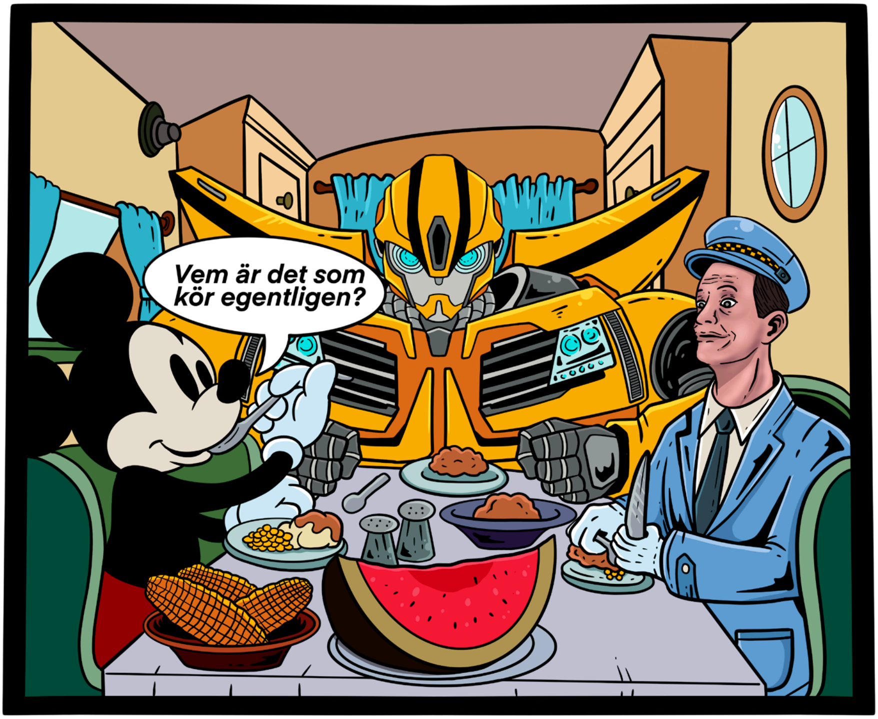
KTH ROYAL INSTITUTE OF TECHNOLOGY

Doctoral Thesis in Machine Design

Beyond Technology

Understanding Societal Impacts of Implementing Self-Driving Vehicle Systems on Road Transport

ERIK ALMLÖF



Stockholm, Sweden 2024

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ERIK ALMLÖF

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I. Abstract

During the last decade, self-driving vehicles have become a major topic of interest, promising to transform transport by making travel safer and more efficient. However, as we move closer to making these vehicles a reality, it has become clear that introducing them into society might not be as straightforward as once thought, and there are growing doubts about the benefits they are supposed to offer.

In this thesis, I investigate the societal impacts of self-driving vehicles by exploring four aspects: reasons for researching self-driving vehicles, how these vehicles could be implemented, the societal impacts of fully implementing self-driving vehicles, and their relationship to sustainability goals.

I find that the motivation for researching this topic is often opaque, and the existence of the technology itself is used as a justification for more research.

Furthermore, most research into realising self-driving vehicles focuses on purely technical aspects such as designing better algorithms. However, I show that many challenges remain connected to the sociotechnical intertwinement of self-driving vehicles. For instance, I illustrate how they will interact with pedestrians and how services using self-driving vehicles would be practically organised.

Additionally, self-driving vehicles are likely to impact many aspects of society, such as congestion, accessibility, and economic factors. However, I demonstrate that no single framework successfully captures all the identified societal impacts, which are likely to depend on diverse factors such as geographical variations.

The impacts further affect sustainability, where new challenges are likely to emerge. I show that while current tools to govern the transport system are still relevant, a comprehensive approach is needed to ensure that policymakers make well-considered decisions.

In conclusion, I call for a more balanced view of self-driving vehicles. Introducing this new technology requires careful planning and governance to ensure that self-driving vehicle systems genuinely enhance our quality of life and help build a sustainable future.

II. Sammanfattning

Självkörande fordon har framställts som en viktig pusselbit för att uppnå hållbara och säkra resor, med möjligheter att förbättra trafikflödet, minska utsläppen och öka trafiksäkerheten. Det har dock visat sig att introduktionen av denna nya teknik inte var så enkel som det till en början framställdes, och att effekterna inte nödvändigtvis bara är positiva.

I denna avhandling undersöker jag de samhälleliga effekterna av att införa självkörande fordon, uppdelat i fyra områden: varför forskning sker på området, hur de skulle realiseras, de samhälleliga effekterna av ett införande, samt relationen mellan självkörande fordon och hållbarhet.

Jag visar att motiveringen för att göra forskning på området ofta är oklar och att själva existensen av forskning på området används för att självrättfärdiga mer forskning.

Den mesta forskningen om att realisera självkörande fordon fokuserar på rent tekniska aspekter, såsom bättre algoritmer. Även om många utmaningar kvarstår på det området visar jag även att många andra praktiska problem kvarstår, kopplade till den sociotekniska kopplingen mellan teknik och samhälle. Till exempel saknas lösningar för hur fordonen skulle interagera med fotgängare, och de självkörande fordonen skulle dessutom behöva organiseras praktiskt på något sätt.

Effekterna av självkörande teknik skulle även påverka många delar av samhället såsom framkomlighet, tillgänglighet och ekonomi. Därutöver demonstrerar jag att inget nuvarande ramverk för att förstå samhällseffekter lyckas fånga samtliga aspekter, och att effekterna skulle variera med hänsyn till t ex geografi.

Dessa samhällseffekter får även påverkan på hållbarhet, där nya utmaningar kan uppstå. Jag visar att nuvarande styrmedel för transportsystemet fortfarande är relevanta, men att en helhetssyn krävs för att effektivt hantera utmaningarna.

Avslutningsvis efterlyser jag en nyanserad bild av självkörande fordon. Att introducera en ny teknik kräver rigorös och framåtsyftande planering och styrning för att säkerställa att självkörande fordon uppnår övergripande hållbarhetsmål och leder till att berika människors liv.

III. Dissertation and list of papers

In Swedish academic settings, a PhD can typically be achieved through a monograph or a compilation dissertation. A monograph is a comprehensive, book-length thesis that focuses on a single topic and provides in-depth exploration. In contrast, a paper-based compilation dissertation consists of a collection of academic papers connected by an overarching theme that is usually published or suitable for publication. This dissertation is the latter and contains, in addition to the appended papers, this 'kappa', a summary chapter that ties together the individual papers and outlines their collective contributions to the research area.

The following papers are appended to the dissertation; the CRediT system is used to highlight my contributions.

Appended papers

Paper A – Beyond the Hype: A Critical Look at the Motivations Driving Automated Driving Systems Research

Almlöf, E., 2024. Beyond the hype: A critical look at the motivations driving automated driving systems research. Transp. Res. Interdiscip. Perspect. 24, 101075. https://doi.org/10.1016/j.trip.2024.101075

Contributions of the author

- Erik Almlöf – Conceptualisation; Data curation; Project Formal analysis; Methodology; Validation; Visualisation; Roles/Writing – original draft.

Paper B – From technological fixes to societal solutions: A sociotechnical framework for understanding self-driving technology implementation

Almlöf, E., Hesselgren, M., 2024. From technological fixes to societal solutions: A sociotechnical framework for understanding self-driving technology implementation, Under Review

Contributions of the authors:

- Erik Almlöf – Conceptualisation; Data curation; Investigation; Methodology; Validation; Visualisation; Roles/Writing – original draft.
- Mia Hesselgren – Conceptualisation; Data curation; Funding acquisition; Methodology; Project administration; Supervision; Validation; Roles/Writing – original draft.

Paper B originated from work on the Research on operatorless driving using autonomous buses project (Sv. *Forskning inom operatörslös körning med autonoma bussar*) funded by Vinnova (reference number 2020-05146).

Paper C – Will leisure trips be more affected than work trips by autonomous technology? Modelling self-driving public transport and cars in Stockholm, Sweden

Almlöf, E., Nybacka, M., Pernestål, A., Jenelius, E., 2022. Will leisure trips be more affected than work trips by autonomous technology? Modelling self-driving public transport and cars in Stockholm, Sweden. Transp. Res. Part Policy Pract. 165, 1–19. https://doi.org/10.1016/j.tra.2022.08.023

Contributions of the authors:

- Erik Almlöf – Conceptualisation, Methodology, Validation, Data curation, Writing – Original Draft, Visualisation.
- Mikael Nybacka – Conceptualisation, Writing – Review & Editing, Supervision.
- Anna Pernestål – Conceptualisation, Writing – Review & Editing, Supervision, Project administration, Funding acquisition.
- Erik Jenelius – Writing – Review & Editing, Supervision.

Paper C originated from work on the Self-driving technology and public transport project (Sv. *Självkörande fordon – hot och möjligheter*) funded by Region Stockholm (Trafik och Region 2018, grant number LS 2017-0585).

