THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Almost there

Examining the travel demand, emissions, and effects associated with a socio-technical transition to automated vehicles in Sweden.

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Almost there: Examining the travel demand, emissions, and effects associated with a socio-technical transition to automated vehicles in Sweden.

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Abstract

Global average temperatures have increased by 1.1 degrees Celsius since pre-industrial times. We know with near certainty that this warming and the associated climate change are caused by increased emissions of anthropogenic greenhouse gases (GHGs), and transportation is a large source of GHG emissions. Automated Vehicles (AVs) are slowly becoming a viable mode of transportation. There remains, however, uncertainty about how their introduction into the transportation system will happen, what effects this introduction could cause on travel distances, GHG emissions, and more broadly on society overall, and how AVs can be governed to avoid negative sustainability impacts and help achieve existing sustainability goals. The papers in this doctoral thesis aim to address these research gaps.

Paper 1 uses a travel demand model to assess the consumer surplus impact of AVs, their costs, and the ensuing effects on Vehicle Kilometres Travelled (VKT) and lifecycle emissions. The results showed that VKT increases can become substantial and that higher income earners in Sweden are more likely to purchase an AV and increase their travel distance than lower income groups.

Paper 2 uses mixed methods to examine the driving and restraining forces and pressures that could influence the introduction of AV technology in the City of Gothenburg. **Paper 3** studies the societal consequences of AV technology, and policies to control negative potential consequences and stimulate the positive ones. These papers found that explicit policy planning for AVs is likely needed if the existing transportation goals within the City of Gothenburg are to be met, and that cooperation between different actors and reflexivity will be crucial as new iterations of AV technology are introduced.

Paper 4 uses a backcasting-inspired approach to first envision a future where AVs are fully deployed and sustainability goals are met and then to examine how that future image could be obtained for some selected technology systems and policies. It was found that increased national funding to regions and cities, along with improved cooperation between all levels of government on policies like a kilometre tax, is crucial in this scenario. Measures such as Bus Rapid Transit and Demand-Responsive Transit could benefit from these efforts, especially before AV technology is fully mature. However, successfully implementing these policies will require careful planning and cooperation between municipal, regional, and national governments.

In conclusion, it is clear that although there is little AV-specific policy in Sweden **(Paper 2)**, there are environmental and transport policy goals at all levels of government that are well-suited to guide the introduction of the technology **(Papers 3 and 4)** so that potential negative impacts can be avoided **(Paper 1)**. Finally, while it is theoretically possible to meet domestic emissions reductions goals without AV technology, the findings in **Paper 3** and **Paper 4** show that with careful planning AVs can help contribute to the fulfilment of sustainability goals related to a myriad of indicators including safety, accessibility, and supply-chain emissions, as well as domestic emissions reductions.

Keywords: AV (Automated Vehicle), socio-technical transition, sustainability goals, travel demand, Transition Management, governance.

Samanfattning

Den globala medeltemperaturen har ökat med 1,1 grader Celsius sedan industrialiseringen tog fart. Vi vet med stor säkerhet att den globala uppvärmningen och de tillhörande klimatförändringarna har orsakats av ökade utsläpp av antropogena växthusgaser, och att transporter är en stor källa till dessa utsläpp. Automatiserade fordon (AV) håller sakta men säkert på att bli ett viktigt transportmedel. Det råder dock fortfarande osäkerhet om vilka effekter denna introduktion kan ha på resmönster, utsläpp av växthusgaser och samhället i stort, samt hur tekniken kan regleras för att undvika negativa hållbarhetseffekter och bidra till att uppnå befintliga hållbarhetsmål. Artiklarna i denna doktorsavhandling bidrar till att fylla dessa luckor i forskningen.

Artikel 1 använder en modell över efterfrågan på resor för att bedöma hur konsumentöverskott påverkas av AV resekostnader, och vilka effekter det får på körda fordonskilometer samt livscykelutsläpp. Resultaten visar att ökningarna i körda fordonskilometer kan bli betydande vid introduktionen av AV och att höginkomsttagare i Sverige är mer benägna än låginkomsttagare att skaffa en AV och öka sina körsträckor.

Artikel 2 använder kvantitativa och kvalitativa metoder för att undersöka vilka hinder och drivkrafter som kan påverka införandet av AV i Göteborgs Stad. **Artikel 3** utforskar de samhälleliga konsekvenserna av AV och den reglering som behövs för att minimera potentiellt negativa och stimulera positiva konsekvenser av tekniken. Dessa artiklar identifierar att explicit planering för AV sannolikt behövs om de befintliga transportmålen inom Göteborgs Stad ska uppnås, och att samarbete mellan olika aktörer och reflexivitet kommer att vara avgörande när nya versioner av AV-tekniken introduceras.

Artikel 4 använder en backcasting-inspirerad metod för att först måla upp en framtid där AV:er är fullt introducerade i samhället och hållbarhetsmålen är uppnådda, för att sedan undersöka hur den framtidsbilden kan uppnås för vissa utvalda tekniksystem och styrmedel. Resultaten visar att ökat nationellt stöd till regioner och städer, tillsammans med förbättrat samarbete mellan offentliga beslutfattare på olika nivåer kring styrmedel, såsom en kilometerskatt, är avgörande i detta scenario. Åtgärder som ”Bus Rapid Transit” och ”Demand-Responsive Transit” skulle kunna dra nytta av dessa insatser, särskilt innan AV-tekniken är helt mogen. Att framgångsrikt

genomföra dessa styrmedel kommer dock att kräva noggrann planering och samarbete mellan kommuner, regioner och staten.

Sammanfattningsvis är det tydligt att även om det finns lite AV-specifik politik i Sverige (**Artikel 2**) finns miljö- och transportpolitiska mål på alla förvaltningsnivåer som är väl lämpade för att reglera införandet av tekniken (**Artikel 3 och 4**) så att potentiella negativa effekter kan undvikas (**Artikel 1**). Slutligen visar resultaten i **Artikel 3** och **Artikel 4** att AVs kan bidra till uppfyllandet av hållbarhetsmål relaterade till en mängd indikatorer som säkerhet, tillgänglighet och minskade livscykelutsläpp likväl som att uppnå inhemska utsläppsmål, även om dessa är teoretiskt möjliga att uppnå utan tekniken.

List of appended papers

I **Rebalski, E.**, and Johansson, D. J. A. (2024) Too Far? Autonomous vehicles, travel demand, and carbon dioxide emissions in Sweden. *European Transport Studies*, 1, 100006. https://doi.org/10.1016/j.ets.2024.100006

II **Rebalski, E.**, Adelfio, M., Sprei, F., & Johansson, D. J. A. (2022). Too much pressure? Driving and restraining forces and pressures relating to the state of connected and autonomous vehicles in cities. *Transportation Research Interdisciplinary Perspectives*, 13, 100507. https://doi.org/10.1016/j.trip.2021.100507

III **Rebalski, E.**, Adelfio, M., Sprei, F., & Johansson, D. J. A. (2024). Brace for impacts: Perceived impacts and responses relating to the state of connected and autonomous vehicles in Gothenburg. *Case Studies on Transport Policy*, 15, 101140. https://doi.org/10.1016/j.cstp.2023.101140

IV **Rebalski, E.**, Johansson, D. J. A., Sprei, F. Getting there: the role of autonomous vehicles in a future sustainable regional transportation system. *Submitted to the journal Futures.*

Author Contributions

Paper I DJ designed the study with input from ER. DJ and ER developed the theoretical model framework, ER implemented the numerical simulation model and performed the numerical analysis, ER wrote the original draft with input from DJ. ER and DJ reviewed and edited the final manuscript.

Paper II All authors designed the study. ER and MA curated the data and wrote the original draft. All authors were involved in the reviewing and editing of the final manuscript.

Paper III All authors designed the study. ER and MA curated the data and wrote the original draft. All authors were involved in the reviewing and editing of the final manuscript.

Paper IV ER designed the study with input from DJ and FS. ER curated the data and wrote the original draft. All authors were involved in the reviewing and editing of the final manuscript.

Publications not included in this thesis

Curtale, R., Liao, F., & **Rebalski, E.** (2022). Transitional behavioral intention to use autonomous electric car-sharing services: Evidence from four European countries. *Transportation Research Part C: Emerging Technologies*, 135, 103516. https://doi.org/10.1016/j.trc.2021.103516

Ja visst gör det ont när knoppar brister.
Varför skulle annars våren tveka?
Varför skulle all vår heta längtan
bindas i det frusna bitterbleka?
Höljet var ju knoppen hela vintern.
Vad är det för nytt, som tär och spränger?
Ja visst gör det ont när knoppar brister,
ont för det som växer
och det som stänger.

Of course it hurts when the bud breaks.
Why, otherwise, would spring hesitate?
Why would all our desperate longing
be kept under wraps in the frozen, bitter bleakness?
It was just a little bud all through the winter.
What is this new, that rips and cracks?
Of course it hurts when the bud breaks,
it hurts as something opens
and something closes.

From the poem *Ja Visst Gör det Ont* by Karin Boye

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I have had the immense privilege to receive support in many different forms from many different people since I started this PhD. I would like to borrow from Billy Porter and say this: if I forget to mention your name here, please charge it to my brain, and not my heart. For my heart is full.

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Ella Rebalski

Galiano Island, August 2024

Table of contents

List of commonly used abbreviations

AV:	Automated Vehicle
BRT:	Bus Rapid Transportation
CO2:	Carbon Dioxide
CS:	Consumer Surplus
DRT:	Demand Responsive Transportation
DSPIR:	Drivers, Pressures, States, Impacts, Responses
EU:	European Union
GHG:	Greenhouse Gas
GR:	Gothenburg Region
ODD:	Operational Design Domain
TG:	Transition Governance
TM:	Transition Management
UNECE:	United Nations Economic Commission for Europe
VKT:	Vehicle Kilometers Travelled
VoTT:	Value of Travel Time
VGR:	Västra Götalandsregion

Foreword

This PhD thesis is a study of change and how humans react to it. The change in this case is the introduction of Automated Vehicles (AVs).

The poem Ja Visst Gör det Ont (Of Course it Hurts) by Karin Boye that introduces my thesis is about the pain and beauty of a drastic change. It also refers to an ending, and a beginning. This can apply to a new technology replacing an old one, or on a personal level, the end of one chapter of my professional life and the beginning of the next.

I embarked on this PhD because I was excited by the idea of examining a technology whose deployment was a foregone conclusion, that was coming whether we liked it or not, and I just had to determine where it was going to take us. This was before the first fatal AV accident, before a virus took over the world and made it much more uninviting to share a vehicle with other people, and before it became brutally clear that AV technology is going to be extremely difficult to deploy at scale.

And yet at the time of writing, the technology is gaining traction again. The sheer volume of scientific studies on AVs is enormous, and growing steadily. This includes a number of excellent PhD theses that specifically study the societal effects of AVs. Some whose work I have found particularly interesting are Baiba Pudāne, Erik Almlöf, Bård Torvetjønn Haugland, Sigma Dolins, and Janne J. Olin, and they represent a just a tiny drop in the bucket.

The title of this thesis,"Almost there", refers to a question that I have been asked frequently over the years: When are we getting AVs? I don't have an answer, though we do make some educated guesses in Papers 1 and 4. But the title also refers to a very tricky reality in scientific research: we can never be completely certain of a conclusion, but it's in getting as close as we can that we discover the interesting stuff.

1. Introduction

Global average temperatures have increased by 1.1 degrees Celsius since pre-industrial times. We know with near certainty that this warming and the associated climate change are caused by increased emissions of anthropogenic greenhouse gases (GHGs). The consequences of climate change include higher temperatures, unstable weather patterns, drought, and likely an increasing numbers of climate refugees as large areas become uninhabitable (IPCC, 2023).

One of the largest sources of GHG emissions is the transportation sector, which accounts for 23% of global energy-related carbon dioxide emissions (International Transport Forum, 2023), and approximately one third of emissions in Sweden (Swedish Climate Policy Council, 2024), which is the geographic focus of this thesis. In 1963 the Riksdag (the Swedish parliament) set forth the country's transport policy objective: that all parts of the country should have satisfactory transportation, at the lowest possible cost, carried out in a manner that supported commerce and the sound development of the transport system (Government of Sweden, 2009). Since then, that transport policy objective has become multiple objectives that include indicators measuring accessibility, physically active trips, safety, energy efficiency, and effects on the environment (Transport Analysis, 2024a). Today, the transport policy objectives overlap and interact with sustainability goals such as Sweden's generational goal, which states that Swedish environmental policy is to hand over to the next generation a society in which the major environmental problems have been solved, without increasing environmental and health problems outside Sweden's borders, and the country's main climate goal of net-zero greenhouse gases (GHGs) by 2045 and negative emissions after that (Swedish Climate Policy Council, 2024; Swedish EPA, 2024).

The generational goal is connected to transportation in many ways, a prime example being its focus on sustainable patterns of consumption, which includes combining transport efficiency with electrification to minimize the negative effects inherent in automobile manufacturing (Swedish EPA, 2022). Progress evaluation for both the generational goal and the transport policy objectives are done regularly, and the latest governmental reports from the relevant agencies show that many of the transport policy objectives are trending negatively. Emissions from transportation are shrinking, but not at a fast enough rate to stay on the timeline for net-zero emissions by 2045 (Transport Analysis, 2024a).

But how do Autonomous Vehicles (AVs) factor into this context? The four articles in this doctoral thesis examine the potential effects that this technology could have on the Swedish transportation system and society. If one looks at AVs from the perspective of reaching national sustainability goals, they could matter a great deal. More specifically, if they enable increased ride-sharing (Soteropoulos et al., 2019) and more efficient modes of transportation (Lorig et al., 2023), they could help to reduce greenhouse gas emissions from passenger cars in Sweden, which totalled 8.27 million tonnes in 2022 (Swedish EPA, 2024). However, this depends on how the technology is used (Almlöf, 2024; Haugland, 2022; Hopkins & Schwanen, 2018). For example, potential user groups who were previously unable to drive could now have access to private cars (Lee & Kockelman, 2015); passengers could drastically increase the length and frequency of car trips because they would be able to use the time in the car for other activities (Wadud, 2017); and when passengers are deposited at their destination, the empty AV could continue driving to its next stop, therefore driving much farther than a conventional car (Annema, 2020). Put together, these trends could cause a substantial increase in emissions from passenger cars as well as other negative effects such as noise, congestion, barrier effects (Schröder et al., 2023), suburban sprawl (Moore et al., 2020; Pernestål et al., 2020), and life-cycle emissions from vehicle manufacturing (Morfeldt et al., 2021).

In order to avoid potential large-scale problems and steer towards the potential benefits of the technology, the introduction of AV technology needs to be carefully planned and executed. And this planning would hopefully benefit from being informed by scientific research that carefully studies the possible scenarios stemming from this as yet relatively untested (at a societal level) technology. The papers included in this thesis contribute to this research.

1.1 Aims

The research in this doctoral thesis aims to examine the introduction of Autonomous Vehicles (AVs) in Sweden, the effects of this technology, and how it could be governed. More specifically, this includes: an analysis of how the introduction of, and the socio-technical transition to, AVs will be influenced by different forces in society, industry, and other relevant areas; examining the potential effects of the technology on travel distance, and the wider effects on society and GHG emissions; and looking further into how AV technology could potentially help meet national, regional and local climate and transport sustainability goals.

1.2 Research Questions

To meet the aims set out in the previous section, the research questions in this doctoral thesis are:

RQ1: How might a change in the Value of Travel Time because of the use of AVs impact travel demand and lifecycle greenhouse gas emissions?

This question is addressed in **Paper 1**.

RQ 2: What Drivers, Pressures, Impacts and Responses are important for a socio-technical transition to AVs?

Sub questions: How do driving and restraining forces and more specific pressures facilitate or hinder such a transition? What stakeholders are connected to the driving and restraining forces and pressures? How do local stakeholders perceive the impacts of AVs? How can the complexity of the responses be captured and interpreted for policy interventions using Transition Management?

These questions are addressed in **Papers 2 and 3.**

RQ 3: How can autonomous vehicles be integrated into the Gothenburg Region's transport system to achieve sustainability and climate goals?

This question is addressed in **Paper 4.**

1.3 Contributions

This thesis and the appended papers make the following contributions to the field of transportation research in a sustainability context. **Paper 1** uses empirical data from the Swedish context to calibrate a travel demand model and assess the consumer surplus impact of AVs compared to their costs, and the ensuing effects on Vehicle Kilometres Travelled (VKT) and lifecycle emissions. **Paper 2** combines two theoretical frameworks, the casual chain of Drivers, Pressures, State, Impacts and Responses, (DPSIR) and force-field theory, using mixed methods to examine the driving and restraining forces and pressures that could influence the introduction of AV technology. **Paper 3** combines DPSIR and Transition Management (TM) in a novel way to study the societal consequences of AV technology, and policies to control negative potential consequences and stimulate the positive ones. Finally, many studies examine a future where AVs are fully deployed, but few examine the pathway to that future (Staricco et al., 2020). **Paper 4** uses a backcasting inspired approach to first envision a future where AVs are fully deployed and sustainability goals are met, and then examining how that future image could be obtained for some selected technology systems and policies.

1.4 Use of the term AV and SAE Levels of Automation

Please note that in this thesis I use the term AV to refer to Automated Vehicles, meaning vehicles that are level 4 or 5 in the Society of Automotive Engineers (SAE) system. The research in the appended papers is almost exclusively about these levels of automation. The exceptions are in Paper 3, where I mention AV regulations; and in Paper 4, which discusses the pathway towards AVs, and thus includes a discussion of a transition period where lower levels of automation are used.

The SAE levels of automation are the most commonly used system for classifying AVs depending on what kind of self-driving capability the vehicle has. There are six levels (SAE International, 2021):

- Level 0, No Driving Automation.
- Level 1, Driver Assistance, which can include steering or braking and acceleration support to the driver.
- Level 2, Partial Driving Automation, which can include the combination of steering and braking and acceleration support to the driver.
- Level 3, Conditional Driving Automation, where the vehicle can be automated under certain conditions, but the driver must be ready to take control.
- Level 4, High Driving Automation, where the vehicle is able to drive itself under many conditions.
- Level 5, Full Driving Automation, the vehicle is able to drive itself under all conditions that a human would be able to.

