothenburg that are characterised by a traditional block structure is the uplifting absence of parked vehicles and the possibility of using streets for purposes other than transportation. The section of street space used for transportation can be heavily reduced as vehicles gain the ability to operate safely without buffer space. Ecosystem services, social spaces, small businesses and micro consolidation centres inter alia, can be assigned valuable space in the city centre.

8.1.3.2 Traffic separated high rise

Areas with traffic separated high rise buildings have the potential to become much denser as parking areas are developed into residential, commercial, public or mix-used buildings. The scattered structure can gain foundation for a more diverse functions, services and transportation. A better range of services in the neighbourhood gives people to possibility to travel less and can have a positive effect on the overall traffic volume.

8.1.3.3 Residential garden city

Areas with the characteristics of a residential garden city are not likely to have the same visual transformation of the physical structure as the other investigated typologies. Although, the need for private car ownership is reduced to zero and the houses will no longer need vehicles parked outside. The streets can become lusher with gardens that stretch all the way out to the road and the area will be safer for children to play on the streets. Ridesharing has the potential to become more common in than previously as such arrangements no longer must be made in advance. Extending the sharing mentality to include material capital such as tools, lawn movers and other equipment could bring further environmental, economic and social benefits and incite the concept of circular economy. Redundant parking spaces can be used for larger gardens or new buildings and garage space can be converted to workshops or living quarters. The additional space can be rented out to generate extra income.

8.2 Strengths and weaknesses

Vehicle automation seems to be happening faster than anyone could have anticipated. The situation today is significantly different compared to when the seed that grew into the idea for this thesis, was found less than a year ago. Handling this continuous, fast and rather unpredictable development during the process of this thesis has been a challenge, but has also highlighted the comprehensive speed of development and disruptive capacity of the technology,

The strength in this report lies in its interdisciplinary approach and thorough background. Combining knowledge from different research projects to create a more holistic picture of the situation made the analysis more accurate and realistic. However, a weakness lies in the selection of reports and scenarios that were included in the PUGH matrix. A more comprehensive mapping of the current research situation could have been made to ensure an unbiased result. At the beginning of the project there was not as much information available on the topic and many of the reports included were published during the course of this thesis.

Another weakness is the lack of incorporation of the urban typologies in the results and discussion. The local perspective could have been more prominent throughout the report as the research question clearly sets the geographical boundaries to Gothenburg. However, the results and discussion are valid for the area and can also conveniently be extended to other cities.

Finding research and statistical data on the traffic volume in Gothenburg was challenging. There is no holistic or comprehensive information on total vehicle kilometre travelled or number of trips, available to the public. Furthermore, the studies and estimations that have been conducted may not be representative for the situation today.

A comprehensive answer to the research questions has not been given. This suggests that the questions were too big to begin with and further limitations could have been positive for the overall process as well as the final results. The future transportation system for Gothenburg could have been given a more in-depth description including stakeholders and conditions for network integration. The environmental consequences of a transition to the new system have been discussed qualitatively rather than specifically quantified. This can be considered both a strength and a weakness as it makes the study more applicable on other contexts but also limits the influential capacity of the conclusions made.

The relevant environmental goals and targets as well as current trends and development trajectories were clearly described in the background chapter. Focus has been more on threats and benefits inherent to different autonomous transportation systems, including effects on fleet size and VKT, rather than the specific effects on a local implementation of a well-defined system. Finally, the question of how much space could be freed up in Gothenburg thanks to the implementation of autonomous transportation remains. The report makes a few different suggestions on how much of current parking areas would be rendered obsolete due to different conditions for autonomous urban mobility systems. The typologies are used to make a few locally valid points, but an estimation or description of the overall effect is lacking.

8.3 Suggestions for further research

The topic of autonomous transportation and its impacts on social, economic and environmental sustainability is immense. This report has only just scratched the surface of the knowledge and understandings required to design and implement the perfect system for urban mobility. Although the technology is well developed, the need for additional research and development about sustainable application is ever-present. There are many aspects within the topic of this report that could be developed further. Some suggestions for further research that could be useful for the transition are;

- Mapping of parking in Gothenburg, current distribution and alternative uses.
- Local conditions and stakeholders for AV implementation.