Paper D – Frameworks for assessing societal impacts of automated driving technology

Almlöf, E., Zhao, X., Pernestål, A., Jenelius, E., Nybacka, M., 2022. Frameworks for assessing societal impacts of automated driving technology. Transp. Plan. Technol. 45, 545–572. https://doi.org/10.1080/03081060.2022.2134866

Contributions of the authors:

- Erik Almlöf – Conceptualisation, Methodology, Validation, Data curation, Writing – Original Draft, Visualisation.
- Xiaoyun Zhao – Conceptualisation, Methodology Writing – Review & Editing, Supervision.
- Anna Pernestål – Conceptualisation, Writing – Review & Editing, Supervision, Project administration, Funding acquisition.
- Erik Jenelius – Writing – Review & Editing, Supervision.
- Mikael Nybacka – Writing – Review & Editing, Supervision.

Paper D originated from the Södertörn Crosslink project (Sv. *Självkörande eldriven stombuss på Tvärförbindelse Södertörn – En skalbar fallstudie*) funded by the Swedish Transport Administration (grant number TRV 2019/118695).

Paper E – Using vignettes to explore policy tools for a self-driving transport future

Almlöf, E., 2023. Using vignettes to explore policy tools for a self-driving transport future. Transp. Res. Interdiscip. Perspect. 22, 100922. https://doi.org/10.1016/j.trip.2023.100922

Contributions of the author:

- Erik Almlöf – Conceptualisation, Methodology, Validation, Funding acquisition, Data curation, Writing – Original Draft, Visualisation.

Paper E originated from the Policies for sustainable, self-driving and shared vehicles project (Sv. *Självkörande, delade fordon - koncept och policys för kollektivtrafiken*) funded by Region Stockholm (Trafik och Region 2021, grant number RS 2020–0353).

Additional publications

The author has also contributed to the following publications that are not included in this thesis.

- Acosta Carrascal, H., Micallef, D., Almlöf, E., n.d., The Rise of E-Scooters: An Analysis of Trip Alternatives in Gothenburg, Sweden, Rev.
- Almlöf, E., Acosta Carrascal, H., Micallef, D., 2023. Project ELKOLL. KTH Royal Institute of Technology. URL https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-327895 (accessed 2023-06-29).
- Almlöf, E., Nybacka, M., Pernestål, A., 2020. Will public transport be relevant in a self-driving future? A demand model simulation of four scenarios for Stockholm, Sweden. Transp. Res. Procedia 49, 60–69. https://doi.org/10.1016/j.trpro.2020.09.006
- Almlöf, E., Rubensson, I., Cebecauer, M., Jenelius, E., 2021. Who continued travelling by public transport during COVID-19? Socioeconomic factors explaining travel behaviour in Stockholm 2020 based on smart card data. Eur. Transp. Res. Rev. 13, 31. https://doi.org/10.1186/s12544-021-00488-0
- Hultén, J., Wildt-Persson, A., Alm, J., Almlöf, E., Hedegaard Sørensen, C., Paulsson, A., Pernestål, A., Wallsten, A., 2021. Att styra det nya (No.

2021:1), K2 Outreach. URL https://www.k2centrum.se/sites/default/files/fields/field_uppladdad_rapport/k2_outreach_2021_1.pdf (accessed 11.2.21).

- Pernestål, A., Almlöf, E., 2019. Scenarier för ny mobilitet och samhällsplanering (K2 Working Paper No. 2019:7). K2. URL https://www.k2centrum.se/sites/default/files/fields/field_uppladdad_rapport/scenarier_for_ny_mobilitet.pdf (accessed 2023-09-12).
- Sjöström, T., Hjälmdahl, M., Larsson, A., Almlöf, E., Pernestål, A., Zhao, M.X., 2021. Självkörande fullängsbuss på Tvärförbindelse Södertörn. URL https://www.itrl.kth.se/polopoly_fs/1.1076850.1621863151!/ABESodertorn_slutrapport.pdf (accessed 8.11.21)
- Wallsten, A., Paulsson, A., Hultén, J., Sørensen, C.H., Pernestål, A., Almlöf, E., 2019. Statlig styrförmåga i framtider med smart mobilitet (No. 2019:9), K2 Working papers. K2. URL http://www.k2centrum.se/sites/default/files/fields/field_uppladdad_rapport/working_paper_2019_9.pdf (accessed 12.11.19).

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this thesis, ChatGPT was used to improve the text's language. After using this tool/service, I reviewed and edited the content as needed and take full responsibility for the content of this thesis.

IV. Acknowledgements

They say that it takes a village to raise a child, and the same should be said for a Ph.D. student. I owe my sincerest gratitude to a large group of people.

To my colleagues, thank you for the helpful discussions, therapeutic work sessions, and fun along the way. ITRL has a somewhat loose but still tight-knit group of researchers from different fields and with different perspectives, and all of you have contributed to my research, be it in a large or small way.

To my supervisors, Mikael, Mia, and Erik, who have pushed my boundaries and helped me to achieve more. Your varying perspectives have sometimes been hard to align, but I think we got further, thanks to your different viewpoints. In addition, my previous supervisor, Anna, was vital in guiding me through the early stages of my doctoral studies.

To my friends and family for listening to my rants about simulations and policy goals and my general monologues about academic life.

And finally, to all of you who participated in my research in some way, be it as interview subjects, workshop attendees, or discussion partners.

Tack

Erik Almlöf

Stockholm, spring of 2024

V. Table of Contents

1 Foreword

In 2017, I worked as a traffic analyst at the Public Transport Authority in Stockholm. My main task was to develop forecasts for future travel patterns, which were used to assess infrastructure and capacity needs. Together with a colleague, we presented a new forecast for the metro system in Stockholm stretching to 2050, i.e., a really long-term forecast.

At the same time, the hype around self-driving vehicles was at its peak, with promises of their imminent introduction and disruptive changes to the transport system, all of which would usher in safer travel, a more accessible society, and sleeping on your way to work. During our presentation of the metro forecast, we were asked whether self-driving vehicles would affect the forecast, to which I responded that, yes, they would absolutely impact the forecast. The follow-up question was simply, 'How?' to which I responded that I did not know, just that it could be drastic.

This lack of answer on my part had been sitting in the back of my mind for half a year when I encountered a white paper by Anna Pernestål, Ida Kristoffersson and Lars-Göran Mattsson (later published in Pernestål et al., 2019) that outlined four possible scenarios for self-driving vehicles. This presentation of four short stories about possible futures marked the first time I got a deeper understanding of what self-driving technology could mean for society; this was a refreshing change from the speculative numbers and individual impacts I had previously seen in the news.

Therefore, I reached out to Anna to create a research project that would focus on the impacts on public transport in Stockholm – and did not realise then that I had actually created my pathway into research.

The rest is, as they say, history.

2 Introduction

Photo of the Small VEhicles for Autonomy (SVEA) platform and the remote control station at the Integrated Transport Research Lab (ITRL) where I conducted my research.

2 Introduction

In this section, I cover the following topics:

1. The previous research into self-driving vehicle systems and why further research is required.

2. Why I choose to use the term self-driving vehicle systems.

3. An overview of the sociotechnical systems perspective and the framework I use to understand the impacts of self-driving vehicle systems.

4. A description of the aim of this thesis and how I break this aim down into more concrete research questions.

5. A description of how the research questions evolved from the start of my PhD journey.

6. Reflections on my role as a researcher concerning the research I have conducted.

7. And finally, a brief outline of the remaining thesis.

2.1 Self-driving vehicle systems – an overview

The advent of self-driving vehicles marks, according to some (Marsden and Reardon, 2018), a transformative phase in the realm of transport and technology (Marsden and McDonald, 2019; Shladover, 2018). Engineered to navigate without human intervention, self-driving vehicles have, during the last decade, become more prominent on our streets, albeit currently still in test mode (Antonialli, 2019; Muhammad et al., 2022).

Introducing these vehicles may have notable potential benefits, hence the immense interest in them. From reducing traffic congestion (Hoogendoorn et al., 2014) and lowering carbon emissions (Wadud et al., 2016) to the prospect of increased safety on the roads (Tafidis et al., 2022), the advantages appear innumerable and compelling.

However, the advent of self-driving vehicles also brings many problems that cannot be overlooked. Ethical dilemmas surrounding accident responsibility (Zhai et al., 2023), job losses in driving-related professions (Alonso Raposo et al., 2022), and increased pollution linked to more traffic (Taiebat et al., 2018) raise important questions. Moreover, integrating self-driving vehicles into existing infrastructures presents logistical challenges that are yet to be fully understood (Tengilimoglu et al., 2023). Thus, despite the extensive body of knowledge that currently exists, substantial uncertainties remain that warrant further exploration.

I would argue that earlier studies in this domain were often restricted in their focus to isolated issues such as traffic flow optimisation or machine ethics. In contrast, recent academic endeavours have adopted a more holistic approach aimed at providing state-of-the-art overviews that assess multiple areas of impact (e.g. Faisal et al., 2019; Milakis et al., 2017).

Such examinations, while invaluable, still fall short in a crucial aspect: they often view self-driving vehicles as distinct entities, disengaged from the human social fabric. This perspective overlooks the intricate interplay of human relations, not only with each other but also with these technological artefacts. I contend that technology cannot be regarded as an isolated, passive entity; instead, technology must be recognised as a sociotechnical system (Hughes, 1987) where technology forms an integral part of society, where boundaries between technology and humans are blurred and dynamic.

This approach seeks to provide a more comprehensive understanding of the societal impacts of self-driving vehicle systems. By doing so, I aim to contribute not just to academic discourse but also to practical policymaking. I argue that the impacts of self-driving vehicle systems cannot be fully grasped in isolation and that transitioning to a new transport system involves complex, often underestimated challenges.