There are different terms for AVs in the scientific literature and within industry: Self Driving Vehicles (SDVs) is not uncommon (Almlöf, 2024), and in previous research I have also used the term Connected and Autonomous Vehicles, or CAVs. This latter term is considered to be important to use when the “Connected” aspect of automated driving systems is relevant for the research analysis and results, for example when a fleet of vehicles are able to communicate with each other and the surrounding infrastructure to drive more efficiently. I have observed, however, that in recent years a great deal of peer-reviewed academic literature uses the term AV, and I find AV to be the most recognizable and easily understandable acronym to describe the transportation phenomenon that I study. It is important to communicate about research as clearly and simply as possible, without sacrificing the underlying facts. Thus, I use the term AV in this thesis.

1.5 Structure

The remainder of this thesis is structured as follows: Chapter 2 is the Background, which provides the reader with information on the history of the automobile industry in Sweden, transport policy and greenhouse gas emissions in Sweden, the current state of AV regulations in different jurisdictions, and an overview of relevant academic literature on AVs. Chapters 3, 4 and 5 summarize the appended papers. Chapter 6 concludes the thesis and lays out some ideas for future research.

2. Background

2.1 *Bilsamhället*, or the Swedish car society

The automobile industry is important to the Swedish economy. Volvo Cars, Volvo Group and Scania are the main players in the industry, but there are also many smaller companies that provide services or support their manufacturing in other ways (research and development consulting, testing, etc). It has been suggested that if the number of jobs in the automobile industry[1] were to increase by 1,000, this would result in an additional 1,000 jobs in other industrial sectors; this effect is among the largest in the manufacturing sector (Statistics Sweden, 2017).

In terms of personal travel, cars are the most common mode of transportation in Sweden, and account for approximately half of all domestic trips (including trips by foot, bicycle, public transportation, and other modes) (Transport Analysis, 2024b). The average number of kilometres travelled by car per person in 2023 was 11,260km, and the average level of car ownership across the country was just under one car for every two people. In total, there were just under 5 million private cars on the road in Sweden in 2023 (Transport Analysis, 2024c).

This reliance on cars and the automobile industry can be traced back to the post-World War II period in Sweden. In his 2014 doctoral thesis "The Car Society: Ideology, Expertise and Rule-Making in Post-War Sweden", Per Lundin studied the class of planning experts that appeared during the 1950s and 60s who were fascinated with the American model of a society built around cars (Lundin, 2014). These experts, according to Lundin, also viewed the technological advancement and uptake of the automobile as a foregone conclusion, and thus the concept of urban and larger-scale national infrastructure planning based on cars was not considered to be a political matter, but simply a technical one. This phenomenon is not unknown in the transportation literature. Mattioli et al. refer to it as "the creation of an apolitical facade around pro-car decision-making" (Mattioli et al., 2020, p. 1). In addition to the assumed impartiality of car technology, the separation of cars

[1] The automobile industry here includes suppliers and subcontractors, as well as automobile companies.

and other modes of traffic, especially pedestrian, was viewed as the best and safest way to guide planning.

Lundin's critique of this self-fulfilling planning process is that the problems of traffic accidents and congestion, which were already present in the 1950s and something that planning experts were trying to address, could have been solved in a number of other ways that did not give priority to cars. Many of the problems that resulted from mass car ownership, such as noise, air pollution and CO_2 emissions, and what Lundin refers to as "torn-down and demolished city centres" (2014, p. 279) could thereby have been avoided.

It is important to be aware of this interpretation of the development and subsequent effects of the "car society" when studying today's AV development, because many of the same effects are already being discussed. In fact, the foregone conclusion that AVs will be developed and used by everyone in society, and the push towards creating special lanes just for AV technology (Yu et al., 2019), are two examples of obvious parallels. Stayton and Stilgoe (2020) summarise the issue with the statement that "A schema for innovation that points in one direction and says nothing about the desirability of the destination makes for a poor roadmap" (p. 1). They suggest that the levels of automation created by the SAE, originally as a common way for the accepted hierarchy of AV technology to be widely understood, are used in a way that suggests that full autonomy is the ultimate end goal, rather than as a tool for exploring different context-based scenarios that encompass more diverse use cases. It should be noted that in 2021, SAE International published a revised version of their Levels of Automation that lays out a number of examples where AVs might use different levels of automation under different conditions during the same trip (SAE International, 2021). These examples arguably demonstrate some of the context-based scenarios called for by Stayton and Stilgoe, though it remains to be seen if large-scale AV testing and technology development will start to explore more diverse use cases.

There is a burgeoning body of academic research into the governance of AV technology. Early research tended to focus on the potential consequences of a lack of governance (Cohen & Cavoli, 2019; Papa & Ferreira, 2018; Staricco et al., 2020). Later studies began to examine the dynamics of various experiments and pilot projects (Haugland & Skjølsvold, 2020; McAslan et al., 2021), as well as stakeholders views on the technology. Finally, as regulations for the technology begin to develop, studies of national AV governance strategies and plans are emerging (Hansson, 2020; Haugland, 2020; Olin & Mladenović, 2022; Taeihagh & Lim, 2019; Tennant et al., 2021).

In this thesis, I attempt to address AV governance by connecting to Sweden's national environmental goals, and examining how AVs could help to meet them. The next section gives more insight into the history behind, and the current status of, the environmental goals that I am referring to.

2.2 Swedish policy goals for transport and greenhouse gas emissions

This thesis and the appended papers are guided by policies that have resulted from two sustainability goals that are enshrined in Swedish law: the goal of net zero emissions by 2045 and the generational goal (Swedish Climate Policy Council, 2024; Swedish EPA, 2022). In addition to these goals, the Swedish Government has transport policy objectives that broadly cover access to transportation, safety, and sustainability (Transport Analysis, 2024a). I will discuss these goals and objectives in more detail below and connect them to the context of my research.

Sweden's goal to reach net zero GHG emissions by 2045 is related to the 2015 Paris Agreement, which aims to keep global temperatures well below 2 degrees Celsius above pre-industrial levels. As a signatory to the Paris Agreement, Sweden plans to reduce its territorial emissions by at least 85% compared with 1990 levels and compensate for the remaining emissions so that the country reaches net zero emissions by 2045 (Swedish Climate Policy Council, 2024). An important part of reaching this net zero goal is a 70% reduction in emissions from domestic transportation by 2030, compared to 1990, which is also a target under the transport policy objectives (Transport Analysis, 2024a).

Figure 1 shows emissions from domestic transportation in Sweden from 1990–2022, broken down by mode. Since 1990, these GHG emissions have fluctuated, peaking in 2007 and then mostly sinking slowly. Passenger cars are by far the largest source of domestic transportation emissions in Sweden, with a total of 8.27 million tonnes of CO_2 equivalents emitted in 2022 (about 60% of domestic transportation emissions). Between 2010 and 2022, these emissions were reduced by 35%, largely due to more fuel-efficient vehicles, the increased use of biofuel (although biofuel use requirements were made less strict in 2024), and the increased use of electric cars (Swedish EPA, 2024). The number of kilometres driven, however, has been steadily increasing, with an exception for the COVID-19 period. The pink line in Figure 1 illustrates this trend, starting at just under 56 billion kilometres a year in 1990 to just under 66 billion in 2023, with fluctuations during that time (Transport Analysis, 2024d).

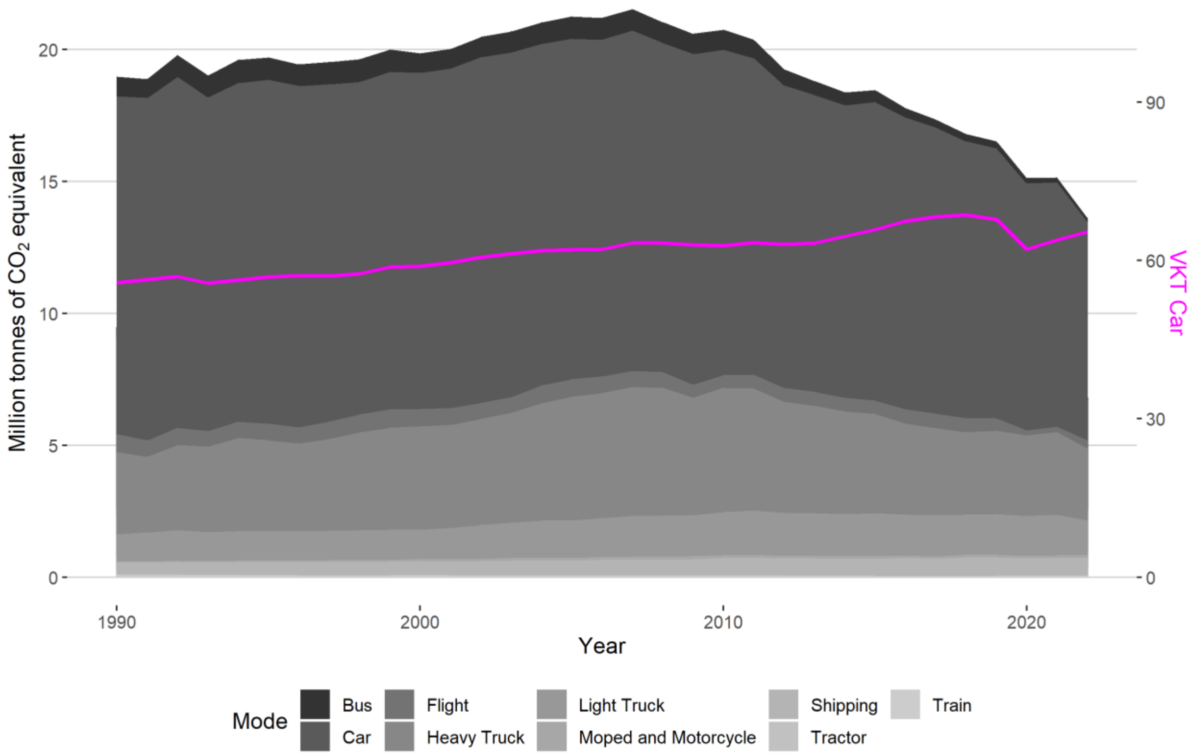

Figure 1: Emissions from domestic transportation and total Vehicle Kilometres travelled by private car in Sweden, 1990–2022. Data from the Swedish EPA (2024) and Transport Analysis (2024d).

The generational goal was brought into law in 2010, and states that the next generation should inherit a society where the major environmental problems have been solved, without increasing environmental and health problems outside Sweden's borders. It is the overarching goal that ties together 16 pre-existing national environmental quality objectives that were voted into law in 1999 in Sweden (Swedish EPA, 2022). In practice, the generational goal can be applied to policy in seven areas, including the efficient use of natural resources and sustainable patterns of consumption. The generational goal and environmental quality objectives are evaluated every year by a group of government agencies. In 2022, the Swedish Environmental Protection Agency (Swedish EPA) published a report stating that the generational goal "will not be fully met by 2030, either within Sweden or with regard to the impact of

Swedish consumption in other countries" (Swedish EPA, 2022, p. 79). The report stresses the importance of sustainable patterns of consumption, and in terms of transportation of combining transport efficiency with electrification to minimize the negative effects of, for example, natural resource extraction in foreign countries that is necessary for battery components (Swedish EPA, 2022).

The generational goal is also connected to Sweden's national transport policy objectives, which are unified in one overall goal for the transport system "to ensure a socio-economically efficient and long-term sustainable transport for the citizenry and business community of all of Sweden" (Transport Analysis, 2024a, p. 3). The transport policy objectives were agreed upon by the Riksdag in 2009 (Government of Sweden, 2009). Within these are the functional objective, which aims to make transport accessible to everyone in Sweden, and the impact objective, which aims for no fatalities or serious injuries, and to contribute to environmental goals and to improving the health of the population. Under the impact and functional objectives are a series of 14 indicators that are used by the government agency Transport Analysis to assess yearly progress towards the objectives. The impact objective is also explicitly connected to the generational goal, and the 16 environmental quality objectives. One of the indicators under the impact objective is that GHG emissions from domestic transportation should be reduced by 70% by 2030, compared to 2010.

Every year the Swedish government agency Transport Analysis reports on trends in the 14 indicators under the impact and functional objectives. The report for 2023 shows that many of the indicators under the functional objective are trending negatively, including transport reliability, financial affordability of transport, perceived usability of the transport system, and physically active trips. Under the impact objective, GHG emissions are reducing, but crucially not at a fast enough rate to reach the 2030 goal (Transport Analysis, 2024a).

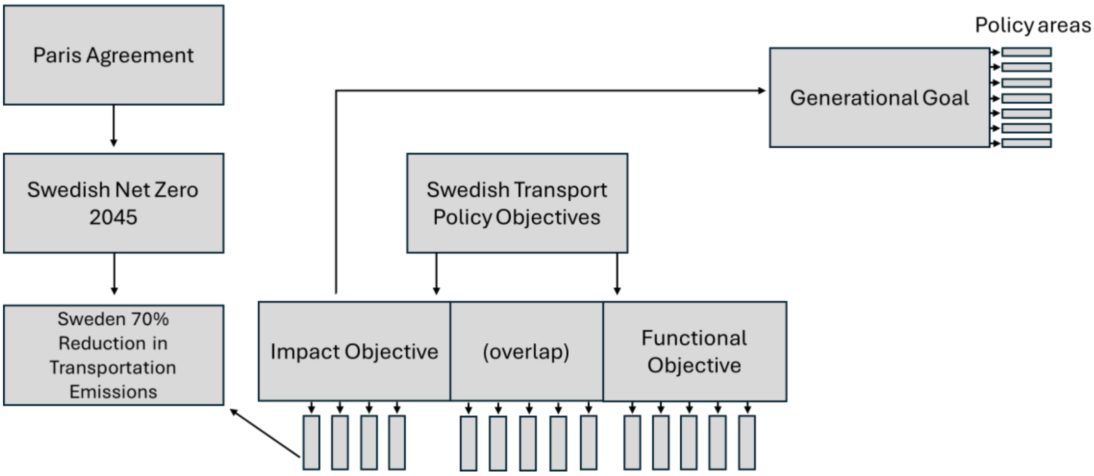

Figure 2: Sweden's environmental and transportation policy goals

Figure 2 is a conceptual diagram that shows how the net zero emissions goal, the generational goal, and the transport policy objectives are connected through the goal of reducing domestic transport emissions by 2030. It is important to note that this is just one way to illustrate how these three goals are connected; in reality they overlap with many different areas of environmental policy. For example, the generational goal and the transport policy objectives are also closely connected through the other indicators "impact on the natural environment" and "impact on the living environment of the people" under the transport policy impact objective.

2.3 AV Regulations in Sweden, the EU, and Internationally

The research in this thesis mostly avoids analysis and discussion of AV technology regulations, with the exception of **Paper 3**. However, the laws, agreements and policies that govern AVs will of course have a large influence on how the technology is used in different countries and areas. This is discussed by Andlauer and Laurell (2024) for example, in their recent report on small autonomous buses and the issue of their stalled deployment from commercial, legal and user perspectives. The authors argue that well-developed legislation is both an important safety requirement and an advantage for investors, who appreciate the certainty that comes with clear legal frameworks (Andlauer & Laurell, 2024). In **Papers 1, 2** and **4,** we largely assume that this certainty already exists, but it is nonetheless important to understand how AV regulations are currently developing, and what this could mean for the future deployment of the technology.

Here I give a brief overview of some of the important laws, regulations and policies around AVs. Please note that this is not meant to be an exhaustive list, and that there are many policies that affect AV use and development through product safety and liability, traffic, entry into the market, and public transportation law (Andlauer & Laurell, 2024) that are not mentioned here because they are less relevant to the research discussed in this thesis. For those interested in a more thorough explanation of international, EU and Swedish AV regulations, an excellent resource is the report *Steering the Future* by Jenny Lundahl (2024).

International

The United Nations Economic Commission for Europe (UNECE) is an important actor at the global level in vehicle regulation, including AV regulation. There are two working groups in particular that are active within this space: the Global Forum for Road Traffic Safety (WP. 1), which focuses on traffic rules; and the World Forum for Harmonisation of Vehicle Regulations (WP. 29), which develops vehicle regulations. WP. 1 mostly works with the 1968 Vienna Convention on Road Traffic to create amendments that cover automated driving systems. The group is currently developing a new "Legal instrument on the use of Automated Vehicles in traffic", which would likely affect both international and domestic traffic regulations (Lundahl, 2024; UNECE, 2023).

WP. 29 adopted the first international type approval document for automated driving functions in 2020. This is UN Regulation No. 175 on Automated Lane Keeping Systems, which regulates how the dynamic driving task of using automated lane keeping should be performed by the driver in a vehicle with lower levels of automation. It has already been updated many times since it was introduced to include different speed limits, vehicle types, and lane-changing capabilities, and more updates are likely in the future (Lundahl, 2024).

EU

At the EU level, the two most important regulations that effect AVs are Regulation 2019/2144, otherwise known as the General Safety Regulation (GSR), and Implementing Regulation 2022/1426. The GSR updates type-approval requirements, meaning the requirements for the safety of a vehicle type that must be certified before automakers can bring a new model to market. Implementing Regulation 2022/1426 regulates uniform procedures and technical specifications for the type approval of the automated driving system for AVs (EU, 2022).

Sweden

There is already a push from the Swedish Government for policy to be developed that will regulate AVs in a socially equitable manner. In 2015, the

Government commissioned a Government inquiry (*offentlig utredning*) to analyse what changes to the law would be needed for an introduction of driving-supporting, and partial or fully self-driving, vehicles (SOU, 2018). In the report from the inquiry, the results suggest a number of changes to specific laws and provides context in terms of technological capabilities, societal effects, international law and policy, and vehicle use in Sweden. The final report recommended that by 2023, Swedish law should be prepared for automated driving, most importantly to allow for the possibility of projects utilising advanced automated functions for platooning, goods transportation, and personal transportation (SOU, 2018, p. 35).