- Develop a framework for design of infrastructure elements to allow flexible use and accommodate current as well as future needs.
- Investigate public acceptance of vehicle automation and ride sharing.
- Redesign of public spaces in Gothenburg to embrace and benefit from vehicle automation.
- Studies on how travelling patterns may change and the overall impact on the traffic volume.

8.4 Recommendation

There are many different policy pathways that may facilitate the development of a SAV-based transportation system and all its concomitant positive effects on the city and its environment. Making the right choices is also imperative to avoid the possible adverse effects that a technological paradigm shift can convey.

One important factor is to support the testing and wide-scale adoption of electric AVs. This is already being done in Gothenburg, with the Volvo DriveMe pilot project. The level 5 AV testing is however limited to certain routes. The next step is city-wide testing and testing in areas where motorized traffic is mixed with pedestrians and cyclists. Establishing legal standards for the handling of passenger data and who is allowed access to the data and with what purpose it may be used is also an important step in the process of enabling SAV-based mobility. The system must ensure complete safety for vehicle networks, passenger data and M2M communication.

Public acceptance can be enhanced through educative campaigns, highlighting the financial, social, health and environmental benefits of a SAV-based urban mobility system. Benefits can also be optimized by encouraging open-access technology and data to attract more developers and lower the threshold to invest in AV technology and mobility services. Stakeholder diversity is important in hindering large corporation oligopolies and ensuring that benefits from lower cost per VKT is passed on to consumers in all markets (Arbib and Seba, 2017).

From an urban planning perspective, strategies for making the best use of obsolete parking lots, roadside parking spaces and unneeded transport infrastructure are necessary in shaping the city of the future. Regulatory frameworks for converting unneeded commercial garages to social and productive uses should also be reiterated. Suggested uses could be; affordable housing, co-working spaces, art studios, in-law units, student housing or walk-up spaces (Arbib and Seba, 2017). Furthermore, the concept of nodal development could be questioned as a free-flowing and adaptive public transportation system is not as dependent on mobility hubs as traditional public transportation system. General urban consolidation and micro-polycentric networks may be a better approach.

- Develop models for sharing economy and change the general mentality towards sharing, without compromising safety and integrity.
- Plan proactively to prepare and adapt infrastructure for level 5 automation.
- Support research on alternative fuels to develop a dominant technology sooner rather than later. Electrification may or may not be the winning design.
- Plan the city to minimize transportation and yet ensure freedom of mobility for the citizens.
- Use parking regulations as an effective policy instrument to heavily reduce traffic from private vehicles.
- Ban all fossil fuel vehicles and eventually all non-AVs within the city limits. Announce the ban sooner rather than later to boost adaptation of the industry.
- Implement active policies to prevent urban sprawl due to AV adoption.
- Establish the new market in a way that ensures an inclusive system with the aim to provide equal access for all.
- Clearly define the conditions for operating AV as part of the transportation network.
- Eventually implement a citywide superstructure and local networks to define the modal priority of all public spaces.
- Aim for 100% implementation and avoid a protracted transition period.
- Use AV technology in public transportation.

Figure 8.2 – Street view with current paradigm. *Illustration by the author and Anna Svending.*

Figure 8.3 – Street view after transition to autonomous mobility system. *Illustration by the author and Anna Svending.*

9 Closing remark

Vehicle automation presents an opportunity of fundamental change. It has the power to transcend paradigm and change of the very machine of modern city operates. Functions that have been perceived as evident components of the urban context since the industrial revolution, may now become superfluous. However, there are also vulnerabilities involved and an imminent risk of shaping cities that are even more dependent on individual consumption, energy generation and material depletion.

This report discusses the potential benefits of vehicle automation, in terms of environmental, economic, social, operational and spatial components in an urban context, and how these benefits can be enjoyed while avoiding impediments and undesirable consequences. Reaping the benefits of technological advancement can be done by practising proactive planning and having a clear political and communal ambition. Planners and decision-makers must become aware of the scale, speed and effects of the imminent disruption in the transportation sector that technical advancement conveys within the next few decades. Proactive planning is imperative to sustainable urban improvement.

I am looking forward to following the development of a new paradigm within the transportation sector and I hope that the City of Gothenburg can embrace and benefit from the technological leap of vehicle automation in a way that enhances the overall sustainability of the city.

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