Furthermore, while notable effort has been put into realising self-driving vehicles and the impacts of self-driving vehicles have a notable research stream, little attention has been given to how this technology affects sustainability (Gandia et al., 2019; Marsden and Reardon, 2018). Therefore, I intend to showcase the impacts of fully implementing self-driving technology and the governance of such transport systems to achieve goals related to sustainability.

2.2 The term self-driving vehicle system

The term 'self-driving' is frequently used in the discourse surrounding vehicle automation, but it is crucial to delineate its specific meaning, especially within the context of this thesis.

The SAE J3016 standard (SAE International, 2021) is commonly used in the field of self-driving vehicles. It delineates the responsibilities of the human driver and the vehicle across various levels of self-driving capabilities:

- Level 0: At this level, the human driver is entirely responsible for controlling the vehicle, including all driving tasks like steering, braking, and accelerating, even if the car has warning systems to help the driver.

- Level 1 – Driver Assistance: Here, a single automated system assists the driver with either lateral (i.e. keeping within the lane) or longitudinal movement (i.e. keeping the distance to vehicles in front), such as adaptive cruise control or lane-keeping. However, the human driver must always remain engaged and supervise the driving environment.

- Level 2 – Partial Automation: In Level 2, the vehicle can control both steering and acceleration/deceleration, but human intervention is still needed for all aspects of driving. The driver is expected to monitor all movement of the vehicle constantly.

- Level 3 – Conditional Automation: At this level, the vehicle can manage all aspects of driving, including monitoring the environment, but human intervention is still expected at a moment's notice.

- Level 4 – High-Level Automation: Vehicles at this level can perform all driving tasks without human intervention but may still encounter situations the vehicle cannot handle. In these encounters, human intervention is not expected instantly. Instead, the vehicle can always handle the situation safely, for instance, by stopping and waiting for further instructions or interventions from a human driver.

- Level 5 – Full Automation: Level 5 vehicles can complete autonomous operation under 'normal' conditions, i.e. all conditions a human driver could handle.

However, a vehicle's level of autonomy can vary depending on its Operational Design Domain (Ulrich et al., 2020). For instance, a vehicle may be rated as Level 4 for high-speed motorway driving but fall to Level 2 for urban driving. Likewise, a vehicle may be categorised as Level 3 for daytime driving during sunny conditions but only Level 1 for nighttime or snowy weather.

As noted by Gandia et al. (2019) and Shladover (2018), the field of vehicle automation has a plethora of terms used to describe similar concepts, such as 'autonomous,' 'automated,' 'self-driving,' 'driverless,' and 'intelligent'. The term 'intelligent', while commonly used, is unfortunately also very general and used for several fields (Gandia et al., 2019). There are advantages to it, nonetheless, as it can describe a general feeling of 'smartness' or describe aspects beyond self-driving capabilities (e.g. communication with infrastructure) that are still relevant for improving roadway capacity (Shladover, 2018). Still, for academic purposes, the term is too vague to be helpful.

While 'autonomous' or 'automated' are more frequently used, I find these terms too general since they are applicable to multiple aspects of the vehicle, such as automated air conditioning or autonomous windshield vipers. Hence, they are less effective for specifically discussing the car's driving capabilities.

This thesis mainly investigates the societal impacts of the higher level, i.e. SAE Level 5, for most operational design domains, which make such a service more widely available. Therefore, I predominantly use the term 'self-driving' in this thesis because it zeroes in on the vehicle's driving capabilities. The term explicitly denotes a focus on automating driving tasks, making it easier to understand, especially for non-academics.

2.3 Sociotechnical systems

A sociotechnical perspective is helpful to gain a more nuanced understanding of the relationship between technological artefacts and society (Nye, 2006). This perspective considers technology and society as part of an integrated system where the boundaries are neither fixed nor clearly delineated but constantly in flux (Hughes, 1987). Within this complex perspective, the concept of 'path dependence' (David, 2007) plays a significant role by positing that technological designs are often constrained by their historical development. A classic example would be the width of train tracks, which has largely remained consistent since Roman times and illustrates the lasting impact of previous designs on current and future technologies (David, 2007).

While technology has the power to shape society by providing tools that facilitate mobility or communication, sociotechnical systems literature also emphasises that societal factors likewise shape technological development and expression (Vermaas et al., 2011). For instance, transport systems are organised differently worldwide and are influenced by various cultural, geographical, and economic factors.

Furthermore, it is also essential to note that new technologies rarely replace existing ones outright; rather, they tend to supplement them (Vermaas et al., 2011). For instance, while automobiles may have reduced the prevalence of bicycles during the 1950s, they did not eliminate their use. Moreover, certain technologies can find niche applications, such as with hovercrafts, even if they are not universally adopted. These devices may not revolutionise society, but they can still have an impact by fitting into specialised roles or by contributing to the development of other technologies (Vermaas et al., 2011).

Additionally, the sociotechnical perspective on technological adoption can help dispel the notion that the 'best' technology will inevitably succeed. Instead, it is the technology that best aligns with existing systems and practices that fills the 'acceptance gap' and gains widespread use (Bergek et al., 2008).

Furthermore, technological development often has consequences beyond the immediate field in which it is introduced. For example, mobile phones have had far-reaching impacts on communication, human behaviour and social interactions in general (Yan et al., 2013).

In summary, examining technology from a sociotechnical perspective enables a more holistic understanding of its role and impact. This perspective challenges us to move beyond binary or isolated viewpoints and embrace the complex web of influences and dependencies that characterise the relationship between technology, humans and society.

2.3.1 Sociotechnical self-driving vehicle systems

Considering the previous section, I argue that self-driving vehicles cannot be seen as a separate entity from society and that introducing self-driving vehicle systems will have ramifications throughout many different areas. Furthermore, neither self-driving vehicle technology nor the affected areas can be outlined simply and delimited from one another. Instead, the boundaries between areas are indistinct.

Therefore, throughout this thesis, I employ the term 'self-driving vehicle systems' to denote the more extensive sociotechnical system in which this transport technology exists. Furthermore, I refer to 'self-driving vehicles' to denote the vehicles themselves and the term 'self-driving technologies' to denote technological artefacts that enable self-driving capabilities, e.g. physical equipment or digital software for localisation, mapping and navigation, and communication related to the driving task.

More specifically, I argue that self-driving vehicle systems can be divided into five areas: vehicle behaviour, organisation of transport, regulation, people, and the transport system. This categorisation is inspired by the work of Taiebat et al. (2018), Milakis et al. (2015), Faisal et al. (2019) and Milakis and Müller (2021):

- Vehicle behaviour describes how vehicles on the road would change with regard to their driving patterns, communication, and relationship with other vehicles.

- The organisation of transport would need to change, e.g. by introducing new types of traffic control centres or ambulatory personnel to replace the tasks currently conducted by the driver.

- Laws and regulations would further need to account for the missing driver and change our perspectives on such topics as risk, for example, since self-driving vehicle systems would likely lead to new types of security threats.

- People’s perceptions of vehicles, transport, and the physical space they share would change; for example, the communication between vehicles and pedestrians at a crosswalk.

- Finally, the broader transport system needs to consider aspects such as CO_2 emissions and economic impacts.

I want to emphasise that this categorisation into five areas should not be seen as distinct. Instead, the areas intersect and cause interacting impacts; for example, changes in organisational structures create the need for new legislation, which can affect people's perception of self-driving vehicles.

2.4 Research aim, objectives, and questions

The aim of this thesis is to understand the societal impacts of fully implementing self-driving vehicle systems and how these systems should be governed to ensure that sustainability goals are reached.

To achieve this aim, I focus on four main objectives:

1. Exploring the motivations behind self-driving vehicle system development.
2. Investigating how self-driving vehicle systems are realised.
3. Analysing societal impacts of self-driving vehicle systems, given a laissez-faire approach.
4. Exploring how self-driving vehicle systems should be governed to fulfil sustainability goals.

The third objective explores a future with a laissez-faire approach, i.e. a hands-off stance where self-driving vehicles are expected to operate within a system similar to our current one, with no further governmental intervention. This objective contrasts with the fourth objective, in which the identified problems are tackled using various governance strategies.

In the context of sustainability, my initial reference point is the United Nations Sustainable Development Goals (United Nations General Assembly, 2017), which encompass a broad spectrum of goals from poverty alleviation to climate action. More specifically, within the scope of Paper E, I draw upon the work of Karjalainen and Juhola (2021), who synthesized a targeted set of goals related to the sustainability of transportation.

The four objectives are addressed first by answering the following research questions using the appended Papers:

1. How is the development of self-driving vehicle systems motivated? (Objective 1)
2. Given the currently known technical limitations, what adaptations would be needed to fully implement self-driving vehicle systems? (Objective 2)
3. What societal impacts will fully implemented self-driving vehicle systems have, given a laissez-faire approach? (Objective 3)
4. Given fully implemented self-driving vehicle systems, what policy tools would steer Stockholm towards current transport sustainability goals? (Objective 4)

After answering these four questions, I revisit the objectives to discuss and integrate my findings with existing literature to draw broader conclusions from both my research and the work of others in the field.