In 2021, a new piece of legislation based on the 2018 Government inquiry results was proposed. This was entitled *Ansvarsfrågan vid automatiserad körning samt nya regler i syfte att främja en ökad användning av geostaket (Ds 2021:28) (The responsibility issue in automated driving and new rules to promote increased use of geofences)* (Government of Sweden, 2021). In this report, a new driver role which roughly translates to "driver in readiness" was introduced, to describe a driver who would act slightly differently than in a conventional vehicle, with fewer driving tasks and some different driving tasks. Responsibility for traffic insurance and vehicle safety were also specified in the report (Lundahl, 2024).

As of July 2024, however, permission for any use of an automated vehicle must still be granted by the Swedish Transport Agency on a case-by-case basis (Swedish Transport Agency, 2024).

2.4 How AVs could affect emissions

The ASIF Formula

Central for this thesis is the ongoing research about potential changes in emissions and other societal effects that could be caused by AVs. A conceptual and formulaic way to look at this is to utilise the influential Activity, modal Share, energy Intensity of mode, and carbon intensity of Fuel (ASIF) model (Schipper & Marie-Lilliu, 1999). The formula is stated as:

$$E = A \cdot S \cdot I \cdot F \qquad (1)$$

where E is emissions, A is travel activity, S is structure, often represented as modal share, I is the energy intensity of the mode, and F is the carbon intensity of the energy source. The ASIF formula is used here as a structure for reviewing existing academic literature that connects AVs with GHG emissions and other societal effects. The articles discussed below provide insight into the makeup of each term in the ASIF formula.

In general, transportation behaviour research examines the [A] term travel activity and the [S] term of modal share. In 2018, Harb et al. published a study that used chauffeured vehicles to simulate AVs. They measured VKT before, during and after the period when the 13 households had access to the chauffeurs, and found that total VKT increased by 83% during the chauffeured period (Harb et al., 2018). The same research group published a paper in 2022 based on a similar study that examined a much larger group of 43 households with access to chauffeured vehicles. In this study, they found that VKT also increased substantially, and furthermore there was a shift away from forms of transportation not involving a household vehicle, such as ride-hailing or carpooling with others. There was also a shift away from public transport trips, which dropped by 71%, and biking trips, which dropped by 37% (Harb et al., 2022).

The Harb et al. studies were mainly focused on changes in VKT with different modes, but similar studies have also been done to examine what people might do in an AV if they do not have to concentrate on driving tasks. For example, Wadud and Huda (2019) surveyed chauffeured passengers in two cities in Bangladesh, and found that there was a correlation between what the research subjects did in their chauffeured vehicles and what researchers have suggested people might do in AVs. Most notably, they found that the passengers were able to do work-related activities, or other activities that they considered to be a good use of their time, which would suggest that those riding in AVs could have an incentive to limit their VKT due to time constraints.

Some studies collect stated preference data about specific scenarios involving an AV, after providing respondents with some kind of written explanation of what the technology looks like (Moore et al., 2020) or a video that demonstrates the scenario (Pudāne et al., 2019). Moore et al. (2020) used survey data to model how different behavioural dimensions could affect the decision to relocate if the individual can commute with a private AV and found that the resulting potential urban sprawl could be as large as a 68% increase in the horizontal spread of some cities. Pudāne et al. (2019) took data from focus groups to model the re-arrangement of daily activities resulting from on-board activities in an AV and found that time pressure could be eased depending on the re-arrangement of daily activity patterns.

An approach that has become very salient in recent years is the use of storytelling or vignettes to facilitate data collection about travel behaviour and

AVs. Cohen and Cavoli (2019) used this method to examine the effects that different governance approaches to AVs could have on traffic flow and accessibility in the UK. They held deliberative workshops with 30–50 participants from academia, government, transport operators, NGOs, and consultants. The workshops started with participants reading through different short descriptions of a future with AVs. Their results showed a range of different government interventions that could be applied to ease traffic flow and increase accessibility. In Sweden, Almlöf (2023) used vignettes as a starting point for data collection through interviews and a workshop with public officials. The results identified 30 policy tools for AV technology, and Almlöf noted that the vignettes were very useful for helping respondents to think outside the box (2023, p. 6).

Others have avoided doing experiments with test subjects by instead creating models based on existing information and literature, as is done in **Paper 1**. Wadud et al. (2016) model the potential changes in energy demand caused by different levels of AV adoption, using peer-reviewed literature as the basis for parameterisation. Wadud (2017a) then models the levels of AV adoption in different transportation sectors and subsequent changes in travel demand, again using data collected from academic literature as well as government and industry reports. In the latter study, the value of the travel time (VoTT) emerges as an important characteristic (due to its relatively large share of the Generalised Travel Cost, or GTC), which was also found in Taiebat et al. (2019).

The next part of the ASIF formula is modal energy intensity [I], which is made up of the technical energy efficiency of the mode, and dependent on characteristics of the specific vehicle (such as weight), and vehicle occupancy (for passenger vehicles) (Schipper & Marie-Lilliu, 1999). The technical energy efficiency component can be related to driving behaviour, which could be more efficient than conventional vehicles if AVs drive more smoothly as part of a connected fleet, or purposefully drive in a more energy-efficient manner. However, AV driving behaviour could be less efficient than human driving as well, for example, if driving at a higher speed, which increases aerodynamic resistance and thereby also the energy intensity of the mode since AVs may be able to drive safely at higher speeds (Lee & Kockelman, 2019)

The ‘other characteristics of the vehicle’ component is important to consider for AVs, since AV technology needs extra energy (compared to a conventional vehicle) for operating sensors and for computing. Gawron et al. (2018) estimated the increase in energy use to be about 3–20% on a life-cycle basis, primarily through increased energy needs for computing followed by the energy needed for sensors. In terms of the physical characteristics of AVs, Mohan et al. (2020) found that drag could increase significantly in the rather unlikely event that the sensors are placed on top of the vehicle.

The final component of modal energy intensity [I] is vehicle occupancy. In a study of non-AV travel modes, Schäfer and Yeh (2020) compare the GHG emissions per passenger-kilometre travelled across cars, buses, trains and planes and found that occupancy explains somewhere between 70 and 90% of the variation around the mean energy intensity. In terms of research on AVs, many studies have examined the potential for car sharing, where energy intensity can be related to changes in the necessary number of cars or vehicle kilometres travelled in a given system. The International Transport Forum published a study in 2015 that showed AV taxis combined with a high-capacity public transport system could remove 90% of cars in the city of Lisbon, but if shared rides were to replace public transit rides there could be a significant increase in VKT (OECD/ITF, 2015). Other studies have also highlighted that it is important to consider which modes shared rides are replacing (Fielbaum et al., 2023). In Sweden, Lorig et al. (2023) found that one shared AV could potentially replace 5 private cars during the morning peak travel period in a simulation study of the city of Gothenburg and its surrounding suburbs.

Carbon intensity of the fuel supply [F] is the last term in the ASIF formula. Much of the literature relating to the [F] term in the context of AVs relates to electric AVs, where the carbon intensity of electricity can be as low as zero if it comes from a renewable source.

Systemic effects of AVs

Research about AV electrification is often part of studies that examine the systemic effects of automated, electrified, and shared vehicles. For example, Fulton (2018) warned that while electric and autonomous vehicles could create important benefits, they could also contribute to congestion and urban sprawl if not combined with shared transportation systems. Arbib and Seba (2017) suggested a very optimistic scenario where autonomous and electric vehicle fleets could drastically lower travel costs. Looking at a more specific group of scenarios, Compostella et al. (2020) found that battery electric AVs could be cost-competitive with internal combustion engine vehicles by approximately 2030–2035.

There are also studies that examine broad societal effects of AVs and thus relate to many parts of the ASIF framework. Milakis et al.'s 2017 article on the interrelated ripple effects of AVs is a good example of this. There, the effects of

AVs are organised into first-, second-, and third-order effects, and visualised by concentric circles with the AVs at the centre. The first-order effects, closest to the centre, include traffic, travel cost, and travel choices; the second-order effects include vehicle ownership and sharing, location choices and land use, and transport infrastructure; and the third-order effects are "wider societal implications", such as energy consumption, air pollution, safety, social equity, economy, and public health (Milakis et al., 2017, p. 326). The ripple effect concept is applied in such a way that the effects can be interrelated across widely ranging time frames, and the authors conclude that first-order, short-term benefits are expected to be beneficial, while third-order effects are unclear (Milakis et al., 2017).

Another example of a study that examines broader effects of AVs is that by Pernestål et al. (2020). They took a novel approach in this field and used causal loop diagrams to map the systemic effects that AVs could have, in order to inform policy suggestions with respect to working towards the UN sustainable development goals. The findings suggest that vehicular-level benefits of AVs, such as fewer accidents per vehicle, are negated at a system level where an increase in VKT results in an increase in total accidents (Pernestål et al., 2020).

3. Summary of Paper 1

3.1 Theory and Methodology in Paper 1

Budget models and trip models: contextualising the value of travel time within transportation research

One of the most important concepts in **Paper 1** of this thesis is the value of travel time (VoTT). Much of the expected economic benefit of the introduction of AVs is related to the change in the use of time for the person, who may no longer have to actively drive the vehicle. In an AV, the (former) driver will potentially be able to work, relax, or engage in other activities (Pudāne et al., 2018; Wardman et al., 2019), which could change how their time spent travelling is valued (Becker, 1965; DeSerpa, 1971). The VoTT, or how much the time that a person spends travelling is worth, is given in monetary units per unit time.

VoTT has its theoretical origins in economic models where the amount of time that the individual spends on travel is determined by utility maximisation, where the decisionmaker takes all available time (e.g. 24 hours of a day), and all available activities (e.g. work, leisure, sleeping, etc) into account. The concept of time valuation was developed by Gary Becker in 1965. Becker suggested that the opportunity cost of time is equal to a person's wage rate (Becker, 1965). Johnson (1966), Oort (1969), and De Serpa (1971) added to the theory and distinguished between, for example, the value of leisure time and that of time spent travelling. Today, VoTT[2] is commonly used in transport appraisal projects.

Paper 1 is based on a theoretical model of VoTT and how it may be affected by AVs. We based the reasoning in our model mainly on the work of Oort (1969). The VoTT that we used can be understood as the marginal value of leisure time plus the monetary value of the disutility of spending time in the vehicle. The formula for our calculated VoTT can be conceptually summarised as:

$$VoTT = opportunity\ cost\ of\ time + disutility\ of\ spending\ time\ in\ the\ vehicle$$

[2] It could be important to point out here that VoTT is sometimes referred to in academic literature as Value of Travel Time Savings, or VTTS. In this thesis, both terms mean the same thing. VTTS is defined as the benefit, or savings, of a shorter trip.

The opportunity cost of time here is the value of giving up a leisure activity (which in turn equals the wage rate less the disutility of working) that could have been done otherwise.

In an applied transportation research context, the VoTT is usually included as one cost component of the general travel cost for a specific mode of transport, where each trip is examined individually. This type of modelling is the conventional form of transportation modelling used by analysts when planning things like road capacity, public transport routes, and other transportation infrastructure investments. Here, each trip is modelled based on choices that the individual traveller makes regarding variables such as the activity in question, destination, mode, time, and route, allowing the benefit and costs of different investments to be estimated (Ortúzar & Willumsen, 2011).

Another form of reasoning is that known as travel budget modelling, where all trips during a day are aggregated so that the time used to make the trip is part of a daily travel time budget, which is a fixed amount of time devoted to travel, while the rest of the day is devoted to other activities. Approaching transportation modelling from the perspective of budget modelling means that available time and money are the starting points for the model. This is the basis for the seminal work done by Zahavi and Tavilitie (1980), where the authors showed that the amount of time (i.e. the travel time budget) and the share of income devoted to travel (i.e., the travel money budget) on weekdays is very similar across different regions and countries. Zahavi and Talvitie emphasize that their findings only hold on average, and for homogenous groups of travellers in cities of developed countries, and across all modes of transport (walking, public transport, and driving). Given these limitations, the global travel money budget was found to be approximately 10-11% of income for car-owning households, and 3-5% for households who did not own cars. The global travel time budget was found to be approximately 1.0–1.5 hours per day (Zahavi & Talvitie, 1980).

Schäfer and Victor (2000) build on this work by including all regions in the world, and modelling traffic volume and mode share with the time horizon of 50 years into the future. They found that people spend a constant share of their time and money on travel: as incomes rise, so does demand for mobility, and as total mobility rises, people switch to faster modes of transport, but tend to travel for only 1.1 hours per person per day (Schäfer & Victor, 2000).

Value of Travel Time and AVs

The VoTT could change for two reasons. Firstly, the person in the vehicle might be able to engage in leisure or work activities that they would not be able to do while performing driving tasks. Secondly, the monetary value of the disutility of spending time in the vehicle could change, which is more difficult to gauge. It is possible, however, that AV technology could cause this value to change because the person might enjoy their time in the vehicle more, perhaps because the AV is more comfortable than a conventional vehicle. This would cause a reduction in disutility. If the sum of both components of the formula decrease, then the VoTT will also decrease.

Many research studies examine changes in VoTT in relation to CAVs (Bansal & Kockelman, 2017; Gao et al., 2019; Harb et al., 2018; Pudāne et al., 2018, 2019; Pudāne & Correia, 2020; Wadud & Huda, 2019; Wardman et al., 2019). A change in VoTT can be analysed in terms of the reason for the change, which depends on what the traveller is able to do in the vehicle, and the magnitude of the change, which depends on the utility that the traveller gains from that activity. The reason for a change in VoTT could be related to an increase in subjective well-being (Singleton, 2019), multitasking (Malokin et al., 2019), or work done (Correia et al., 2019). The magnitude of the change is very difficult to approximate, and there is considerable debate about the usefulness of travel-based multitasking and a connection to lower VoTT (Cyganski et al., 2015; Singleton, 2019).

Without explicitly considering CAVs, the International Transport Forum (ITF) suggests that VoTT could be reduced by 20–25% if travellers were able to do something with their time. Gao et al. (2019) analysed stated preference survey data on ride-hailing services and found a 13–45% reduction in VoTT with the use of ride-hailing services compared to a personal vehicle during commuting trips. In terms of assumptions about changes in the VoTT, Singleton (2019) reviewed a number of studies that made VoTT assumptions in relation to CAVs, and found that the assumptions spanned a wide range based on different contexts, ranging from no change to a 100% change.

The scenarios presented in **Paper 1** assume that there are differences between VoTT for commuting and for other activities following Correia (2019), who found VoTT during a commute should be lower using theoretical and empirical (stated-choice) methods. The reduction in VoTT during commuting is assumed to be larger than during other types of trips, which then is reflected in the modelled changes in GTC and travel distances. We also assumed that VoTT increases linearly with income. The elasticity of VoTT with respect to income is uncertain, though some empirical studies suggest that it could be close to or slightly below unity (Mackie et al., 2001; Wardman et al., 2016). Börjesson & Eliasson, (2014) analysed two Swedish VoTT studies performed 13 years apart and found that income elasticity with respect to VoTT increases with income, being close to zero when below the median income and unity or higher above the median income.

In addition to this, some transportation authorities assume an income elasticity of unity to account for income growth when they analyse projects that will have an impact on travel over a longer time frame (Swedish Transport Administration, 2018; UK Department for Transport, 2019). Thus, we adjust VoTT to reflect different income quintiles, using the Swedish Transport Administration's VoTT for the median income quintile and a VoTT income elasticity of unity.

Generalized Travel Cost, Consumer Surplus and Break-Even Estimations

Generalized Travel Cost (GTC) captures the levelized cost of travelling per unit distance. GTC for private cars can be broken down into fixed cost, being vehicle depreciation with respect to calendar age, and taxes; and variable cost, being fuel cost, maintenance, insurance and VoTT.

For most goods, the price elasticity of demand is negative, implying that if the price (or cost) of the service or product decreases the demand increases. In the case of GTC and travel demand, this has been clearly observed by two well-known effects: (1) the rebound effect, in which increased fuel efficiency tends to lead to a lower variable cost of travel, which in turn leads to increased mileage (Small & Van Dender, 2007); and (2) the induced travel effect, where improved "speed" in going from A to B as a result of, for example, new highway capacity and/or reduced congestion, tends to generate more travel (Goodwin, 1996). In the first case, the fuel cost component of GTC is reduced; in the second, the VoTT per km is reduced, in that less time is needed.

Consistent with standard partial equilibrium modelling we assume that the marginal utility of consumption is constant and the VoTT is independent of travel time, meaning that the marginal value of travel time per unit time does not change if one travels more or less. Consequently, the monetary value of the utility obtained from AV use, i.e. the Consumer Surplus, can easily be estimated through the reduction in VoTT and the benefit of additional travel (European Commission, 2015). The approach is often referred to as the rule of half, and implies a linearization of the isoelastic demand curve between the equilibrium point obtained with the conventional vehicle, and the equilibrium point obtained with an AV (European Commission, 2015; Williams, 1976).

The impact on travelling distance, d_{CAV}, can be estimated using an isoelastic demand function.

$$d_{CAV} = d_0 \left(\frac{k + \frac{VoTT_{CAV}}{s}}{k + \frac{VoTT_0}{s}} \right)^{\varepsilon} \qquad (2)$$

where ε is the long-run variable cost elasticity with respect to GTC, d is daily distance travelled by car, k is the variable travel cost per unit distance, s is speed, and $\frac{VoTT}{s}$ is VoTT per unit distance. 0 represents the situation without AV adoption, and AV with AV adoption. In our research, we assume that k is the same for AV and other vehicles.

The willingness to pay, i.e. the change in Consumer Surplus, obtained with an AV (ΔCS_{AV}) can be estimated as the reduction in VoTT multiplied by the current distance travelled plus the benefit obtained from the induced travel. Hence, the willingness to pay for an AV can be estimated as

$$\Delta CS_{CAV} = \frac{VoTT_0 - VoTT_{CAV}}{s} \cdot d_0 + \frac{\left(\frac{VoTT_0 - VoTT_{CAV}}{s}\right) \cdot (d_{CAV} - d_0)}{2} \qquad (3)$$

The second term on the right-hand side is the increase in the willingness to pay for an AV depending on the induced travel. In previous studies (Wadud, 2017a; Wadud & Mattioli, 2021a), only the first term on the right-hand side has been take into consideration.