Finally, I synthesise the insights garnered from these objectives to deliberate on policy impacts and then endeavour to answer the overarching aim, which is understanding the societal impacts of self-driving vehicle systems and how they should be governed to ensure sustainability.

A breakdown of the aim, objectives, and questions is shown in Figure 1.

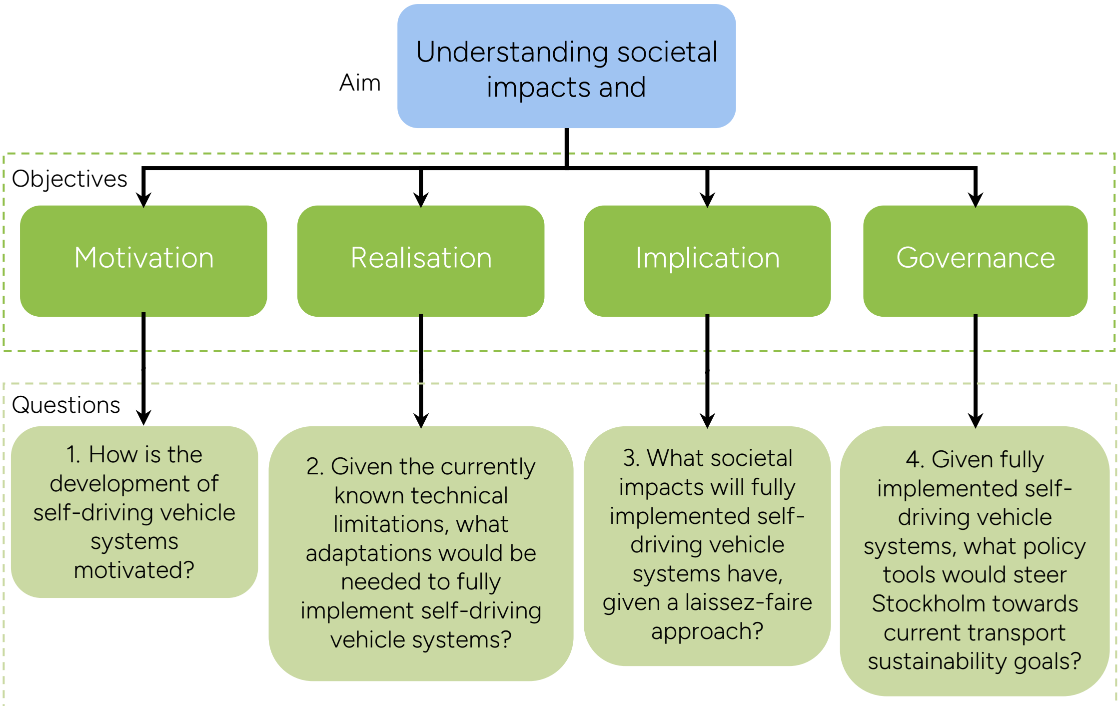


Figure 1. Overview of the research aim, objectives, and questions.

2.4.1 Delimitations

In this thesis, I investigate a possible future transport landscape dominated by technologically mature self-driving vehicles, i.e. SAE Level 5 in all or most operational design domains. The focus is specifically on passenger transport via roads, which encompasses cars and buses. Consequently, this thesis does not encompass self-driving technology applications in other areas, such as rail transport, aviation, freight logistics or drone operations.

To provide a thorough insight into the societal impacts of self-driving vehicle systems, it is imperative to acknowledge the novelty of this technology. The future trajectory of self-driving vehicle systems and their societal ramifications remain fundamentally uncertain. This thesis should thus be interpreted as a synthesis between my research and the existing literature on the societal impacts of self-driving vehicle systems. It represents our current understanding within a continually evolving field subject to ongoing scholarly exploration rather than a definitive, all-encompassing description of an actual reality.

2.5 Development of research questions

When I started my PhD studies, I was initially interested in understanding the impacts of self-driving technology on the transport system and, more broadly, on society. This interest was the basis of Paper C, which was written as part of the *Self-Driving Technology and Public Transport* project. In this paper, with my supervisors, I investigate how the transport system would be affected using tools I was already familiar with, specifically simulation tools.

As I became more acquainted with the literature on the subject, I understood that the impacts of self-driving technology were manifold and affected many aspects. However, understanding the scale of various impacts was difficult; often, impacts on the economy, accident prevention or energy needs were mentioned simultaneously without any clear indication of which were the most profound.

Therefore, I investigated these aspects with my co-authors within the *Södertörn Crosslink* project; this culminated in the writing of Paper D, in which we try to assess all the impacts of a self-driving bus line. While we do not attest to having compared *all* aspects, the study still manages to put a sense of scale to various impacts; for example, we show that accident reduction was a minimal factor compared to infrastructure requirements.

While writing these papers and through discussions with my colleagues, I increasingly felt that I had stopped halfway by asking, 'What societal impacts would self-driving vehicle systems have?' Inadvertently, I had positioned society as an inactive receiver of impacts rather than an active co-collaborator that could affect the outcome. The follow-up question should thus be, 'What should we do to ensure sustainability?' Together, these two questions formed the aim of this thesis, as outlined in Section 2.4.

The latter question was the focus of Paper E, written as part of the *Policies for Sustainable, Self-Driving and Shared Vehicles* project. In this paper, I took the findings from Paper C and surveyed public officials on how they would combat sustainability issues given the results of Paper C. Furthermore, this Paper was a chance for me to broaden my methodological approaches and incorporate qualitative analysis into my previous quantitative work.

Following my bird's eye view of societal impacts in Papers C and D, I wanted to change my focus and understand more about how self-driving vehicle systems were organised in practice. This area seemed sparsely explored, and, e.g., Waymo had toned down their previously optimistic forecasts for the realisation of self-driving capabilities (Tibken, 2018). This lack of research was the basis of my work within the *Research on Operatorless Driving using Autonomous Buses* project, which resulted in Paper B. This paper, for which I interviewed onboard operators and personnel connected to the trials in Barkarby in Stockholm, gave me a chance to develop my qualitative skills further and incorporate the sociotechnical systems perspective, which I had long aspired to make an integral part of my thesis.

Throughout my work, I had recurring discussions with colleagues for several years about the motivation for working on self-driving vehicle systems and their impact. At an early stage, I read Marsden and Reardon (2018), who discussed the often opaque motivation and the extensive greenwashing of projects. Although enlightening, their work was qualitative in nature and provided mainly anecdotal evidence. Then, in late 2022, ChatGPT was released; I was discussing the possibilities of using this new tool with two colleagues, and one idea that dawned upon me was to look through large sets of texts, something that had previously been practically difficult. Hence, Paper A was written in an attempt to understand the motivations of researchers who conducted research in self-driving technology.

An overview of each project's timeline and the appended papers is shown in Figure 2.

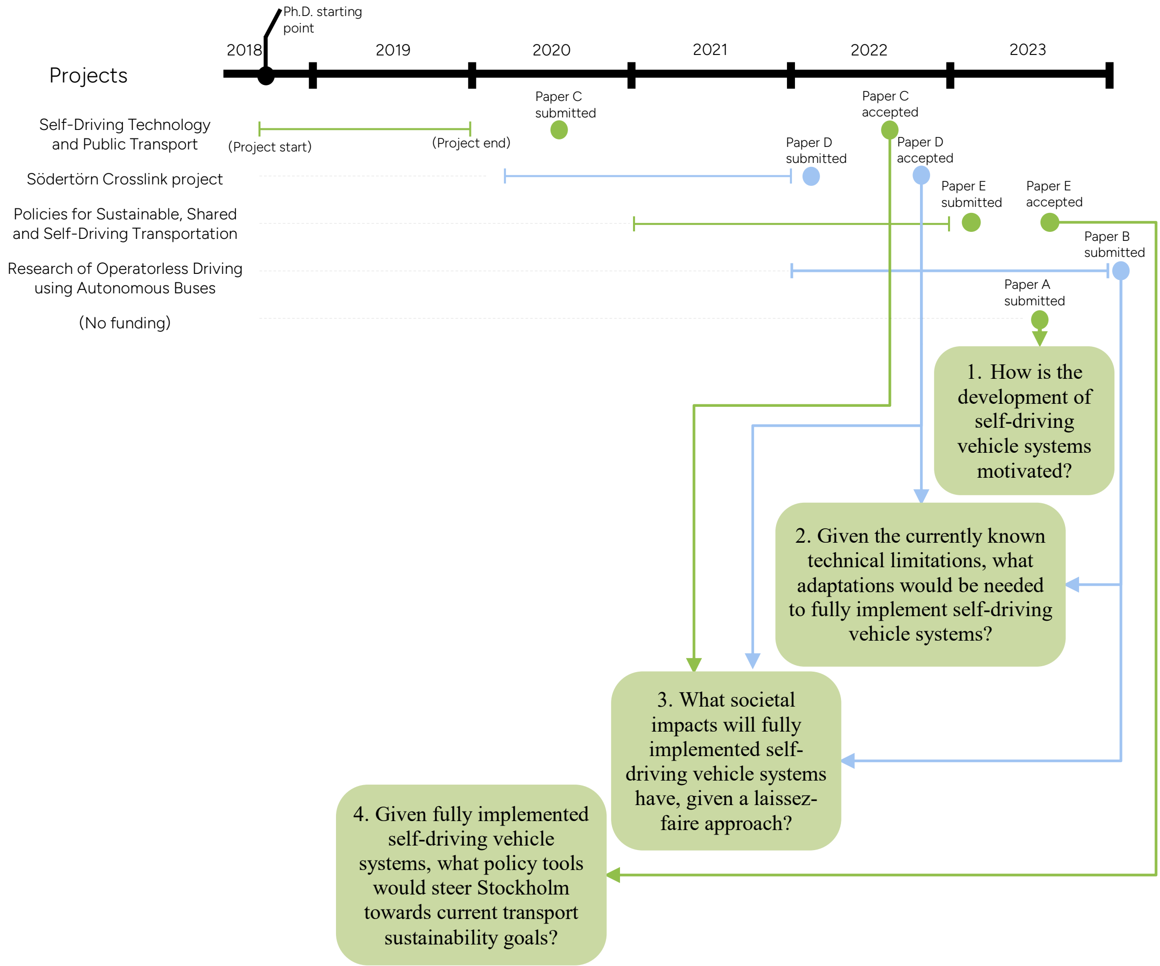


Figure 2. Timeline for each project and affiliated paper, and how each paper contributes to answering the four research questions. Paper A was not conducted as part of any funded project.