The rule of half can be illustrated as follows: the light grey section in Figure 3 shows the Consumer Surplus for a conventional vehicle, CS_{CONV} (for a linear demand curve). The light-grey dotted section shows the benefit of the VoTT reduction given that the travel distance remains fixed. The dark-grey dotted section shows the user benefit resulting from induced travel with an AV. Both dotted sections taken together are the Consumer Surplus with AV (CS_{AV}).

We assume that a person will purchase an AV if the CS_{AV} is larger than the technology costs. In other words, the purchase decision is based on an individual Cost Benefit Analysis (CBA), similar to the reasoning used by Wadud (2017).

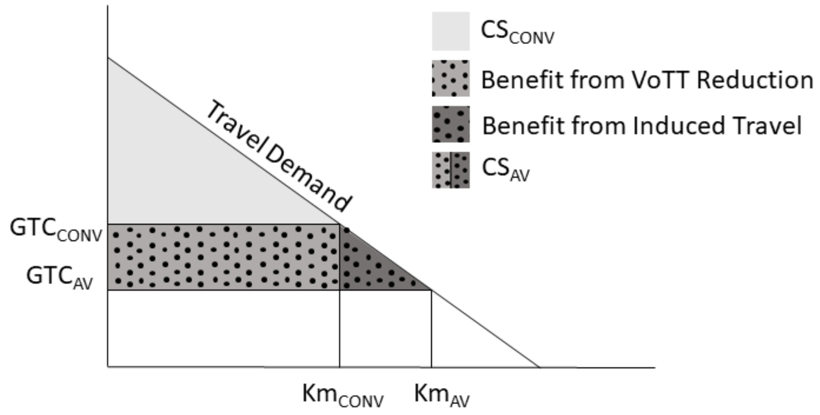

Figure 3. The rule of half, showing the theoretical relationship between GTC, travel distance, and travel demand.

3.2 Data and Methods in Paper 1

Basis for numerical assumptions in the model

Here we give a brief overview of the assumptions that are made in order to calibrate the model of AV technology purchases and the VKT impacts of AVs. The section concludes with an explanation of how the model is run with a large set of different combinations of parameter assumptions to understand the robustness of the model results, and which parameters are most important for determining the results.

Changes in VoTT

We use the projected VoTT for 2040 from the Swedish Transport Administration and extend it to 2045, adjusting it for various income quintiles and assuming a 1.5% annual income growth (Swedish Transport Administration, 2020), and income elasticity of VoTT equal to one. The VoTT numbers we use are SEK 154 per hour for commuting trips, SEK 104 per hour for other purposes, and SEK 192 per hour for long-distance travel. Considering potential reductions in VoTT due to autonomous vehicle (AV) use and the ability to work in the car, we estimate decreases ranging from 15% to 50% for non-commuting trips, and 25% to 60% for commuting trips, depending on remote working capability. These estimates are based on various studies and capture the uncertainty associated with AV adoption (Correia et al., 2019; Harb et al., 2022; ITF, 2019; Kolarova et al., 2019; Singleton, 2019). As stated above, we assume a 10% unit difference between commuting and non-commuting

VoTT if people can work in the car, based on our assumption that there is a correlation between how people value their time while commuting (since people are more likely to work under these circumstances) and while travelling for other purposes (see for example Correia et al. (2019)).

Technology cost

The costs of AV technology are pivotal for its adoption, but they remain very uncertain. Estimates from industry leaders vary widely, with examples such as Volvo Cars projecting a $10,000 increase for level 4 technology in 2021 (Edelstein, 2017; Lesage, 2016), and Tesla offering a $7,000 "self-driving capability" for its vehicles which are formally at level 2, but argued to have functionality for higher levels of autonomy (Hawkins, 2019). Table 1 demonstrates that there is a wide range of cost assumptions made in the research literature. Thus, the scenarios in **Paper 1** cover a range between SEK 30,000 and SEK 310,000 in 2045.

Table 1: Costs of AV Technology (advanced level 4 or level 5) from the research literature.

Study Author	Low cost (SEK)	Medium cost (SEK)	High cost (SEK)	Year
Bansal & Kockelman, 2017	--	80,600	--	2045
Wadud, 2017	112,500	136,400	179,400	2020
Lavasani et al., 2016	28,000	50,000	94,000	2025
Compostella et al., 2020	30,500	95,000	280,000	2030-2035

Interest rates

For calculating the annualized AV technology cost, we need to make assumptions about the interest rate used for the vehicle purchase and the economic lifetime of the car. We assume the car has an economic lifetime of 10 years.

We consider interest rates to be between 1% to 10% per year based on the following sources:

- 5% for car purchasing decisions (Swedish Transport Administration, 2020).

- Bank loans for general consumption in Sweden have varied between about 4% per year and 8.5% per year over the period 2006 and 2022 (Statistics Sweden, 2023).
- Bank loans for housing in Sweden have varied between about 1.5% per year and 6.5% per year over the period 2006 and 2022 (Statistics Sweden, 2023).

Travel Demand Elasticities

The theoretical and empirical findings for price-responsive behaviour to fuel-price changes, the rebound effect through energy-efficiency improvements, and induced travel demand through infrastructure and congestion-mitigation projects show that a reduced GTC will have an impact on travel demand. Some research suggests that the rebound effect declines as income declines since fuel cost as a share of GTC typically declines as VoTT increases (Greene, 2012; Small & Van Dender, 2007).

In terms of empirical effects, studies have shown a long-run rebound effect of around 0.1–0.3, (elasticity of travel distance with respect to fuel cost per km), meaning that a 10% increase in fuel efficiency would generate a 1–3% increase in annual VKT (D. Andersson et al., 2019; Dimitropoulos et al., 2018). The long-run induced travel demand elasticity has been estimated to be in the order of -0.5 to -1 (elasticity of travel distance with respect to travel time from A to B), in the sense that a 10% reduction in travel time tends to induce a 5–10% increase in travel volume from (M. Andersson & Smidfelt Rosqvist, 2011; De Jong & Gunn, 2001; Goodwin, 1996).

The share of fuel cost in the GTC declines as VoTT increases with income, and if we assume a constant demand elasticity with respect to GTC, the demand response to fuel cost changes will decrease as income increases, consistent with Small & Van Dender (2007) and Greene (2012). Hence, for this reason we will assume that demand elasticity with respect to GTC is constant and independent of income.

Sensitivity Analysis creation

Five parameters are discretized into different bins: AV Technology Cost into 8 equally sized bins, Interest Rate into 10 equally sized bins, Elasticity of Travel Demand into 6 equally sized bins, and Reduction in VoTT into 8 equally sized bins, for each type of VoTT. This results in 3840 parameter combinations in the sensitivity analysis (note that the reductions in different types of VoTT are linearly related, so for sensitivity analysis purposes we only consider them to be one set of bins).

Population

For calibrating the population characteristics, we used the finest grained self-reported data on mode of transport and trip distances from the Swedish National Travel Survey that stretches over the period 2011–2016 (Transport Analysis, 2017). We selected respondents who reported the following information: income, trip purpose, trip distance, if they travelled in their own car, and if they had the option to work remotely. Of the 38,258 respondents in the initial dataset, 9,305 had reported the relevant information and thus met the criteria for the study.

Table 2. Work remotely, proportion per quintile.

Quintile	Work Remotely	Share of income quintile
Q1	Yes	10%
	No	90%
Q2	Yes	15%
	No	85%
Q3	Yes	26%
	No	74%
Q4	Yes	39%
	No	61%
Q5	Yes	67%
	No	33%

This population of 9,305 respondents was disaggregated into five income quintiles, and each quintile was divided into one group who could work remotely and one who could not work remotely (being a proxy for if the respondent could work in the car) as shown in Table 2. The reported income in the national travel survey was adjusted to 2016 for inflation using the consumer price index (Swedish Transport Administration, 2020). Within each quintile, we calculated the current average travelling distances of car drivers for commuting and other purposes, for both long (>100 km) and short distance (≤100 km) trips, as shown in Figure 4. It shows the trend in VKT increasing with income, but we show it here as part of the data collection because these calculations were part of the data cleaning and organization for the model.

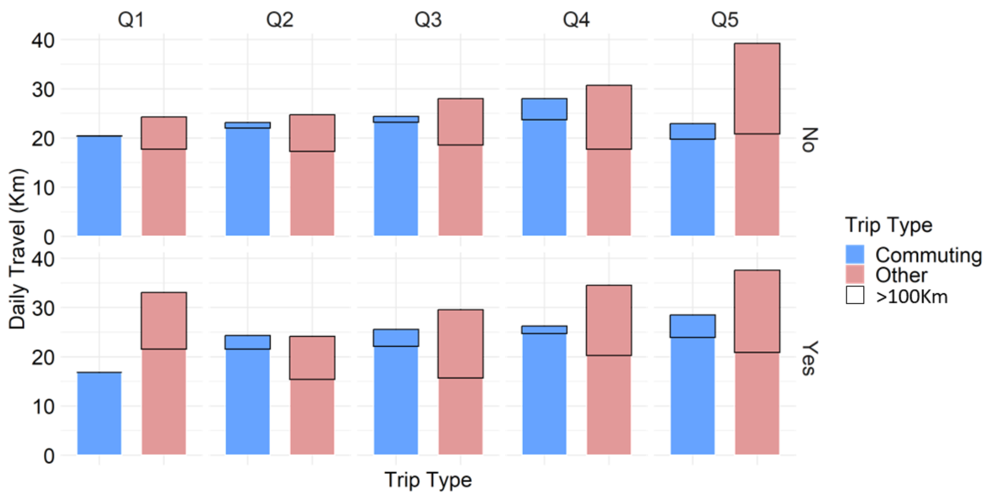

Figure 4. Average distance travelled per day by trip type (commuting or other), trip distance (if the trip is less or more than 100 km), and option to work from home. The >100 km boxes indicate daily average trip distance of long distances trips as being above 100 km.

3.3 Paper 1 Results and Discussion

Results

The results of **Paper 1** are an analysis of under what conditions consumers would purchase an AV, what level of travel demand this purchase would induce, and what the resulting life-cycle greenhouse gas emissions could be.

If the increase in daily Consumer Surplus when changing from a regular vehicle to an AV (ΔCS_{AV}) is larger than the levelized daily cost of the AV technology, we assume that an AV is purchased, because that would be beneficial for the owner of the vehicle. In Figure 5 the ΔCS_{AV} is represented by the violin shapes, which show all the possible values of the ΔCS_{AV} for the analysed combination of parameter values on the y-axis for each income quintile indicated on the x-axis. The area of the violin shapes are the same for all income distributions, while the contour of the violin shape indicates how ΔCS_{AV} depends on the different parameters combinations.

The dotted lines in Figure 5 show the levelized daily cost for the lowest (SEK 30,000) and highest (SEK 310,000) cost of AV technology assumed in our sensitivity analysis. None of the violin shapes dip below the lower dotted line, which means that it is beneficial for all income groups to purchase an AV when the technology cost is SEK 30,000. In the lowest two quintiles, it will never be beneficial to purchase an AV if the technology cost is SEK 310,000, and even in the middle quintile it will only be beneficial for a small share of the parameter combinations.

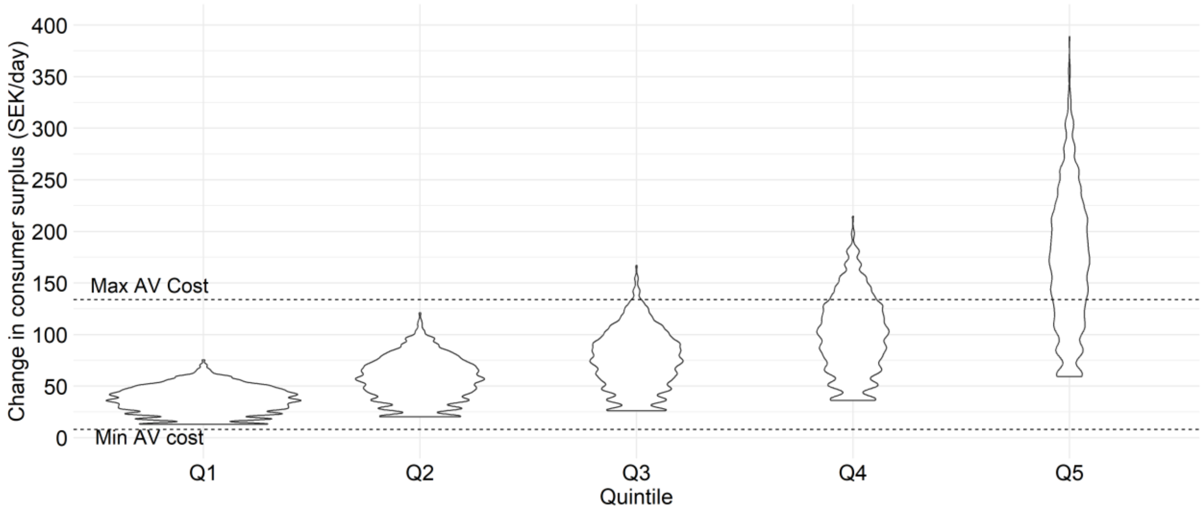

Figure 5: ΔCS_{AV} (violin shapes) compared with the average daily cost of AV technology (space between the dotted lines).

In **Paper 1** we also assess how the purchase of AVs could affect travel demand, again taking into account all the possible combinations of the five parameters considered in the analysis. Figure 6 shows how sensitive the entire studied population's demand is to each parameter, visualising the demand as an increase in distance on the y-axis for each parameter on the x-axis. The line shows the 5th–95th percentiles in each distribution, with the dot showing the median value. We see from this that elasticity of travel demand has the strongest effect on travel demand, followed by Other VoTT Reduction. Cost of the technology also has an impact, although it is smaller. When the cost is small, the median increase in aggregate travel distance is about three times as large as when the cost is high. It is also important to note that where the line touches zero in Figure x, it shows that it is probably not beneficial to purchase an AV, indicated by no increase in travel demand.

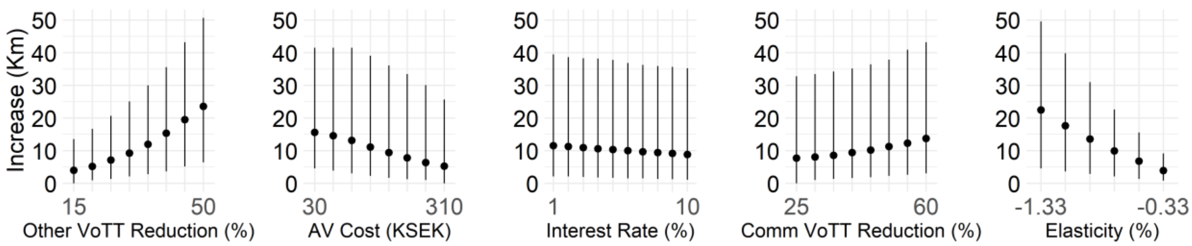

Figure 6: Increase in daily travel after AV introduction, by sensitivity analysis variable.

We calculate the life-cycle emissions impact from the increase in travel demand in 2045. We use data on the life-cycle emissions from the manufacturing and driving of fully electric vehicles from Morfeldt et al. (2021). There are two cases considered: one in which emissions from the production and charging of electric vehicles develops in line with a scenario consistent with the Paris Agreement; and a second case in which emissions from the production and charging of electric vehicles develops in line with currently stated policies. In the Paris Agreement scenario, the emissions factor is 21 grams of CO_2 per km in 2045, and in the Stated Policies scenario, the emissions factor is 50 grams of CO_2 per km in 2045. These two cases, and a reference point showing emissions from the studied population in 2018, are shown in Figure 7. The areas of the two violin shapes are the same in Figure 6, but they become wider when there are more cases of the sensitivity analysis at a certain point on the y-axis. For example, in the blue violin that shows the Paris Agreement emissions, most cases of the sensitivity analysis are just below 0.5 tonnes of CO_2 equivalents. The line and dot show the 5^{th}–95^{th} percentile range and median, respectively, as in Figure 5.

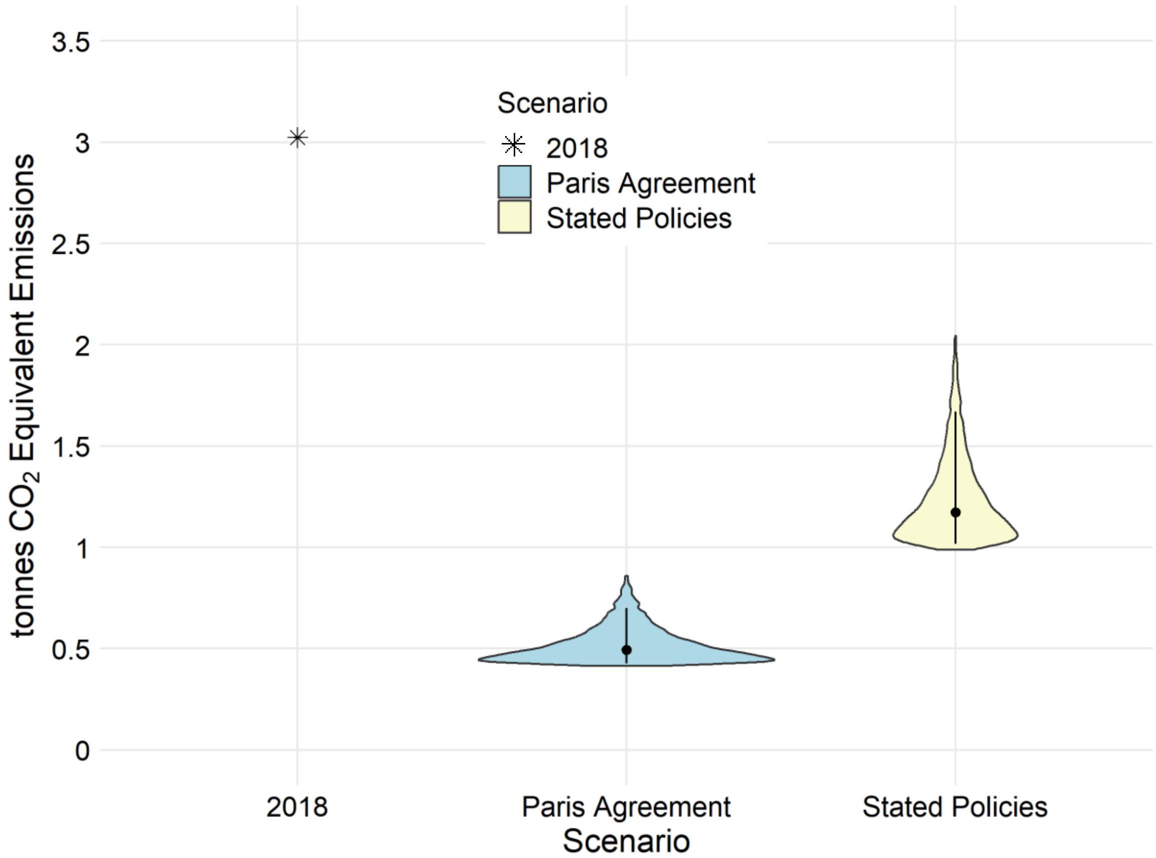

Figure 7: Average car-related life cycle emissions per driver, per year.