2.6 Reflections on my role

As a researcher, I often find myself rejecting a strictly positivist perspective, that I am examining inanimate objects; I acknowledge the subjectivity of both my worldview and the phenomena under investigation (Alvesson, 2003). This worldview represents a broader theme in my work, which is to explore technology not as an objective entity but as a force that shapes and is shaped by societal contexts (Winner, 1980).

My educational background in the Sociotechnical Systems programme at Uppsala University has profoundly influenced this perspective. The programme taught me that technology development must be contextualised within its sociotechnical context and that technology often dictates a specific developmental axis rather than being a neutral tool (Hughes, 1987; Sawyer and Hilton, 1963).

Professionally, I have ten years of experience in the transport sector, first as a traffic planner and analyst with a major public transport operator and then as a traffic analyst at the public transport authority. This background has provided me with an understanding of how transport systems are organised, and it has influenced the research presented in Papers B-E since it allowed me to navigate complex terminologies and organisational structures easily.

However, my ongoing relationship with the public transport authority posed certain limitations, particularly in terms of taking an objective stance in relation to my employer. Therefore, as a measure of transparency, I disclosed my employment with the authority in all the appended papers.

In the interviews conducted for this thesis, which were mainly semi-structured, I found it essential to take on an active role in posing questions to follow up statements and re-address previous questions when they were framed differently by participants. While challenging in maintaining strict comparability, this approach was invaluable for gaining deeper insights, and I found that allowing the research participants to steer the conversation often led to more profound discussions (Weick, 1998). This approach aligns with my belief that research questions and directions often evolve as one gains a deeper understanding of the subject, as noted in Section 2.5.

In summary, my role in this research can best be described by the term 'native' as defined by Creswell and Creswell (2018). My significant prior knowledge of the transport field and the organisations studied provided a unique lens through which the research was conducted, thus contributing to a richer and more nuanced understanding of the subject. However, my prior knowledge may also have led me to introduce preconceived notions of the phenomena, and it is vital to acknowledge this.

2.7 The organisation of the thesis

Following this introduction, the remaining thesis is organised into the following Sections.

Section 3: Background

A review of the history of self-driving vehicle systems research, emphasising existing literature on societal impacts.

Section 4: Research methods

A detailed exposition of the research design and methodologies employed – qualitative, quantitative, and mixed methods. Ethical considerations relevant to the research are also discussed in this section.

Section 5: Summary of the appended papers

Brief summaries of each paper are provided.

Section 6: Key findings

Explores how the included papers help answer the research questions.

Section 7: Discussion

Discussion on how the findings relate to previous research and address the overall objectives and aim. In addition, I discuss the impacts of these findings on policy and practice, discuss the limitations of the research, and finally provide recommendations for future research.

Section 8: Conclusion

Finally, this summative section describes the contributions of the research and key takeaways.

3 Background

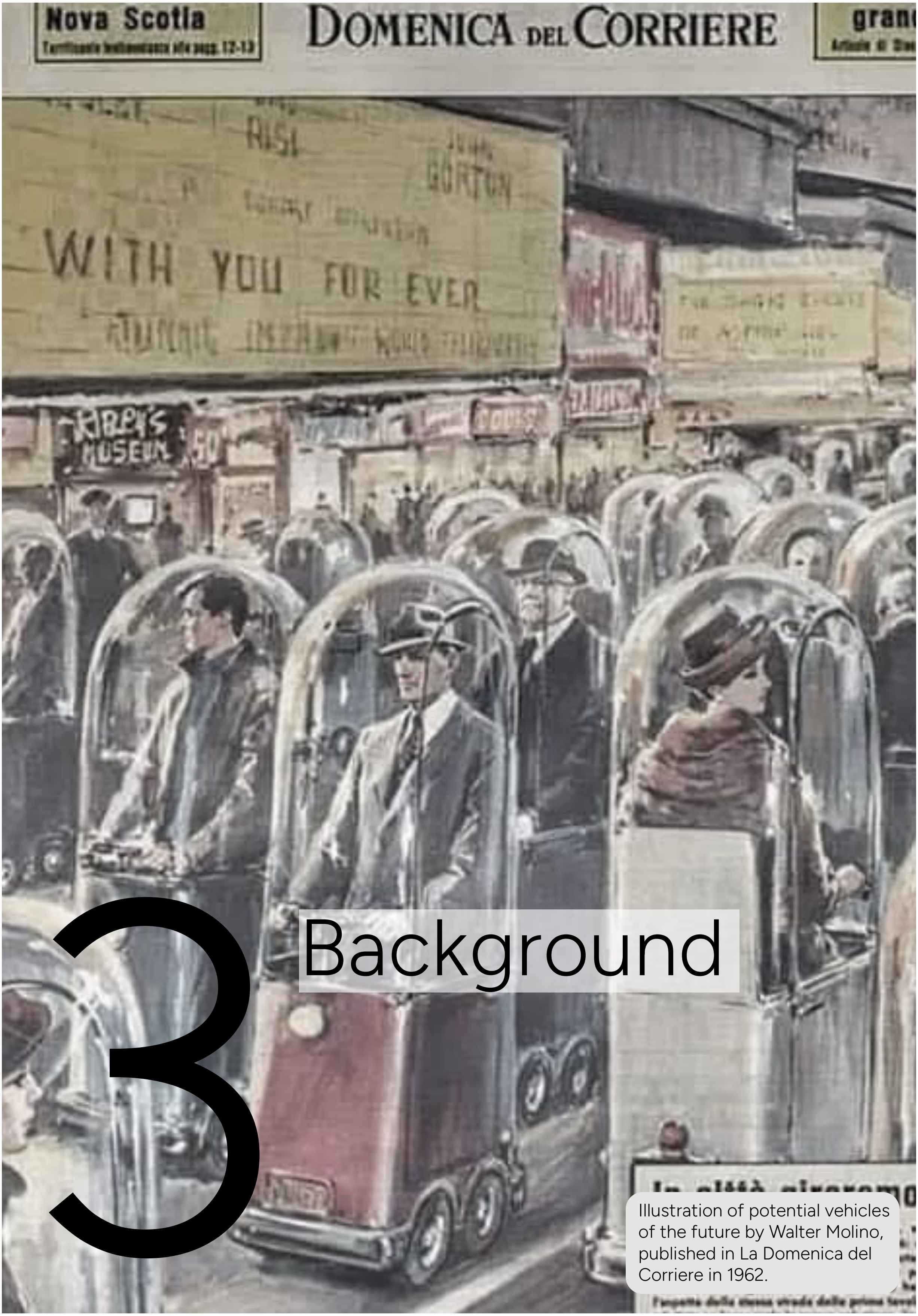


Illustration of potential vehicles of the future by Walter Molino, published in La Domenica del Corriere in 1962.

3 Background

In this section, I provide an overview of the history of self-driving vehicle systems, including current research, and provide an overview of the current state of the art of the field of societal impacts for self-driving vehicle systems.

3.1 Historical background of self-driving road vehicles

The quest for self-driving vehicle technology can be traced back to the advent of the automobile industry. While autopilots in aircraft and auto-tillers in boats predated many innovations, the challenges presented by road transport called for unique solutions (Weber, 2014).

Interestingly, the concept of driverless vehicles was not solely a product of modern artificial intelligence or computational advances. As early as August 1925, Broadway in New York City witnessed an unprecedented event: Houdina Radio Control's 'Linrrican Wonder,' an experimental car, moved down the street without a driver while being controlled by radio equipment from a following vehicle (Stayton, 2015). Further, visions of radio-controlled cars found expression in the 1939 Futurama show (Baker and Villa, 2017). By the 1950s, General Motors and the Radio Corporation of America took steps towards realising these visions, but their 'Firebird' concept car was ahead of its time, limited as it was by technological limitations (Meyer and Beiker, 2014).

The late 1970s saw the Jet Propulsion Laboratory exploring the realm of self-driving vehicles for planetary missions (Stayton, 2015). Concurrently, researchers in Tsukuba, Japan, initiated pioneering work on visual road vehicle guidance using stereo cameras (Bender, 1991).