The top 5% of emissions in both scenarios are strongly dependent on a large negative travel demand elasticity, i.e. between -1.33% and -1.13%, and relatively dependent on at least a medium reduction (more than 35%) in Other VoTT. In the Stated Policies scenario, in 2045 the emissions are between 0.99 and 2.04 tonnes of CO_2 equivalents, with the top 5% from 1.67–2.04, and the median at 1.17 tonnes of CO_2 equivalents. For the Paris Agreement scenario in 2045, our analysis shows annual emissions between 0.42 and 0.86 tonnes CO_2 equivalents. The top 5% of this emissions range is from 0.70–0.86 tonnes of CO_2 equivalents, and the median is 0.49 tonnes of CO_2 equivalents, as seen in Figure 5.

We make one further addition to the model and examine how these future emissions would change if people who could do so work remotely and reduce their daily kilometres travelled. To do this, we assume that those who report that they can work from home (in the National Travel Survey) do so for three days each week. Figure 8 shows the effects of this change on the future emissions cases, which is quite small: the median emissions decrease by less than 1%, and the maximum level of emissions by approximately 8%. Those who are able to work from home are a relatively small portion of the studied population, and people travel on average fewer kilometres for commuting than for other purposes. Lastly, more people in the higher income quintiles can work from home, which creates an outsized effect on the maximum emissions levels, and less of an effect on the median.

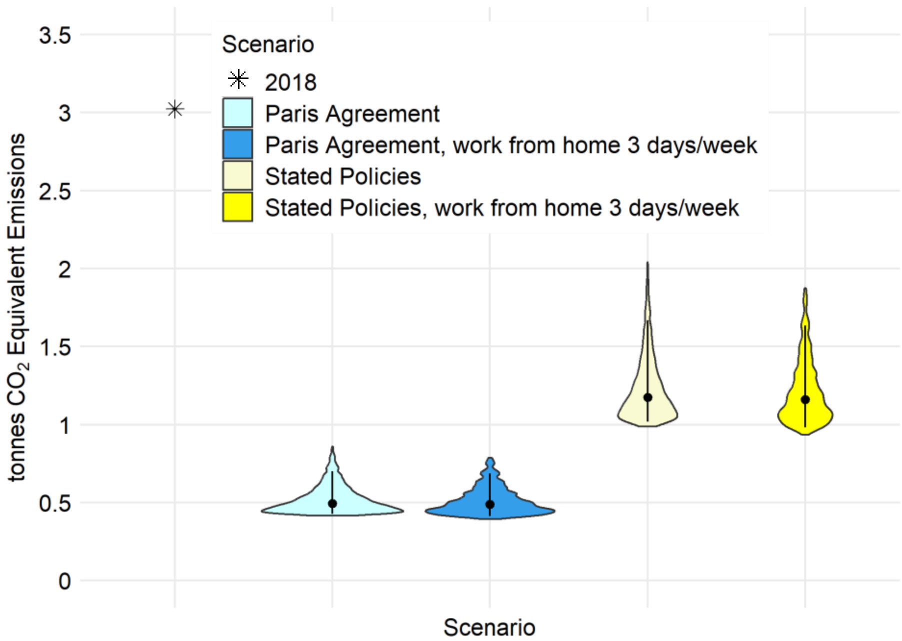

Figure 8: Average emissions per car under different policy scenarios and if people who can work in the car also work from home three days per week.

Discussion

RQ1: How might a change in the Value of Travel Time because of the use of AVs impact travel demand and lifecycle greenhouse gas emissions?

There is a positive correlation between higher income and longer average daily kilometres travelled, which is consistent with findings in other similar countries (ITF, 2023). In addition, a larger share of the respondents in the higher income quintiles can work remotely, which in our model is advantageous for them in terms of being able to work in the AV, thus reducing VoTT more while commuting. This means that if all income groups have the same AV technology cost and relative change in VoTT, the higher income groups will, on average, have a larger (absolute) incentive to purchase an AV. We see in the results of the model that most people in the highest income quintile would purchase an AV (based on the change in Consumer Surplus minus the Cost of the technology), and that those who can work remotely in the highest income quintile would increase their travel distance the most.

The results of **Paper 1** also show that travel demand and emissions are not greatly affected by working from home 3 days a week. Even with policies in place to meet the Paris Agreement and those who can working from home three days a week, the per capita life-cycle emissions of the studied population would still be between 0.42 – 0.86 tonnes of CO_2 equivalent per year from personal car travel. Thus, it would be crucial to target non-commuting trips if the emissions are to be reduced further, and especially long-distance trips on highways, which are already thought to be a suitable operating domain for AVs (He et al., 2022), and which may have a larger potential for VoTT savings since long-distance trips are reported to have a larger VoTT than short-distance trips. One way to do this could be through the use of distance-based taxes, which we take up again in **Paper 4**.

4. Summary of Paper 2 and Paper 3

4.1 Theory and Methodology

Socio-technical transitions

We define a transition according to Grin et al., (2010), as a structural system change in a societal regime over the course of multiple decades. This definition is related to the Multi-Level Perspective (MLP), where societal regimes are defined as the "dominant cultures, structures and practices within a societal system, which can be functional (e.g. mobility, energy, health, education, finance), spatial (a region or city), or organisational (e.g. a company, university or ministry)" (Loorbach et al., 2021, p. 2). The Swedish mobility regime is the main focus of these papers.

Loorbach et al. (2017) name three categories or approaches that commonly arise in transitions studies: socio-technical, socio-institutional, and socio-ecological. In this thesis and the appended papers, we focus on socio-technical transitions, looking specifically at a transition towards increased use of AV technology within the Swedish mobility regime. Geels (2004) explains that socio-technical systems include the production, diffusion and use of technology, and in doing so encompass "the linkages between elements necessary to fulfil societal functions (e.g. transport, communication, nutrition)" (2004, p. 900). Geels (2004) also contends that by studying socio-technical systems, one can focus on the dynamic relationship between technology and society within a larger transition.

These papers build on the body of scientific literature that views AVs as part of a socio-technical system. Many peer-reviewed studies have already used this lens (Cohen et al., 2018; Cohen & Cavoli, 2019; Hopkins & Schwanen, 2018). The importance and usefulness of a system-wide view of AVs is explained particularly well by Cohen et al:

"As with the motorcar in the twentieth century, many of the most profound social changes that will be wrought by self-driving cars will not relate to the lives they take or the lives they save, but rather to the sociotechnical systems that will emerge around them. These changes will not just relate to how we drive or are driven, but also to **how we live, how we work and how we build our environment.**" Cohen et al., (2018, p. 258, emphasis my own).

Drivers, Pressures, State, Impacts, Responses: the DPSIR framework

The starting point for the analysis in **Paper 2** and **Paper 3** is a causal chain framework called DPSIR (being an abbreviation of Driver, Pressure, State, Impact, Response) which was originally created by the European Environment Agency as a tool to give "structure within which to present the indicators needed to enable feedback to policy makers on environmental quality" (Kristensen, 2004, p. 1). It is a causal-chain framework that has traditionally been used for identifying driving forces related to land-use change. DPSIR is mainly used in environmental assessment projects, but more recently it has been used to study other fields such as urban planning (Adelfio et al., 2018). We apply DPSIR to the introduction of AVs to better understand the technology's societal implications.

The entire DPSIR chain is explained in detail below, so that the reader can situate the D, P, S, I, and R components within the broader context of a socio-technical transition involving AVs.

Drivers: These are positive or negative, and are represented by broad driving or restraining forces, e.g., environmental concerns. In **Paper 2** we also sometimes use the term "force" synonymously with "driver".

Pressures: These are related to each driver and emerge as more specific interests expressed by stakeholders, entailing a higher level of specificness compared to Drivers. For instance, two pressures related to the driver of environmental concerns could be the need to reduce fuel use and shared cars easing AV acceptance.

State: A future situation where AVs have been introduced.

Impacts: These refer to the possible consequences, as expressed in the interviews, of future scenarios that might be caused by AVs. Examples are increased suburban sprawl or facilitated transport of people who are not able to drive.

Responses: These can be policies, strategies, or other types of actions related to the Drivers, Pressures, and Impacts. Responses can strengthen the positive Drivers and Pressures, tackle the negative restraining Drivers and Pressures, or be expressed as strategies that respond to the Impacts.

We combine DPSIR with other theoretical frameworks in the appended Papers. This thesis makes a methodological contribution in **Paper 2** by using DPSIR as a guide for interview content analysis, and then combining DPSIR with force-field theory (Burnes & Cooke, 2012) to further analyse the interview data through a survey. In **Paper 3**, we combine DPSIR with Transition Management

(TM) by creating DPSIR chains and using TM to analyse them. Figure 9 visualizes a full DPSIR chain.

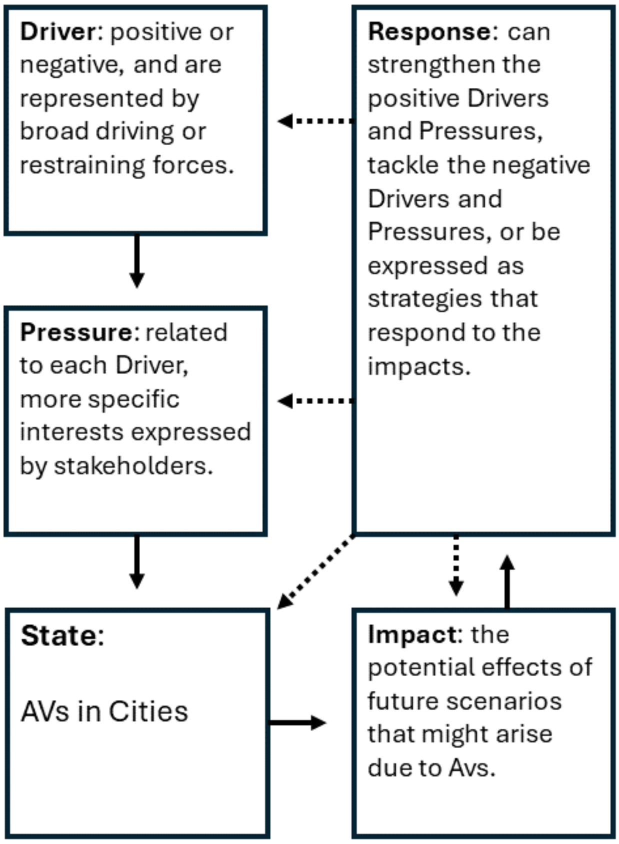

Figure 9. The components of a DPSIR chain and their interactions, from Paper 3. Adapted from Ness et al. (2010).

Combining DPSIR and Force-Field Theory

In **Paper 2**, we combine DPSIR with a tool called force-field analysis. This is based on field theory, which was originally conceived by psychologist Kurt Lewin. Field theory suggests mapping psychological forces that influence the behaviour of an individual or group in order to understand said behaviour (Lewin & Korsch, 1939). In more recent research, field theory has been used to examine organisational and social change (Burnes & Cooke, 2012; Cronshaw & McCulloch, 2008). Force-field analysis is the application of force-field theory in a specific setting, with the purpose of identifying and measuring the forces affecting change. We combine force-field analysis with DPSIR, and in doing so we address some of the criticisms of DPSIR; the most common being that it does not address the complexity of the processes that it attempts to analyse (Niemeijer & De Groot, 2008). The DPSIR framework was useful in that it allowed us to capture the breadth of perspectives that we were searching for, and to organise the interview data in a way that made it possible to do further analysis without reducing the diversity or quality of the information.

We could then use force-field analysis to characterise the Drivers and Pressures as negative (restraining) or positive (driving). Restraining is associated with behaviours that might hinder or 'restrain' the introduction of AVs. Driving is associated with behaviours that might induce or 'drive' the transition. This positive–negative distinction allows us to combine DPSIR with force-field analysis as a "technique for evaluating forces affecting change" (Thomas, 1985, p. 54).

Lewin's original intention for force-field analysis was to analyse the rate and strength of change over time (Cronshaw & McCulloch, 2008). We do not capture the time aspect, but by asking survey respondents to weigh up a list of Pressures, we were able to analyse their strength in terms of how much each Pressure would influence the changing State of AVs in cities (we discuss this process further in the "Data and Methods" and "Results and Discussion" sections of this chapter). The entire analytical process, including the force field, is visualised in Figure 10. Since the Pressures are directly related to the Drivers, the latter are included in the force-field analysis.

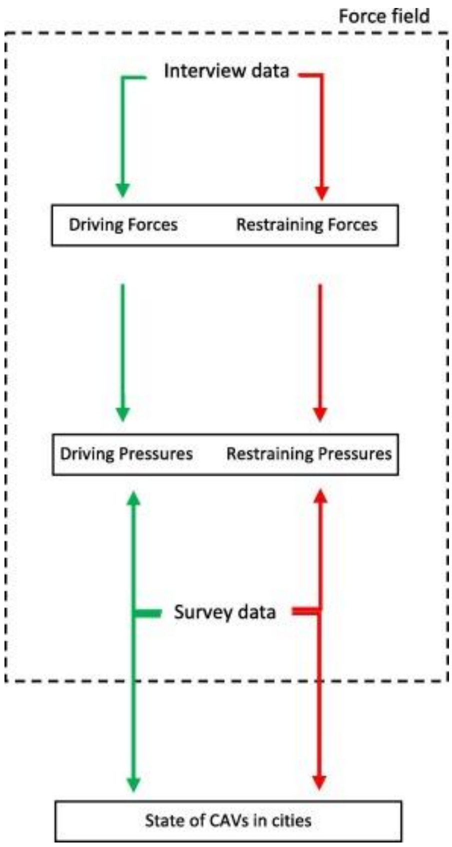

Figure 10. A simplified diagram of the combination of force-field analysis and DPSIR.

Transition Management (TM)

TM attempts to include complex systems theory as well as practical experience by involving practitioners in the iteration of a policy goal. Loorbach (2010, p. 168) describes it as "…an analytical lens to assess how societal actors deal with complex societal issues at different levels but consequently also to develop and implement strategies that influence these "natural" governance processes". TM is prescriptive as a basis for applying policy models, and it takes sustainable development as a long-term goal. It is also requires reflexivity, which is connected to the idea that transitions are the incremental and constantly evolving result of many different developments across many domains that include but are not limited to "…technologies, infrastructure, user practices, cultural values and meanings, markets, business models, regulation, and knowledge" (Hopkins & Schwanen, 2018, p. 3).

One of the main tensions within TM, which has sparked criticism, is that the framework ignores the power dynamics of the political systems within which it exists, which can lead to reproductions or reflections of those power dynamics in the application of TM as a method. Kenis et al. (2016) argue that TM "fails to fully acknowledge power relations, radical pluralism and the possible constitutive role of conflict in society", because the framework focuses on market innovations as opposed to political regimes. This can then result in the re-enforcement of unequal distributions of power.

Hopkins and Schwanen (2018) address the role of governments and the political economy of the automobile industry in the United Kingdom, while still taking some ideas from TM into their research. They focus on the role of incumbent actors in the transition process, which in this case refers to actors from the automobile industry and politics. In the UK, these incumbents have had the most power in the transition towards AVs, a pattern that is also brought up by Hess (2020) when discussing the proliferation of AV technology development programmes in the USA.

4.2 Data and Methods

Interviews

The same interview data was used for **Papers 2** and **3.** All interviews were semi-structured, and the interview guides can be found in the supplementary material accompanying the appended papers. All 11 interviews were done via video chat and recorded, and the interview transcripts were analysed using content analysis (Hsieh & Shannon, 2005) to explore the Drivers and Pressures (**Paper 2**) and Impacts and Responses (**Paper 3**) components of the DPSIR framework.

Quadruple Helix

An important part of **Paper 2** was identifying stakeholders who were related to the AV transition and connecting those stakeholders with Drivers and Pressures. The focus on stakeholders who can drive or restrain an AV transition has a theoretical basis in Transition Management, but in order to select interviewees we needed a more practical, concrete framework. We thus chose the quadruple helix structure, which includes stakeholders from academia, government, industry, and civil society (Carayannis & Campbell, 2009; Hasche et al., 2020). The quadruple helix and its predecessor, the triple helix, come from innovation system studies, and emerged as a way to better understand the flows of knowledge between different places (or strands of the helix) during the process of innovation. Civil society is the final addition to the quadruple helix, and has been characterized in different ways, including as media, culture and civil society (Carayannis and Campbell 2012), members of a community (Kriz, Bankins and Molloy, 2018), or as a more general expression of cultural values (Nordberg 2015, Ivanova 2014).