In the 1980s, parallel developments in self-driving technology were made in the United States and Germany. While DARPA's 'On Strategic Computing' initiative in the U.S. concentrated on artificial intelligence and computer science, Germany adopted a control engineering angle bolstered by emerging microprocessor technologies (Dickmanns, 2003). These separated efforts became mutually acknowledged around 1985 and facilitated international cooperation from 1986 onwards (Thorpe et al., 1988).

A landmark achievement occurred in 1987 when the UBM test vehicle, 'VaMoRs', showcased fully autonomous driving capabilities on the Autobahn for a stretch of 20 km and at speeds of up to 96 km/h (Bender, 1991; Brodsky, 2016). This success led to a surge in European research activities and laid the foundation for the EUREKA project 'Prometheus'. Concurrent successes in DARPA's programmes prompted Japan's MITI, Nissan, and Fujitsu to initiate their 'Personal Vehicle System' (Shladover, 2018). Furthermore, in 1997, the 'ParkShuttle' bus project was introduced, operating a self-driving bus on a separate roadway in the Netherlands using magnets in the roadway for localisation. While this bus interacts with other road users at intersections, the separate roadway limits the number of interactions with pedestrians (Wikipedia, 2023).

The public fascination with self-driving vehicles significantly escalated when Google unveiled a car proficient in navigating real-world traffic in 2010 (Weber, 2014). This watershed moment prompted a flood of investment from various industry sectors (McKinsey & Company, 2019), although the initial enthusiasm has somewhat waned in recent years (Goasduff, 2021).

As with the development of trials for self-driving vehicles, research simultaneously ballooned during the 2000s, especially during the second decade, as seen in Figure 3. The vast majority of this research has been focused on solving engineering tasks associated with the realisation of this technology, such as localisation, communication, and navigation (Gandia et al., 2019). Only a small share of the research on self-driving vehicle systems covers other aspects, such as sustainability issues or legal matters (Milakis and Müller, 2021).

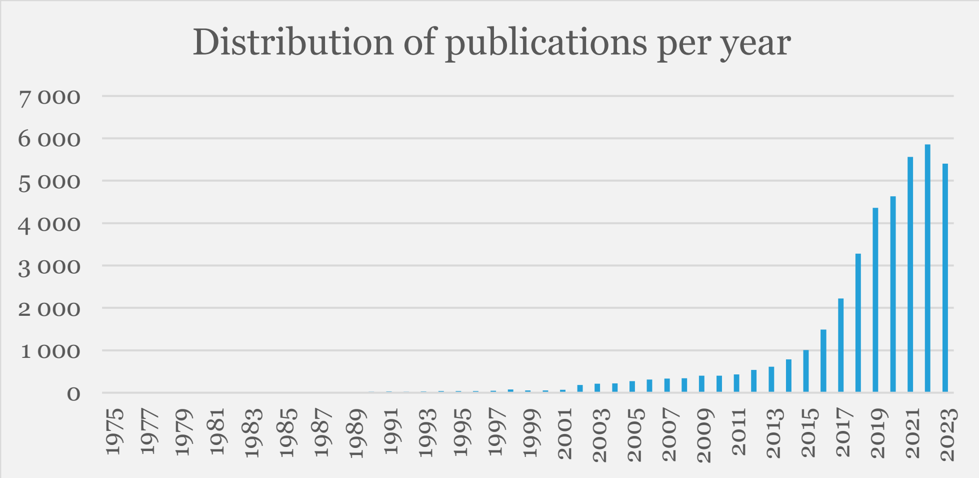


Figure 3. Publications per year for self-driving vehicles up to 2023. The figure was created using the same method as Gandia et al. (2019). Data for 2023 may not be complete.

3.2 Societal impacts

In this Section, I present a literature review of the impacts of self-driving vehicle systems, which is divided into the five categories outlined in Section 2.3.1.

3.2.1 Vehicle behaviour

While human drivers mainly govern current vehicle behaviour, self-driving vehicle systems would likely differ in their behaviour on the road. Many researchers expect self-driving vehicles to engage in more defensive driving behaviour due to safety requirements, which would lessen the number of fatalities due to accidents (Tafidis et al., 2022), decrease vehicle damage (Becker et al., 2020) as well as reduce energy use and pollution per kilometre (Wadud et al., 2016). However, the increased digitisation of vehicles would simultaneously open up new avenues of risk associated with cybersecurity, which could impact the overall risk level of driving (Petit and Shladover, 2015)

One aspect often portrayed as a key potential benefit of self-driving vehicle systems is the potential to increase road capacity due to enhanced vehicle-to-vehicle communication (Faisal et al., 2019). This advanced communication could lead to more efficient traffic management, reduced vehicle spacing and smoother flow, theoretically increasing road throughput (Martínez-Díaz and Soriguera, 2018).

However, this optimistic scenario is complicated by the reality of mixed traffic environments, where self-driving vehicles interact with human-driven vehicles, pedestrians, and cyclists, which could actually decrease the overall traffic flow (Hoogendoorn et al., 2014). Human driving behaviour, which is characterised by – at least superficially – its unpredictable decision-making, could disrupt the intended patterns expected from self-driving vehicles. Therefore, integrating these two types of vehicles poses a significant challenge since the flow dynamics in mixed traffic conditions are considerably different from those in homogenous (all self-driving vehicles) environments (Taiebat et al., 2018).

Additionally, the issue of motion sickness in self-driving vehicles presents another layer of complexity. If passengers in self-driving vehicles experience motion sickness due to activities such as reading or working while in transit, there may be a push for design changes that prioritise passenger comfort (Le Vine et al., 2015). Such changes could potentially affect vehicle dynamics and road capacity since the designs may necessitate slower speeds or increased spacing between vehicles to mitigate the impact of motion sickness (Le Vine et al., 2015).

Moreover, the interaction between self-driving vehicles and conventional road users remains underexplored beyond a few simulation studies (Harb et al., 2021). Specifically, the tacit knowledge intrinsic to human driving – manifested through implicit communication cues and behavioural nuances – is seldom accounted for (Chater et al., 2018; Straub and Schaefer, 2019; Villadsen et al., 2023).

3.2.2 Organisation of transport

Commercial drivers constitute a notable portion of the populace, with approximately 5 million in the EU (Alonso Raposo et al., 2018). Removing these drivers could have a considerable economic impact since they represent nearly 50% of the overall costs of bus operations and approximately 70-80% of taxi services (Becker et al., 2020; Wadud, 2017).

However, it should be noted that drivers of commercial vehicles also take care of many tasks that are not associated with driving itself, such as fault mitigation and customer service, which could account for a notable share of overall costs (Becker et al., 2020). Moreover, considerable manual labour would likely be required to operationalise self-driving vehicle systems, including mapping routes or solving practical issues, areas that have been largely unexplored (Hind, 2022; Tubaro et al., 2020).

Questions of a more practical concern also exist: Who is responsible for cleaning the vehicles? Are vehicle manufacturers or vehicle operators responsible for the behaviour of vehicles? How should passengers communicate with the vehicles or with the fleet operators? These issues, though seemingly mundane, have significant impacts on the system's feasibility and efficiency (Anund et al., 2022; Fritschy and Spinler, 2019; Lang and Mohnen, 2019).

Furthermore, integrating self-driving vehicles within the existing traffic ecosystem, particularly in interactions with ambulances and other emergency vehicles, is largely overlooked (Chater et al., 2018). Current protocols for communication with emergency vehicles are non-existent, thus complicating efforts to ensure seamless traffic flow during emergencies; this is crucial if self-driving vehicles systems are to be introduced (Tennant et al., 2021).

3.2.3 Regulation

The legal dimensions of self-driving vehicle systems remain an area in need of development. While calls have come for a simple adaptation of the legal framework, similar straightforward remarks hide serious conundrums and a complex web of legal documents covering many aspects of driving (Hansson, 2020; Shladover and Nowakowski, 2019). Many questions remain, such as who the responsible party would be should an accident happen. Furthermore, the legal aspects depend on the actual requirements and feasibility of, for example, remote operations and areas where the exact requirements for safe operations remain uncertain (Goodall, 2020).

3.2.4 People

Self-driving vehicle systems are often portrayed as highly advantageous for individuals, mainly because they would relieve the driver from the demands of active driving. This relief would facilitate that individuals could utilise travel time more productively and engage in activities like napping or conducting meetings (Martin, 2021). However, this narrative has been met with scepticism regarding the feasibility and actual utilisation of such freedom (Kolarova, 2021; Singleton, 2019).

Several studies have raised concerns about the practicality of engaging in alternative activities in a self-driving vehicle. Motion sickness has been identified as a potential barrier to performing tasks like reading or working on a laptop (Diels and Bos, 2016; Singleton, 2019). Furthermore, the design of many self-driving vehicles may not be conducive to activities such as holding meetings, and they may lack the necessary space or amenities (Roeckle et al., 2018). Empirical research on individuals with personal drivers supports some scepticism since it reveals that most passengers use their travel time for relaxation rather than work (Wadud and Huda, 2019).

Perceived safety also emerges as a significant concern. Just as some individuals fear flying, a parallel can be drawn with those anxious about trusting a self-driving vehicle (Bala et al., 2023; European Union and Kantar Belgium, 2020). The absence of a human driver, traditionally relied upon for assistance, directions, or even a sense of security, could worsen this anxiety (Paulsson, 2021).

Another issue is the case of acceptance and the heterogeneity of attitudes. The Eurobarometer poll found that about half of respondents had a positive outlook on self-driving cars, while the other half were more sceptical, with significant variations (European Union and Kantar Belgium, 2020). While most would likely develop increased acceptance with technological maturity and familiarity (Bala et al., 2023), a reluctance among some groups may persist, similar to how some people are reluctant to fly. Furthermore, as expressed by many participants in surveys – many people *like* driving (Kyriakidis et al., 2015).

On a more positive note, self-driving vehicle systems promise substantial benefits for those currently unable to drive, such as children, the elderly, or individuals with disabilities. The advent of self-driving vehicle systems could herald a significant increase in accessibility for these groups, thus granting newfound independence and facilitating more effortless and comfortable travel (Taiebat et al., 2018). This potential increase in mobility could have far-reaching impacts on social inclusion and quality of life.

3.2.5 Transport system

The advent of self-driving vehicle systems presents a complex array of broader transport system impacts, as evidenced by literature review research (e.g. Faisal et al., 2019; Milakis et al., 2017).

While vehicles might be used more effectively on the individual level, overall energy consumption, local pollution, and greenhouse gases would likely increase due to induced travel demand and the occurrence of empty vehicle kilometres where cars travel without passengers (Taiebat et al., 2018; Wadud et al., 2016).

Health impacts are closely tied to increased pollution and noise but could be further worsened by reduced physical activity as an impact of the increased accessibility to self-driving vehicles (Faisal et al., 2019; Horschutz Nemoto et al., 2021; Levine et al., 2018; Milakis et al., 2017; Narayanan et al., 2020).

Regarding land use, self-driving vehicle systems could potentially reduce the need for parking spaces, freeing up urban areas. Simultaneously, increased car accessibility would promote more dispersed land use, which would impact urban planning and development while also increasing demand for roadways to connect different parts of less dense regions (Carrese et al., 2019; Gelauff et al., 2019; Hawkins and Nurul Habib, 2019; Kim et al., 2020).

Additionally, infrastructure adaptations to accommodate self-driving vehicle systems have only been superficially addressed, especially where new digital infrastructure might be needed both for 'normal' self-driving operations but even more so for remote driving (Carreras et al., 2018; Farah et al., 2018; Goodall, 2020; Manivasakan et al., 2021; Tengilimoglu et al., 2023). The economic ramifications of this changed infrastructure remain uncertain. Some studies assume unchanged infrastructure needs, while others anticipate increased digital and physical infrastructure requirements (Farah et al., 2018; Kulmala et al., 2019; Lu et al., 2019; Ulrich et al., 2020).

Savings on drivers would unequivocally drive unemployment, although the need for supporting personnel is likely significant, especially in the early stages of development, and a transition to self-driving vehicle systems is likely to be long (Alonso Raposo et al., 2022; Smit et al., 2020; Taiebat et al., 2018).

The impacts are likely positive on a broader economic scale, with increased overall productivity being a key benefit (Hibberd et al., 2018; Innamaa et al., 2018; Smith et al., 2015). However, the costs and benefits across different socio-economic groups remain largely unexplored. Some have expressed concerns that self-driving vehicle systems may worsen economic inequality and pose challenges for travellers needing assistance or those living in less dense areas if pure commercial motives drive these services (Bissell et al., 2020; Nahmias-Biran et al., 2021; Sparrow and Howard, 2020).

In conclusion, the self-driving vehicle systems' array of possible societal impacts is multifaceted, showing how transport is closely linked to all other aspects of society. However, the exact impacts remain largely unknown and seem to depend on assumptions on how self-driving vehicle systems will develop (see e.g. Narayanan et al., 2020).

4 Research methods

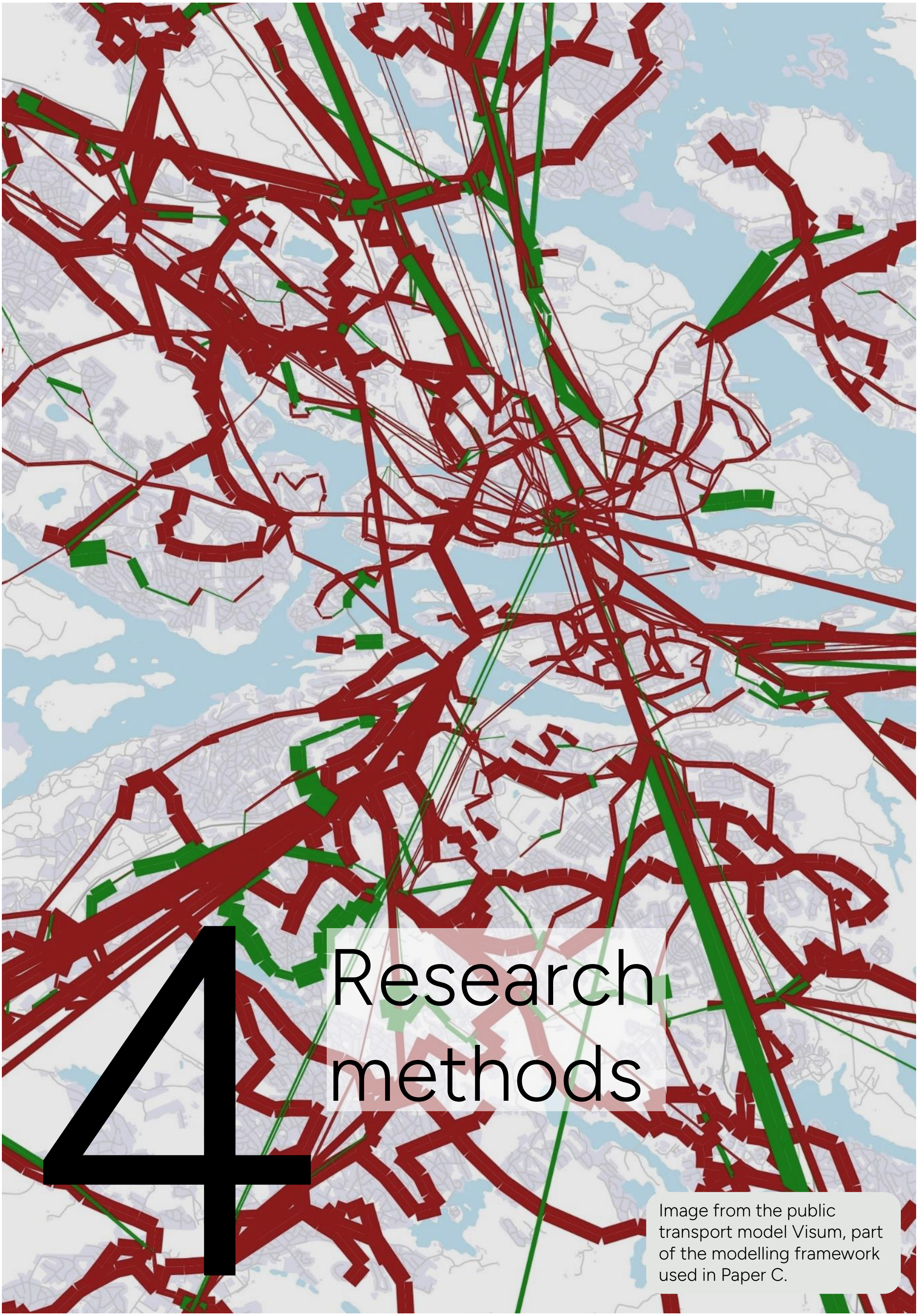


Image from the public transport model Visum, part of the modelling framework used in Paper C.

4 Research methods

This section provides an overview of the different methods used throughout the appended papers.

Research methods are usually divided into three types (Creswell and Creswell, 2018): quantitative (dealing with numbers), qualitative (discussing more abstract concepts that are harder to quantify), and methods that fall in between, called mixed methods, which make use of both quantitative and qualitative methods in interplay.

Table 1 shows the different methods and highlights those used in each appended paper.

Table 1. Overview of research methods used for each paper. X denotes that the Paper uses the method. Paper E only used previous results from a simulation model; hence, (X) indicates an implicit use.

	Method	Paper A	Paper B	Paper C	Paper D	Paper E
Qualitative	Interviews		X		X	X
	Observations		X			
	Workshops			X	X	X
	Coding	X	X			X
Quantitative	Simulation models			X	X	(X)
	Cost-Benefit Calculations				X	
Mixed	Language Analysis	X				
	Vignettes					X

4.1 Qualitative methods

Qualitative methods focus on subjective interpretations, anecdotal evidence, and exploring underlying meanings and patterns rather than finding 'objective' truths (Alvesson, 2003). One key strength of qualitative methods is their ability to capture rich, contextual details, enabling a deeper understanding of the subject matter. Qualitative approaches allow for interpreting complex phenomena in their natural settings, thus offering a nuanced view that complements the broad generalisations made possible through quantitative methods (Creswell and Creswell, 2018).

However, qualitative methods have their limitations. The findings are often less generalisable and are subject to the researcher's and the participants' biases, which makes objectivity challenging (Langley, 1999).

In essence, qualitative methods answer the 'why' and 'how' questions that quantitative methods may overlook (Creswell and Creswell, 2018). While they may lack the empirical strength to offer broad generalisations, they provide essential contextual understanding. The following sections – Interviews, Observations, and Workshops – provide an overview of the methods used in the appended papers. Finally, I explain how the qualitative work has been analysed using qualitative coding.