We set out to select interviewees from every strand of the quadruple helix, and as we explain in **Paper 2,** we succeeded with this: one came from civil society, six from industry, two from government, one from academia, and one person was an academic involved with local government and civil society, so that person covered parts of three categories (this was Interviewee 5). There was also a degree of diversity within the quadruple helix categories, for example the government-related interviewees came from different local government departments, and the industry interviewees were from the automobile industry, and the real estate and architecture industry.

There was, however, a limitation to the sample in that only one interviewee came from a civil society organisation, in addition to the interviewee who covered civil society, government and academia. We felt that this was acceptable, however, since at the time of the interviews there was not a widespread understanding of AVs within the public at large. It is also important to mention here that, during the interview process, we exercised extra care with Interviewee 5 so that we understood when the person was talking specifically about their work as one part of the quadruple helix.

Force-field mapping

Paper 2 uses mixed methods, meaning both qualitative and quantitative data collection and analysis. The quantitative part of this was what we referred to as force-field mapping, which was a way to assign a level of strength to the Pressures that were identified in the interviews. An online survey was sent out to a group of respondents that included the interviewees and additional respondents who were selected using the contingent purposive sampling method (Bryman & Bell, 2015). This means that we used findings that emerged during the research to guide the analysis. Specifically, we identified stakeholder groups that constituted more detailed subcategories of the quadruple helix and distributed the survey to those new stakeholder groups that came up in the interviews as being related to an AV transition, which included the following:

- Car user (passenger or driver)
- Car producer (individual companies)
- Car industry
- Mobility users who cannot drive
- Generic citizen
- Public transport provider
- Private transport provider
- Private transport driver
- Landowner
- Land developer
- Urban planner
- Politician
- Mobility consultant.

A total of 21 people responded to the survey, mainly from industry and academia, but many of them were involved in work with urban planners, landowners and developers, and public transport providers. The survey asked respondents to rank driving and restraining Pressures extracted from the stakeholder interviews on a scale of 1 to 3 (weak, medium, strong). The survey is used as supplementary and to deepen the insights gained from the information that was extracted from the interviews, rather than a purely statistical validation of the interview data; hence, we did not aim for any statistical significance from the survey. The data gathered from the interviews was dense, and thus the first two sections of the survey exceeded 50 questions about driving and restraining Pressures.

Combining DPSIR and Transition Management

In **Paper 3**, Transition Management is also used as a method to categorize and analyse the DPSIR chains that were identified in the interviews. To do this, we used the four stages, or spheres, of TM that Loorbach refers to as "governance activities" (Van Der Brugge & Van Raak, 2007). These are the strategic, tactical, operational and reflexive spheres (Loorbach, 2010).

We use the TM spheres to analyse the responses from the interviews and relevant literature, and the relationships between the responses and the rest of the DPSIR chain. Our goal is not to measure how strong the responses are, as for example in Berg et al. (2015). Instead, we are trying to understand what each response tells us about the bigger picture of the transition. Also, by detecting new or unusual responses, we aim to add new insights to the AV transition literature (Hopkins & Schwanen, 2018). This might be especially valuable for areas like Gothenburg or similar contexts, where the automobile industry is very dominant.

The strategic sphere involves long-term cultural aspects including the development of a long-term vision and what is known as the transition arena, comprised of stakeholders who have relevant competencies, interests and backgrounds. The tactical sphere focuses on governance structures, regimes and institutions, and barriers to an established vision. Scenario creation can be a key part of the tactical sphere. The operational sphere contains practices such as transition experiments, which we suggest could be pilot projects in the context of an AV introduction. Finally, the reflexive sphere includes monitoring, evaluating, and learning about the progress of the other spheres, specifically regarding established goals, strategies and actions.

The circular arrow in Figure 11 demonstrates that these spheres are connected and related but does not dictate that they must take place in a certain order. It is important to realise that the spheres can take place in any order that is relevant to the given context (Loorbach, 2010).

Figure 11. The Transition Management (TM) framework. Re-drawn from Loorbach (2010).

4.3 Results and Discussion

Paper 2 Results

The results of **Paper 2** are the Drivers, Pressures and associated stakeholders that were brought up in interviews, and a force-field map of the most salient Pressures, weighted according to a survey response. Here we refer to the Drivers as driving forces (associated with behaviours that might induce the transition) and restraining forces (associated with behaviours that might hinder or restrain the transition).

The driving forces that emerged in the interviews were: environmental concerns, market economy, technological progress, urban planning, politics and policy, health, and socio-cultural habits. The driving pressures are associated with the driving forces. Table 3 shows the driving forces and pressures, and their associated stakeholders.

Table 3: Driving forces and pressures, and their associated stakeholders.

Driving Force	Driving Pressure	Key Stakeholders
Environmental Concerns	AVs expected to drive smoother and slower, using less fuel	Car user, politician
	Car sharing would make AVs more acceptable for environmentally-sensitive people	Generic citizen
Market Economy	Economic interest of car producers	Car producer
	Interest from Mobility-as-a-service providers e.g. car sharing companies, Uber... (saving money by not paying drivers)	MaaS provider

	Promotion and marketing shaping idealised, futuristic imagery of AVs	Car producer
	Cheap land away from city centre can become more accessible with AVs (attractive for land owners and developers)	Land developer, Land owner
	People selling their cars and using shared AVs	Car user
Technological Advance	Expected efficiency advantages with self-driving and self-parking technology	Car producer, land developer?
	Expectation of improved safety with AVs	Car user
	IT industry interested in partnership with car industry	IT industry, car industry
	New technologies' (such as AVs') usefulness taken for granted	IT industry, car industry, car user
	Electrification of cars helps AV promotion (as it provides multiple benefits for AVs such as energy efficiency, money saving, less noise)	Car producer, transport provider, car user
Urban Planning	Mobility consultants supporting local authorities shape visions for the mobility of the future	Mobility consultants
	Need for improved mobility in rural areas (public transport not currently economically efficient)	Urban planners
	Pilot studies are being conducted which anticipate AV introduction	Multi-stakeholder
Politics and Policy	Politicians need to understand the implications of AVs in cities	Politicians
	Government economically dependent on (or, at least, tightly intertwined with) car industry	Politicians
	Authorities with a history of continued investments in upgrading infrastructure can be more responsive when adapting to AVs	Politicians
Health	COVID-19 exacerbating need for flexible transport	Generic citizen
	COVID-19 makes public transport drivers feel unsafe	Public transport provider
Socio-Cultural Habits	People using taxis and public transit are prepared for AVs, especially shared AVs	Generic citizen
	Demand for productive use of time (work or recreation) while driving	Car user
	Some urban dwellers prefer not to own cars (and instead demand shared AVs)	Generic citizen
	People interested in cars and new technologies in general may be interested in AVs	Generic citizen

	People who cannot drive (e.g. elderly, disabled…) have more opportunities with AVs	Generic citizen
	Ongoing work on legislation and regulations as preparatory work for AVs	Multi-stakeholder

The restraining forces that came up in the interviews were the same as the driving forces, but they act in the opposite direction, meaning that they could restrain the transition to AVs, which is further demonstrated by the associated restraining pressures. Table 4 shows the restraining forces and pressures, and their associated stakeholders.

Table 4: Restraining forces and pressures, and their associated stakeholders.

Restraining Force	Restraining Pressure	Key Stakeholders
Environmental Concerns	The sustainability agenda of local authorities can go against the introduction of AVs, as their environmental impact is unclear	Politicians and urban planners
	More cars means increased energy demand	Car producer and car user
	If AVs are electric: Environmental movement concerned that increased electricity supply will come from fossil fuels	Generic citizen
	If AVs are not electric: both air quality norms and climate policy could restrict the increase of AVs based internal combustion engine vehicles	Generic citizen
	Anti-sprawl opinions against AVs as they may encourage people to move away from dense urban centres	Generic citizen
Market Economy	Public transport providers see AV as competitors, and thus want to hinder AV introduction	Public transportation providers
	Dual infrastructure (for AVs and conventional vehicles) is expensive	Politicians and urban planners
	Risk of investing in a technology that fails on the market (e.g. if users don't purchase AVs or subscribe to programs that use AVs)	Multi-stakeholder
Technological Advance	New technologies need to be mature and safe before being introduced to users (e.g. safety concerns from fatal AV accidents).	Car producer, car user, IT industry
	Fear of AV technology being hacked	Car user
	Fear that cities become built around AVs, rather than creating a liveable city and adapting AVs to that	Urban planner
Urban Planning	Walking, biking and public transit as planning priority, not AVs	Urban planners

	In urban development policies the shared use of cars is deemed as more important than the self-driving aspect	Urban planners and politicians
	Streets are not currently designed for AVs	Urban planners
Politics and Policy	Current international and national laws and regulations are not suitable for AVs	Politicians
	Lack of political consensus on visions for the future in cities	Politicians
	Lack of knowledge and agreement about strategies from local authorities	Politicians
	The ethical question of who has priority when there is a risk for collision between a pedestrian and a AV	Generic Citizen
Health	Concern that AVs may increase congestion	Generic citizen, urban planner
	COVID-19 pandemic and fear of shared vehicles	Generic citizen
Socio-Cultural Habits	Conspiracy theories and misinformation about new technologies	Generic citizen
	The group of people who do not want to give up control of their vehicle	Car user
	People who do not like cars	Generic citizen
	Elderly people who are sceptical of new technology	Elderly people
	Cyclists are particularly sceptical about AVs, in terms of safety and access to urban space	Cyclist

The final result in **Paper 2** is a force-field map of certain driving and restraining pressures. As shown in Tables 3 and 4, many driving and restraining pressures came up in the interviews. In total, the survey respondents identified 52 different driving and restraining pressures, and then for the creation of the force-field map we removed those that had a median strength of 2 or -2 under the assumption that those pressures that were classified as “medium” were relevant but did not stand out in any way. Figure 12 shows the median value of the driving and restraining pressures, as well as the 0.25 to 0.75 percentiles to show the range of responses.

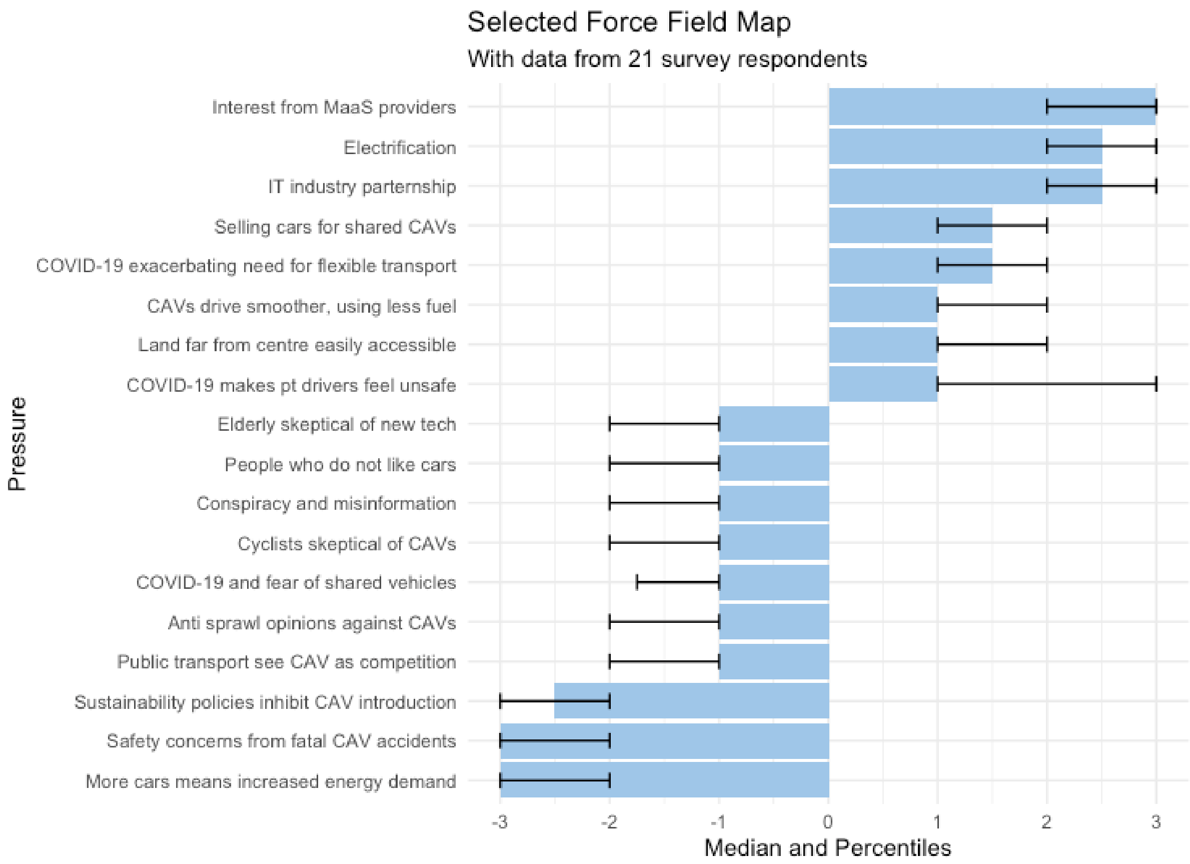

Figure 12: Selected force-field map showing all survey results for all Pressures that did not have a median value of 2.

The driving pressure that was ranked strongest was *Interest from Mobility-as-a-Service Providers*, who could benefit financially when they no longer have to pay drivers. Next strongest were *Electrification* and *IT industry partnerships*, which refers to partnerships with the automotive industry. In terms of negative strength, the largest was a tie between *More cars means more energy demand* and *Safety concerns from fatal AV accidents*.

An observation that we took from the force-field map was that the classification of *AVs drive smoother, using less fuel* as weakly positive and *More cars means more energy demand* as strongly negative suggests that respondents do not perceive AVs as a way to reduce emissions. We interpret this to mean that respondents believe the travel and energy demand impacts could override the benefits of increased energy efficiency. Furthermore, this matches with findings in the academic literature showing that AVs will likely increase travel demand, even if they also help reduce the energy consumption of individual vehicles (Taiebat et al., 2018).

Please note that these survey results are to be viewed as supplementary to the interview data, that the results give an idea of how Pressures that are brought up in the interviews are perceived at a more general level. The survey results are not quantitative evidence of the strengths of the Pressures.

Paper 3 Results

The same interview data was used for **Paper 2** and **Paper 3**. In **Paper 3,** the focus is on the Impacts and Responses that were identified in the interviews and classifying them according to the four spheres from Transition Management. The Impacts and Responses were either explicitly stated or implicitly referred to in the interviews.

An Impact is defined here as a consequence of introducing AVs in cities, as perceived by the interviewee. This is the full list of impacts:

- Better public transport especially in low population density areas
- Increased transport demand
- New infrastructure and use of limited urban space
- Parking companies losing revenue
- More individual decision-making power related to transportation
- Replacing people with technology
- Changes in vehicle to cyclist/pedestrian communication.

A Response can enhance or dampen the driving forces, tackle the restraining forces, or be expressed as strategies that respond to the Impacts. Here is the full list of responses from the interviews and literature:

- A step-by-step introduction of AVs
- Flexibility during city planning
- Barriers in cities caused by the creation of AV-only roads
- Encouraging non-car forms of transport
- Ride-sharing apps
- New jobs in a new transport system
- Cooperation between industry, government, and academia to better understand how AVs will be used
- Policy harmonisation between different tiers of government
- Cities becoming more powerful.

The final step in the results of **Paper 3** was to examine DPSIR chains using the TM spheres. We chose to examine the impact of *Increased Travel Demand* because it is very prevalent in the research literature, with many studies suggesting increased travel demand due to decreased VoTT (Soteropoulos et al., 2019; Taiebat et al., 2019; Wadud, 2017a). This sentiment was also echoed in the interviews. Figure 12 shows the basis for the DPSIR chain that we use.

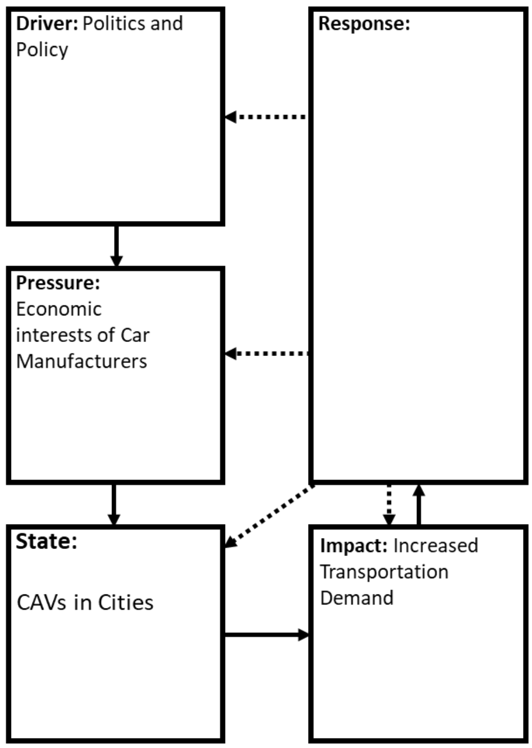

Figure 12: Example of the basic DPSIR chain that is analysed in the Results section of Paper 3.

The Strategic sphere emphasizes the importance of a long-term vision for the transition, which in the case of an introduction of AVs in cities could be created through collaboration between government, industry and users (Acheampong et al., 2023; Hopkins & Schwanen, 2018; Lyons, 2022; Milakis & Müller, 2021; Mladenović et al., 2020; Mukhtar-Landgren & Paulsson, 2021). This led us to the response *Cooperation between industry, government and academia to better understand how AVs will be used.* Of course, a sustainable socio-technical transition to AVs must include policies that address congestion, emissions and increases in travel demand (Milakis et al., 2017; Taiebat et al., 2019), and these issues span different levels of regional, national and international government control. This is captured by the response *Policy harmonisation between different levels of government.*

Although these responses could be aimed at any part of the DPSIR chain, the driver level is likely the most suitable target because political and bureaucratic processes usually require a great deal of time. Furthermore, the implicit knowledge and information that the transition arena creates (Loorbach, 2010) could relate to both responses mentioned above.

The next sphere that we examine is the tactical, which includes governance structures, regimes and institutions, and barriers to an established vision. In the interview data, we found the response *Creation of barriers,* which refers to a new road system where some roads are only for AVs, excluding anyone who does not have access to an AV. In this case, car producers could sell more cars or car-related services, intensifying the impact *Increased Transportation Demand,* whilst the barriers could worsen transportation inequities (Dianin et al., 2021; Wu et al., 2021).

There is also the possibility of a response in the opposite direction, with *Policies that Encourage Non-Car Forms of Transportation*. Since this response requires action from a governing institution, such as the City of Gothenburg, it matches the governance-oriented tactical sphere, and would likely be broad enough to target the driver stage of the DPSIR chain. The City already has a goal that 23% of trips should be made on foot, and 12% by bicycle, by 2035 (City of Gothenburg, 2023).

The operational sphere focuses on transition experiments, which fits well with the response *Ride-sharing apps.* This sphere should ideally involve multiple transition experiments that "complement and strengthen each other" (Loorbach, 2010, p. 176), one of which could be a ride-sharing pilot. The research project Eldsjäl has shown that total vehicle kilometres driven could decrease by 17% if ride-sharing were introduced in Gothenburg and its neighbouring suburbs (Lorig et al., 2023).

We categorise *Ride-sharing apps* as targeting the driver step of the DPSIR chain, because ride-sharing is often perceived as being more inconvenient and more costly than a private vehicle (Wadud & Chintakayala, 2021; Wadud & Mattioli, 2021b), so shifting to ride-sharing could require behavioural change on a large scale.

The Reflexive sphere of TM emphasizes consistent monitoring and learning about the activities happening in the other spheres, especially in terms of goals, strategies and actions that are collectively established by the transition arena or other involved groups. This can be related to the timing and speed at which the Impact happens, such as the graduated timing implied in the Response *A Step-by-Step Introduction of AVs.* AV technology can be seen as a system of many Operational Design Domains (ODD), which the EU defines as "operating conditions under which a given automated driving system is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics" (EU, 2022). A *Step-by-Step Introduction of AVs* could mean introducing a new ODD with each step, which is not so different from how the UN and EU are approaching current regulations for AVs (European Commission, 2022; UNECE, 2022).

Furthermore, the process of introducing new ODDs could be viewed as the introduction of multiple new States with each new ODD, which is why we suggest that this Response targets the State of AVs in Cities (see Figure xx).

The Response *Flexibility in City Planning* is also connected to the reflexive sphere, since it could refer to the regular monitoring and evaluation of AV development, and the consequential change in policies to ensure that the role of AVs in the transportation system matches the long-term goals for the City. This would target the driver stage of the DPSIR chain. In Gothenburg, for example, the municipal goals for transportation planning are revisited in yearly reports (City of Gothenburg, 2023; Hellberg et al., 2014).

Discussion

RQ 2: Which Drivers, Pressures, Impacts and Responses are important for a socio-technical transition to AVs?

How do driving and restraining forces and more specific pressures facilitate or hinder such a transition?

The interview and survey results made it clear that AVs are not seen as an unconditionally positive technology. Instead, many stakeholders believe that a transition to AVs needs to be linked with mobility planning and public transport strategies. Interviewees named specific policy-related actions such as local government studies, infrastructure planning and safety regulations as examples. Furthermore, a general sense of worry and unease was expressed at the idea of AVs being introduced without proper planning, which could result in increased travel and energy demand and related emissions. This echoes a need for planning that has been discussed at length in other places (Duarte & Ratti, 2018; Freemark et al., 2019; Gavanas, 2019). In this work, the results of our force-field mapping show that respondents think there is a need for planning in the Swedish context.

This need for planning can be connected to the driving pressure *Economic dependence on the automobile industry* in the City of Gothenburg, and how that creates a strong interest in AV development and eventual introduction as part of a future business strategy. Approximately 98% of the Swedish car industry is situated in the Gothenburg Region (Business Region Gothenburg, 2024). A related restraining pressure is the idea that Swedish cities would be designed with AVs as the focus, thus creating neighbourhoods and areas that are not suitable for pedestrians and other forms of transportation. De-prioritization of pedestrians and other forms of transportation relates back to Lundin's 2014 dissertation, which examined the development of private car ownership and the automobile industry in Sweden post-WWII (Lundin, 2014). Lundin's work supports the interview findings that dominance on the part of one actor (such as the car industry) can lead to one-sided development. Thus, some kind of combination of private sector technology development (e.g. the Volvo Group, Volvo Cars and other automobile manufacturers) and public planning (e.g. ongoing processes at the City of Gothenburg) are important.

What stakeholders are connected to the driving and restraining forces and pressures?

In the list of stakeholders that we identified as being associated with the Drivers and Pressures in **Paper 2**, there are some who have been mentioned frequently in the research literature. Some examples are older people and disadvantaged people who are unable to drive cars (Fraedrich et al., 2016; Templeton, 2020).

A stakeholder group who are connected to Gothenburg and are also important in other cities around the world are the group of participants and other actors involved in AV pilot projects. This could include politicians, mobility consultants, and urban planners, who are all involved in what we refer to as "the ecosystem of funding and expertise" (Rebalski et al., 2022, p. 10) that is created around such pilots. There is also a connection to the car industry through the driving pressure of commercials associated with pilot projects, in addition to the development of the technology itself. These commercials often portray AVs in a very positive light (Hildebrand & Sheller, 2018), and interviewees stated that this image of AVs was very dominant for them when trying to imagine what AVs might look like in the future.

Pilot projects have been recognized as an important part of AV development, although they do not necessarily lead to the implementation of the technology (McAslan et al., 2021). Furthermore, "critical citizen engagement and participatory deliberation" (Mladenović et al., 2020, p. 258) is an important factor in how much pilot projects actually serve to educate and involve the public in the development of AVs.

Finally, there was an interesting convergence of different stakeholders who were identified as being sceptical of AV technology. Older people, cyclists, people who are concerned because of conspiracies related to new technology, and those who are concerned about environmental effects cover a wide group with many different characteristics, some of which can be associated with technology enthusiasts (Nielsen & Haustein, 2018). This group of unlikely bedfellows could be important for future research on stakeholder groups and AV development.

How do local stakeholders perceive the impacts of AVs?

One impact that was brought up in the interviews and that is also common in the peer-reviewed academic literature is *Increased Travel Demand.* Here, the interviewees' perception matches the literature pretty well, with both sides suggesting that AVs could make car travel cheaper and more convenient, and thus cause more travel demand (Milakis et al., 2017; Taiebat et al., 2019; Wadud & Mattioli, 2021b), which is also demonstrated in **Paper 1**.

There are other examples, however, where the way that impacts were perceived by the interviewees does not fit with the findings in the literature. Two of these were *New infrastructure and use of limited urban space* (for example garages that allow cars to park more closely together) and *Parking companies losing money*. The interviewees focused on a future where cars and parking garages are necessary, but perhaps the garages are dimensioned differently, resulting in an incremental change to the status quo where car ownership is considered a necessity in Sweden. In the literature, however, there is a strong connection between the regulation of parking spaces and how this can be used to steer towards a reduction in car ownership (Johansson et al., 2022; McAslan & Sprei, 2023), which would be a larger change to the status quo.

The idea that AVs could be introduced as part of the public transport system was identified with the impact *Better Public Transport.* While this also comes up in the literature, it seemed that interviewees maybe had a more naïve perception of how integrating AVs into the public transport system would work. Some authors argue that such integration is unlikely without strategic planning (Legacy et al., 2019), especially given the way that incumbent industry actors could benefit from individual car travel (Docherty et al., 2018).

How can the complexity of the responses be captured and interpreted for policy interventions using Transition Management?

This question is answered based on to the spheres of Transition Management, starting with the Strategic sphere. The responses that emphasized long-term visioning were *Cooperation between industry, government and academia to better understand how AVs will be used* and *Policy harmonisation between different levels of government.* While the City of Gothenburg does not have transportation goals regarding AVs, many different research projects on Avs are happening within the City. This may be a missed opportunity for coordination, meaning that these diverse projects could be working towards complementary parts of a common long-term vision. Many other cities in Europe also lack such long-term planning for AVs (Grindsted et al., 2022). This gap was part of the inspiration for the backcasting-based scenario process in **Paper 4**.

The tactical sphere of TM also encompassed two responses: *Creation of barriers* and *Policies that encourage non-car forms of transportation.* Here, the responses are very different from one another. *Creation of barriers* is a short-term solution to AV traffic, where AVs are given their own roads, potentially resulting in a more socially unsustainable transportation system where stakeholders without access to AVs have less convenient transportation options. Regardless of AVs, the issue of barriers is already a priority in Gothenburg, as is shown in the transport planning strategy document *Gothenburg 2035*, which names "Creating a denser and more interconnected network of streets without barriers" as a sub-goal (Hellberg et al., 2014). This focus on interconnectivity and access connects with the second tactical sphere response *Policies that encourage non-car forms of transportation*. Gothenburg has many different projects in place to encourage cycling and walking, one of which includes the creation of a guideline to reduce speed limits to 30 km/hour in the presence of pedestrians or cyclists (in addition to existing speeds limits for schools and other special zones) (City of Gothenburg, 2023).

The operational sphere of TM focuses on transition experiments and putting theory into practice. Here, the impact of *Ride-sharing apps* fits well, although it is important to note that ride-sharing might not be something that enough people can afford or want to try (Wadud & Chintakayala, 2021; Wadud & Mattioli, 2021b), which could mean that it does not have the desired effect of mitigating *Increased Transportation Demand*. If this is the case, a policy intervention at the tactical stage to encourage ride-sharing adoption could be helpful, and this intervention could be part of a broader strategy to address ride-sharing difficulties.

Finally, there were two responses that matched the reflexive sphere of TM: *A step-by-step introduction of AVs* and *Flexibility in city planning*, both of which highlight the need for adaptive governance during the introduction of AVs. Interestingly, Swedish policies on climate targets have mentioned the usefulness of flexible regulatory approaches when working towards long-term goals; see for example Hunhammar et al. (2021) and Nohrén et al. (2022). In 2022 the EU introduced Regulation 1426 to govern automated driving functions such as speed and braking. The EU plans to amend Regulation 1426 at least once in the coming years as AV technology and its associated socio-technical system develop.

5. Summary of Paper 4

5.1 Theory and Methodology

Transition Governance

Paper 4 interprets governance in the way that it is described by Loorbach et al. (2017, p. 612):

"Transitions research advocates that governance is a multi-actor process in which systemic solutions, disruptive innovations, and (reflexive) institutions are formed by experimenting and learning."

In **Paper 4,** we use some aspects of Transition Governance (TG) to frame a backcasting scenario. TG and TM are tightly intertwined and sometimes overlap. As the field of transitions studies developed, TG and TM were sometimes used interchangeably; see for example Bosman and Rotmans (2016, p. 3) who state that:

"Research into the possibility of influencing or steering transition processes is referred to as transition governance or transition management. In practice the distinction is not that clear since trying to influence transitions requires a sound understanding of transition dynamics".

However, in more recent research, TM is seen as the operational approach that is based on the guiding principles of TG which are (Loorbach et al., 2021, p. 2):

- "Systemic: engage with emerging dynamics across societal levels
- Back-casting: envisioning and scenarios as instruments for change
- Selective: focus on change agents, frontrunners to create transformative networks
- Adaptive: experimenting towards multiple goals and transition pathways
- Learning-by-doing and doing-by-learning: ensure monitoring and reflexivity"

TG is thus closely related to concepts such as Reflexive Governance, and Anticipatory Governance. Reflexive Governance is especially related to the evolution that comes from learning-by-doing and doing-by-learning, and refers to "thinking and acting with respect to an object of steering [which also] affects the subject and its ability to steer"(Voß & Kemp, 2015, p. 4). Multi-actor involvement is generally thought to be important for this process, but Pickering (2019, p. 1150) cautions that "…whether participatory goal formulation contributes to reflexivity is a question of empirical fact, not a constitutive feature of reflexive governance itself: it remains possible that a reflexive process could be driven by elite actors, or that extensive stakeholder participation could fail to generate new thinking."

Anticipatory Governance attempts to make sense of uncertain futures, and engage with those futures in a way that can steer present-day action (Muiderman et al., 2022) by engaging with the development of a given technology (Cohen & Cavoli, 2019). It has roots in science and technology studies, responsible innovation, and environment policy and governance (Muiderman et al., 2020), and emphasizes the importance of stakeholder involvement in the decision-making process (McAslan et al., 2024). Cohen and Cavoli argue that anticipatory governance is going to be very important for governing AVs because it "is grounded in the explicit acceptance that a great deal remains unknown about the emerging technology but that this is not a sound argument for doing nothing" (2019, p. 142).

Another form of governance that has been suggested for AV technology is adaptive governance (Tan & Taeihagh, 2021). This comes from public service innovation and is similar to reflexive governance in that it requires governance processes to be agile, make incremental revisions, and constantly learn by doing. Adaptive governance is practised by government bureaucracies, whereas reflexive governance goes so far as to "question the foundations of governance itself" (Voss & Kemp, 2005, p. 4), including the very existence of those bureaucracies.

Futures studies, scenarios and backcasting

Backasting is part of the broader academic field of futures studies (Holmberg & Robert, 2000; Johansson, 2021). There are many ways to describe and delineate the elements of futures studies, and here I will use the typology put forth by (Börjeson et al., 2006), because their focus on and connection with real-world applications is particularly relevant for how we used backcasting in Paper 4. Börjeson et al. classify scenarios into three categories: predictive, explorative, and normative. These categories are then further divided into different types, which are shown in Figure 14.

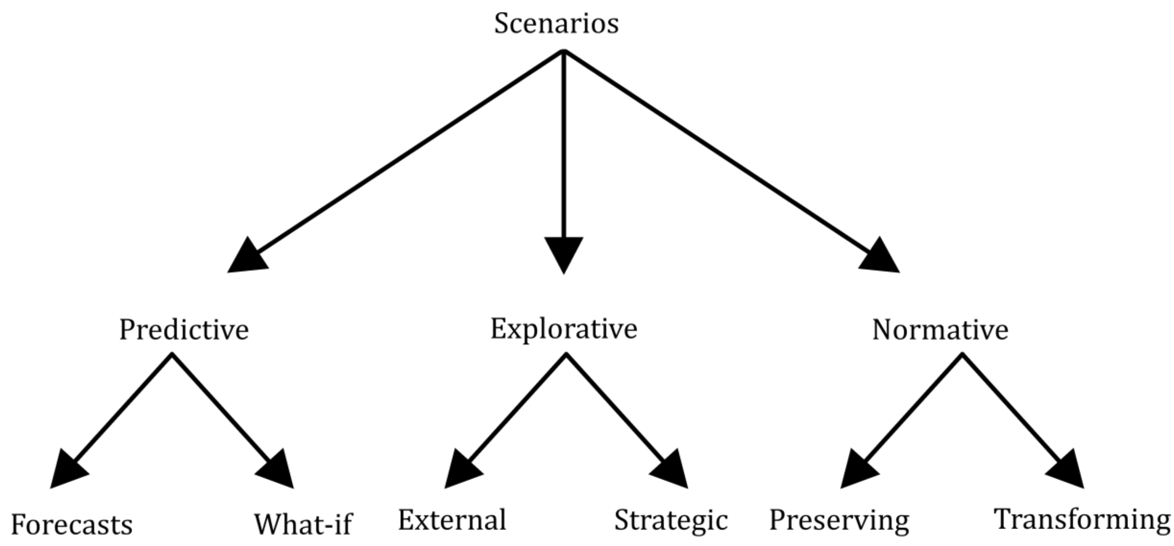

Figure 14. Re-drawn from Börjeson et al. (2006), scenario categories and types.

Backcasting is classified as a normative, transforming type of scenario-based research. Normativity is a key characteristic, meaning that backcasting examines a desired outcome, rather than the most likely outcome given certain factors (Börjeson et al., 2006). Furthermore, backcasting starts from the assumption that some kind of transformative, systemic change is necessary to achieve a desired outcome. Dreborg presents this as "an approach that focusses on the problem to be solved rather than on the present conditions and current trends"(1996, p. 815). It is a methodological technique where the researcher, often together with stakeholders, designs an image of the future based on a certain goal, and then determines how that future image could be attained (Robinson, 1982). Backcasting was first used by Amory Lovins to study energy futures (Dreborg, 1996), and soon after that Robinson (1982) popularized it as a method. It has been used within Swedish transportation research for many years (Åkerman & Höjer, 2006; Berg Mårtensson et al., 2023; Dreborg, 1996; Höjer & Mattsson, 2000; Johansson et al., 2022).

Dreborg argues that backcasting has the ability to promote creativity and exploration, and while it can be used in the context of replicable scientific research, it should be viewed as an approach that sets out to inspire new ideas, not to prove hypotheses. He suggests that backcasting has a connection to the principle of teleology, which states that actions can be explained by the desires and beliefs of the actors involved, and while these actions might seem logical in hindsight, they cannot be predicted by any general law. Thus, combining teleology with the more dominant principle of causality as part of a backcasting approach is useful for capturing a broader range of possible, and desirable, futures (Dreborg, 1996). It is a particularly useful methodology to use when there is a high degree of uncertainty (Dreborg, 1996), which makes it an effective technique for studying futures with AVs (Li et al., 2019; Marchau & Van Der Heijden, 2003). Dreborg (1996) argues that backcasting is especially useful as a planning tool in situations which include the following characteristics (citation below):

" a) when the problem to be studied is complex, affecting many sectors and levels of society;

b) when there is a need for major change, i.e., when marginal changes within the prevailing order will not be sufficient;

c) when dominant trends are part of the problem - these trends are often the cornerstones of forecasts;

d) when the problem to a great extent is a matter of externalities, which the market cannot treat satisfactorily;

e) when the time horizon is long enough to allow considerable scope for deliberate choice."

5.2 Data and Methods

Document Analysis

The first data-gathering step in **Paper 4** was to collect and analyse documents related to municipal, regional, and national transportation sustainability policies in Sweden. This included government reports, policy documents, supplementary material to those documents, and press releases. In cases where policies overlapped, or it was unclear if the policy was legally binding or simply suggested, I contacted government officials for clarification.

In addition to policy documents, relevant scientific research was also collected and analysed to create the initial targets that formed the basis for the scenarios used in the interviews.

Interviews

The data collection for **Paper 4** included 21 interviews with 22 transportation experts from government, academia, the automobile industry, public transport authorities, and research firms. Two different scenarios for the Gothenburg

Region in 2050 were presented at the beginning of the interviews, and then all interviewees were asked a list of the same questions. If an interviewee had extra knowledge in a certain area, they were asked extra questions about that area. The two scenarios and the full list of interview questions are available in the Supplementary Material of **Paper 4**. The interview transcriptions were analysed using content analysis (Hsieh & Shannon, 2005).

Backcasting

As was mentioned above, Paper 4 uses a methodology inspired by backcasting. The steps that we took were based on those suggested by Höjer and Mattsson (2000):

- Setting of one or a few long term-targets
- Evaluating each target against the current situation, prevailing trends, and expected developments
- Generating future images that fulfil the target(s)
- Analysing the future images in terms of feasibility and pathways to the images, for example.

In Paper 4 we extended these steps as below:

- Setting targets and scenarios for 2050:
  - Literature (reports, policy documents, press releases) related to municipal, regional and national transportation sustainability policies in Sweden and relevant scientific research were used to create the initial targets and scenario elements. These scenarios were then used to inform interviewees about the backcasting study and set the context for interview questions.
- Evaluating the targets and scenarios against "the current situation, prevailing trends and expected developments" (Åkerman & Höjer, 2006):
  - The interview data and the literature review data were used to finalise the choice of scenario.
- Creating a future image of the Gothenburg Region[3] in 2050, where the targets are met, and a pathway for some selected sub-parts of the system to that future image:
  - The literature review and interviews were used for both the future image and pathway.

[3] Note that the Gothenburg Region is a group of 13 municipalities including Gothenburg and the surrounding area. For a more detailed description, see Paper 4.

- Analysing the feasibility of the pathway for the selected sub-parts of the system to the future image.
    - Interview data as well as additional communication with certain interviewees about more specific questions (such as follow-up regarding certain government policies and studies) is used to inform the analysis.

5.3 Results and Discussion

Results

Paper 4 is a scenario study where we used backcasting to formulate a Future Image and Pathway of selected sub-systems to the Future image. The Feasibility Analysis of the Pathway to the Future Image then serves as the discussion. The future image in 2050 envisions a passenger transportation system in the Gothenburg Region that requires minimal emissions and material use in the production of vehicles, while maintaining accessibility and steadily increasing the share of trips on foot, by bicycle and by public transport. We assume that the system will be fully electrified in 2050, and we only considered transport inside the Gothenburg Region. The formative components of the Future Image are a kilometre tax, a Demand Responsive Transport (DRT) system, a Bus Rapid Transit (BRT) system, and a related decrease in car ownership.

BRT and DRT are not necessarily based on AV technology, but both systems would become more affordable if no driver was required. DRT is "a service where the vehicle tailors its route based on passengers' transportation needs at a certain time" (Persson et al., 2023, p. 5). It uses small buses to complement fixed public transport routes, or to provide access to transport in areas where there is infrequent or no public transport. BRT is a bus system where the buses have their own lanes or priority over other vehicles, can carry more passengers than regular buses, and are able to travel at higher speeds on highways or prioritized roads. There are already some express buses in the Gothenburg Region that provide a simple version of BRT, but there have been policy studies examining the creation of new lines (Swedish Transport Administration et al., 2021).

In the pathway, we assume that the kilometre tax applies to all passenger vehicles that are not used for public transport and is differentiated according to time and location. It is assumed that the tax is introduced when electric vehicle sales comprise between 70–90% of new car sales in Sweden (Hennlock et al., 2020). It is further assumed that the revenue from the tax will be used to subsidize the construction costs of BRT and the wages of drivers before DRT is fully automated, and once those costs are paid for, the tax revenue replaces fossil-fuel tax revenues. The tax encourages a shift from private vehicles to public transport. Furthermore, it has a Pigouvian design so that the tax level is equal to the marginal cost of the externalities caused by the use of the car, thus keeping VKT below the untaxed level as the price elasticity of demand is negative (Small & Van Dender, 2007).

The BRT system is in some cases faster and less expensive than driving a private car, especially for tangential trips from one side of the city to another, or between suburbs. Initially, lower levels of automation can help bus drivers with driving tasks such as braking smoothly or stopping at bus stops.

The DRT system uses small busses with no host on board. The system starts with small pilot projects in sparsely populated areas (similar to the pilots already happening in Sweden and around the world), and these projects slowly scale up (Vansteenwegen et al., 2022). DRT is part of the public transport system, so the ticket price is the same as for other PT services (thanks in part to subsidies possible because of the kilometre tax revenue).

Car ownership in the Gothenburg Region has decreased, largely because of the reliable and flexible public transport system, but also due to the kilometre tax and the increased cost of driving a private car.

Discussion

RQ 3: How can autonomous vehicles be integrated into the Gothenburg Region's transport system to achieve sustainability and climate goals?

To make the future image where AVs are part of a sustainable transportation system feasible, strong policies are needed. It is helpful to view the transition to this future image through the lens of Transition Governance (TG), which is a systemic and adaptive approach to managing changes in systems that emphasizes the importance of "learning-by-doing" and "doing-by-learning" (Loorbach, 2022, p. 2). We also relate the complexity of this socio-technical transition to AVs to Collingridge's dilemma of control. This examines the trade-off between regulating a new technology early on in the transition or introduction, before all the societal effects are well understood, or waiting and perhaps allowing the technology to become embedded in a way that makes regulation more challenging (Collingridge, 1980). Our chosen method to address this dilemma is called “enhancing controllability” (Genus & Stirling, 2018, p. 63), where broad social agency is exercised early on to steer the technology. This is essentially what this backcasting study does when it examines a kilometre tax, BRT and DRT.

The wider social agency mentioned by Genus and Stirling in this case could be applied by a diverse group including municipal, regional and national governments, and those who vote for them (i.e. citizens), in addition to public transport providers. Non-governmental parties who are involved in regional transportation infrastructure projects are also important, because there is a large amount of transportation knowledge within the automobile industry, research institutes, consulting firms and other non-governmental parties in Sweden (Rebalski et al., 2022).

Both the literature review of policy documents and the interviews delivered the finding that the group of actors who could drive this transition is diverse, and thus collaboration between different actors will be important. For example, different tiers of government may need to work together to establish common goals and specific action plans for each tier of government (Sanne et al., 2023). It is also important to establish which tier of government (or other actor, such as the public transport provider) is ultimately responsible for implementing a certain measure, to avoid a lack of leadership and threaten its feasibility.

The feasibility of the kilometre tax seems to be very vulnerable to public resistance, given the reaction to the existing Gothenburg congestion tax. Prior to the official establishment of the tax, 57% of voters sided against it in a referendum (Jagers et al., 2017). The most recent opinion numbers from 2022 show that 48% of people in Gothenburg have a negative opinion of the congestion tax (SOM Institute, 2023). These two statistics come from different contexts, as the first is the result from a referendum on the matter, and the second is the calculated polling result of a survey. One can nonetheless draw the conclusion that public opinion has become less negative, but the congestion tax remains unpopular, and the lasting effects of its introduction could make it very challenging to achieve public support for a kilometre tax.

We suggest an approach that is modified slightly from that put forth by Carattini et al. (2018):

- Redistributing tax revenues to improve perceived fairness, by either tax transfers or enhanced levels of public transport services to those most negatively affected by the kilometre tax.

- Phasing in the kilometre tax over time to increase the possibility for adaption to new circumstances.
- Information sharing and communication in both directions between the government and the public to boost mutual learning and acceptance. Public information campaigns should focus on long-term benefits (Hansla et al., 2017), not just immediate changes.
- Earmarking tax revenues for improved public transport services such as DRT and BRT. Earmarking tax revenue is in general considered to be important for increasing the acceptance of environmental taxes (Sterner et al., 2024). Part of the current congestion tax revenues go to public transport in Stockholm and towards infrastructure costs in Gothenburg, so this is not unprecedented (Ahlbäck et al., 2022). We suggest that some revenues from the tax could be diverted towards DRT and BRT, to subsidize driver wages and construction costs.

DRT systems are very much in the testing phase right now, with approximately 870 pilot projects happening around the world (2 in Sweden, one in VGR). One of the interviewees summed this up by saying "*[I] wouldn't say we're there yet in terms of [DRT] being procured on a regular basis and on a large scale, but this phase which is about pilots, there's momentum there. Then I don't think that you will get sufficient financial gain before the vehicles are autonomous and the driver cost disappears*" (Interviewee 19, Automobile Industry).

It is difficult to know when the DRT system would start to use AVs, but the increased testing in cities will likely provide knowledge on what conditions are necessary for a successful transition. Sipetas et al. (2023) note that the transition period from human-driven vehicles to AVs is the most costly phase of implementing a DRT system, both for the operators and for the passengers in terms of (among other things) the cost of passengers' time and convenience. At the same time, this mixed phase is important in order to help users become accustomed to the technology, which relates to the learning-by-doing (passengers adapting to the removal of the driver) and doing-by-learning (technology and public transport providers learning how to best deploy the technology) aspects of TG.

BRT does already exist to a limited degree in the Gothenburg Region, but the feasibility of a more widespread system immediately runs up against very high building costs. A recent report found that the construction of a BRT system in and around Gothenburg could cost SEK 6–9 billion (Swedish Transport

Administration et al., 2021), which is much more than the total amount (SEK 0.4 billion) allocated to VGR's transportation infrastructure plan in 2022.

We highlight one more factor that could affect the feasibility of BRT: different tiers of government and industry collaborating to form a "transformative network" as described by Loorbach in the TG literature (2022). The selective nature of TG is important here, as this transformative network should ideally be made up of actors who have the vision and agency to effect change. This matches well with the networks that have already been created around the existing push for BRT, as they have both the authority and the vision to plan for a major change in the public transport system.

The final piece of the future image that we analyse in terms of feasibility is a decrease in car ownership in the GR. A good way to set the stage for this was summed up by an interviewee who said: *"If you look at all the infrastructure and all the tax money that is used to subsidize private car ownership directly or indirectly, there are quite a few things that you can remove. And it's easy, in practical terms. But in political terms, taking things away from people is of course very difficult." (Interviewee 7, Research Institute)*

In order to dispel the idea that this would be "taking things away", alternatives to transportation by car need to be readily available for car-dependent households. For DRT and BRT, and the rest of the public transport system, this could mean guaranteed wait times, travel times and extended hours of operation (Moody et al., 2021). AV technology will hopefully help by lowering the costs (Sipetas et al., 2023) of DRT, car sharing, private taxis, and other parts of the public transport system. If DRT and BRT can become fully automated and implemented where needed, public transport should be a good enough alternative so that decreases in the rate of car ownership are feasible.

6. Concluding Remarks

6.1 Limitations

Each of the appended papers has faced practical and theoretical limitations. **Paper 1** is based around principles of economics, i.e. that individuals act rationally and with complete information and knowledge of a situation. In Paper 1 we also assume that they only consider the cost of the AV technology compared to the potentially reduced GTC from a reduced Value of Travel Time when deciding whether or not to purchase an AV. Even putting the unlikeliness of this somewhat narrowly defined decision-making aside, there are many other factors that affect purchasing decisions, such as social status or pressure (Rezvani et al., 2018), safety, or a lack of trust in AV technology (Gao et al., 2019; Yap et al., 2016).

In terms of the more detailed modelling assumptions in **Paper 1,** there is the possibility that we are underestimating the benefits associated with AV purchase, since we assume that there are no changes in energy, maintenance, or insurance costs between now and 2045, and between a conventional car and an AV. Furthermore, we assume that every income group pays the same amount for the AV technology, but in reality, higher earners might purchase more expensive AV technologies. In this case, the cost of the technology could be a larger portion of the GTC per km, and this in turn could affect the purchasing decision and travel demand. However, a more costly and potentially a more advanced AV technology could also bring about better services causing a larger reduction in VoTT.

In **Papers 2**, **3** and **4** a main limitation is that the vast majority of the interview and literature review data discusses a technology that is not yet available to most of the public. The way that both the scientific literature, and the interviewees, view AVs is likely different than what will happen in reality. This has been exemplified by technologies like nuclear energy that caused initial optimistic excitement, but eventually were not used on the anticipated scale due to issues such as cost and safety concerns (Collingridge, 1980).

Sometimes, a common understanding of what a future with AVs might look like is the starting point for a study, but it can be difficult to ensure that all parties involved in a scientific study are envisioning AVs in the same way. As was mentioned in Chapter 2, one way that some authors partly address this issue is by using storytelling or 'vignettes', where respondents are first given a very clear idea of what the scenario with AVs looks like. Arguably, I used a simplistic version of vignettes when I described future scenarios to interviewees during the data collection for **Paper 4**. By using vignettes or storytelling, the scientists can know what kind of future scenario the respondents are discussing, although there is still the limitation of the future being unknown to all of us.

Finally, an important limitation throughout this PhD work has been the rate at which AV technology and testing is developing, and the connected rate at which academic, peer-reviewed research is published on a variety of topics related to AVs. This was most limiting during the research and writing of **Paper 1**, which uses a quantitative model that builds upon previous travel demand and VoTT research and was arguably very popular when I started my doctoral studies.

6.2 Conclusions

This doctoral thesis and the appended papers are unified by the aim of examining the introduction of AVs in Sweden from a sustainability perspective. This began with a study into the impacts of a change in VoTT due to AVs in **Paper 1**, which showed that Sweden is similar to other countries in that those with a higher income tend to travel further distances by car. Higher income earners in Sweden are more likely to purchase an AV (if their decisions are based on the break-even estimations in **Paper 1**) and increase their travel distance, causing various life-cycle impacts in the production and use of the vehicle.

Paper 2 concluded that stakeholders believe explicit policy planning for AVs is necessary, and that there could be unusual combinations of stakeholders who form groups that resist the introduction of the technology. This need for planning is taken up again in **Paper 3**, where the importance of cooperation between different parties is a main takeaway. Furthermore, **Paper 3** established that there are many transportation goals within the City of Gothenburg that could be a useful starting point for regulating AV technology, and that reflexivity will be crucial as new iterations of AV technology are introduced and as actors learn about the technology and its consequences.

Paper 4 took the conclusions from **Papers 1–3** and created a future image of the Gothenburg Region in 2050 where the transportation system requires minimal material requirements from a life cycle perspective and urban environments have increased liveability because the total number of private cars has been reduced. A kilometre tax and BRT and DRT systems are proposed and analysed. The importance of cooperation between different actors emerges again as a conclusion, in this case in the form of increased cooperation regarding policies that are administrated at a national level but are carried out at a local level, like the suggested kilometre tax. It also concluded that since systems such as BRT and DRT require large monetary investments for infrastructure (BRT) and operation (DRT, before the system is driverless), different tiers of government could collaborate around the planning and funding of these services.

Throughout all the appended papers, it became clear that although there is little policy in place in Sweden that specifically targets AVs **(Paper 2)**, there are environmental and transport policy goals at all tiers of government that are well-suited to guide the introduction of the technology **(Papers 3 and 4)**. These goals relate to GHG emissions, environmental sustainability, accessibility, equity, health and a range of other metrics that oppose the continuation of a transportation system built to prioritize private passenger cars and the connected risks of congestion, noise, barriers and other negative effects. Each of these goals is connected to quantitative indicators and progress is evaluated annually by different government agencies. It could be theoretically possible to meet domestic emissions reductions goals through electrification and biofuel use, while not meeting the generational goal policy areas and the transport policy objectives related to supply chain emissions and accessibility. However, the findings in **Paper 3** and **Paper 4** show that technology like AVs can help contribute to the fulfilment of national goals related to emissions, safety, accessibility, supply-chain issues, and other effects.

In conclusion, AVs can be used to avoid potential large-scale problems such as increased travel demand, congestion, and life-cycle emissions, and steer towards transport policy objectives related to sustainability and accessibility, but in order to do so the introduction of AV technology needs to be carefully planned and executed.

6.3 Future Research

One area where future research could provide insight into VoTT and the use of time in the vehicle is AV pilot projects in real-world environments where the technology can be used as an aid for people who are required to drive cars for their work. This could include professions where people drive between many different locations during the course of their workday and might be able to use the time in the vehicle to do administrative work, or to rest, such as homecare services, nurses, or even real estate agents. What professions could be affected by this, and how they might benefit from using AVs, could be an interesting area for future research.

Furthermore, there could be a relevant use case for AVs when it comes to transporting children to various after-school and weekend activities. If and why parents are willing to allow their children to travel alone in an AV, the savings in VoTT for households based on current travel patterns and effects on future travel demand would all be interesting to consider.

From a policy perspective, there has been much research recently in Swedish transportation policy about "goal-directed" planning (Eriksson et al., 2024; Sanne et al., 2023) where a future sustainability goal is used as the basis for transportation planning, as opposed to planning for infrastructure based on forecast travel demand. **Paper 4** built on this to a certain extent, but there is room for more backcasting or similar scenario-based research that examines how AVs can be used to reach environmental and transport policy goals in Sweden. This could be especially interesting when considering trips where vehicles are operating in different levels of automation at different points during the trip depending on the circumstances, for example a bus that is level 4 in a special lane on a highway, and then level 2 when it enters a city centre.

Finally, the theme of collaboration between different tiers of government came up frequently in **Papers 3** and **4** especially. There is a great deal of research into collaboration around transport policy between different tiers of government and other actors in Sweden Eriksson et al 2024, (Eriksson et al., 2024; Paulsson et al., 2018; Pyddoke & Thoresson, 2023; Tornberg & Odhage, 2022). It would be interesting to see how the outcomes of these studies can be applied to the introduction of AV technology, especially considering the long-term reflexive nature of the transition to AVs.

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