4.1.1 Interviews

Interviews serve as a cornerstone for qualitative research, offering valuable insights into user experiences, ethical ramifications, and public opinions (Bansal and Corley, 2011). Compared to quantitative methods, which often rely on preconceived questions that yield less nuanced data, interviews allow for a richer but more subjective analysis, where the role of the interviewer is more pronounced (Gioia et al., 2013). This depth of understanding is especially beneficial for exploring complex attitudes and facilitating a comprehensive grasp of human behaviour and decision-making (Eisenhardt and Graebner, 2007). Interviews also offer the advantage of contextualisation; researchers can adapt their line of questioning in real time to elicit the most relevant information (Pawson, 1996). This real-time adjustment not only improves the validity of the data but also allows for immediate clarification and the probing of topics of interest.

However, interviews have their limitations. It is time-consuming to conduct, transcribe, and analyse and requires significant resources (Creswell and Creswell, 2018). Additionally, the qualitative nature of interviews can introduce a level of subjectivity that may affect the reliability and replicability of the findings. This potential for bias exists because interviewers and participants can skew results through leading questions or answers, such as when the participant gives answers they think the interviewer wants to hear (Alvesson, 2003). Furthermore, the small sample sizes usually do not adequately represent the broader population. Despite these drawbacks, interviews are particularly apt for obtaining in-depth perspectives that are often overlooked or insufficiently explored in purely quantitative research (Creswell and Creswell, 2018).

Papers B, D, and E

I employed semi-structured interviews for the included papers that allowed for a blend of guided questions and open-ended discussions (Gioia et al., 2013). In terms of sample selection, I tried to select participants who, together, occupied an entire field of competence while simultaneously representing a variety of ages, genders, and roles (Papers B, D, and E).

Data collection occurred in-person or via video conferencing, depending on the participants' preferences and locations. Furthermore, parts of the research were carried out during the COVID-19 pandemic, which limited physical interactions but simultaneously increased competence in using digital tools.

Each interview session was audio-recorded with the participants' informed consent, and they usually lasted between 50 and 60 minutes. Before the interview was conducted, participants were briefed on the background of the study and my role as a researcher. All participants were ensured that they would remain anonymous and that confidential data would be managed in accordance with KTH’s standards.

4.1.2 Observations

While interviews offer more depth of understanding by allowing for the exploration of individual perspectives, they come with their own set of limitations. Primarily, interviews depend on the participants' self-reports and interpretations, which can introduce various biases (Pawson, 1996).

Meanwhile, observations allow for real-time, contextual data gathering, albeit sometimes at the cost of understanding the internal states or motivations behind the observed behaviours (McDonald and Simpson, 2014). Observations are particularly potent for capturing various variables such as non-verbal behaviours, interactions and environmental factors, thereby providing contextually rich data (Creswell and Creswell, 2018). However, like interviews, observations also have their share of limitations. An observer's mere presence can alter the subjects' behaviour, making the data somewhat biased (Bansal and Corley, 2011). Like interviews, the method is time-consuming, resource-intensive, and provides practical challenges such as physically accessing the research site.

Observations also come with unique challenges, such as limited control over variables that might influence the data and ethical concerns that may arise if subjects are observed without their explicit consent. Despite these drawbacks, observational methods often serve as a valuable companion to interviews since they afford a more well-rounded, holistic understanding of the subject being studied (Creswell and Creswell, 2018).

Paper B

In the work with Paper B, observations came as a natural extension of the interviews since many interviews were conducted onboard the vehicle, where I could observe how participants handled the vehicles practically. This approach led to interview questions based on observations, which, therefore, could be naturally integrated into the interview process.

However, I have not fully integrated observations as a formal method, for example, by taking more structured notes or by regularly reflecting and documenting my findings, nor have observations been part of a structured coding. Instead, the observations were more informal and should be seen as integrated into the interviews carried out in Paper B.

Nevertheless, I consider that the observations have been vital in forming my understanding of the bus shuttle service featured in Paper B and thus increased the quality of the interviews.

4.1.3 Workshops

Workshops serve a unique function by facilitating interactive group dynamics, thus allowing for further examination of the qualitative data gathered from the preceding methods (Eisenhardt and Graebner, 2007). They offer a dynamic environment within which participants can interact directly with each other and the research themes, thus crafting a comprehensive narrative that embraces individual views, social interactions, and real-world contexts (Creswell and Creswell, 2018).

Workshops come with their own set of advantages. For instance, they facilitate discussions and brainstorming sessions, which allows for the exploration of collective ideas. This collaborative approach can yield richer and more complex data than individual methods since participants can build on each other's statements (Creswell and Creswell, 2018). Furthermore, the interactive setting enables researchers to receive immediate feedback and clarifications, something not as readily available in interviews or observations. Additionally, this feedback comes from other participants, ensuring that the researcher can further embrace their role as an outsider. By bringing together participants from diverse backgrounds and roles, workshops offer a more holistic perspective on the research problem (Bansal and Corley, 2011). Additionally, the controlled environment ensures that the research objectives are focused upon instead of the varied contexts that interviews and observations might encompass (Creswell and Creswell, 2018).

However, workshops are not without their challenges. Like interviews and observations, they can be resource-intensive, requiring considerable planning, facilitation, and subsequent analysis (Creswell and Creswell, 2018). The group setting also has its limitations, such as the potential for groupthink, where conformity could suppress dissenting opinions or innovative ideas (Ørngreen and Levinsen, 2017). Logistical elements such as coordinating schedules and securing a venue can further complicate matters.

Papers C, D, and E

Workshops were utilised for Papers C, D, and E, albeit with somewhat different goals. Regarding Papers C and D, the workshops mainly presented the research design and discussed the assumptions used for the simulation model and cost-benefit calculation to ensure that the assumptions had a broader knowledge base. These workshops were more loosely organised, with only notes taken, and since the workshops took place over a long period of the study, the content changed throughout.

Paper E was focused on finding appropriate policy tools to govern a future with self-driving vehicle systems. One workshop was carried out in the study to expand upon results from previously conducted interviews. In this workshop, the participants were presented with the policy tools identified from the interviews and asked to reflect on these results. They were also asked to expand upon the results list and to see whether certain aspects had been missed. Finally, they were asked to prioritise the policy tools. While this prioritisation task was seemingly about finding the 'best' tool, the aim was instead to see whether any tools the participants deemed necessary were missing.

4.1.4 Coding

To understand the results of qualitative work, often in the form of interviews, data analysis is carried out using a coding framework (Flick, 2014). In most qualitative work, coding is essential to thoroughly analyse the gathered material and ensure a structured and transparent process for understanding the results (Langley, 1999).

This process also enables the researcher to validate their findings, usually by recruiting other coders to analyse the same material independently (Langley, 1999). However, when examining material, researchers may diverge substantially in their findings, mainly due to focusing on different aspects of the material; therefore, a coding framework is vital to ensure consistency (Van de Ven and Poole, 1990).

Papers A, B, and E

I performed coding as part of the work with Papers A, B, and E using similar work processes even though the material differed somewhat. These processes were carried out using the guidelines of Flick (2014), Creswell and Creswell (2018), and Gioia et al. (2013).

First, the material was prepared to ensure compatibility with the coding procedure, mainly by transcribing interviews, which was done by either me or another collaborator for Papers B and E. Second, the material was reviewed to find overarching themes or interesting parts in order to understand the material. Third, a coding framework was constructed using the themes in the first step. For Paper B, this process also involved two other researchers, and as such, this step involved ongoing discussions to determine the final framework. For Papers A and E, this step instead involved recruiting researchers from my lab to analyse the same material with the same framework to establish rigour in the coding.

Fourth, all the material was revisited to code it according to the framework. In this step, new sub-themes or variations of the themes were revealed, thus forcing a partial re-evaluation of the coding framework to develop the final version. Finally, all the material was revisited once more to align it to the definitive coding framework before producing the final result.

For Paper E, the coding software NVivo was used ("NVivo (Version 12)," 2018), whereas MAXQDA (VERBI Software, 2021) was used for Paper A and B.

4.2 Quantitative methods

Quantitative methods act as a valuable counterpart to qualitative techniques in academic research. Unlike qualitative methods, which rely on subjective interpretations and anecdotal data, quantitative approaches use numerical data and statistical analyses.

These methods come with several advantages. For example, they enable broader generalisation of the findings, which are often applicable beyond the study's context. The methods also lend more empirical rigour to the research through precise measurements and quantifiable data (Creswell and Creswell, 2018).

However, these methods are not without drawbacks. They can miss the rich contextual details that qualitative methods excel at capturing. Additionally, the complexity of the data often requires a robust understanding of statistical analysis, potentially limiting the methods' accessibility (Creswell and Creswell, 2018).

4.2.1 Simulation models

Simulation models have been used extensively as a quantitative tool to study self-driving vehicle systems (Narayanan et al., 2020). These models are usually based on known connections between variables or studies on how people behave in the transport system, and they have existed in various forms over the last 50 years (de Dios Ortúzar and Willumsen, 2011).

These models bring distinct advantages. First and foremost, they possess a predictive capability that allows for proactive planning based on assumptions of a future scenario (de Dios Ortúzar and Willumsen, 2011). This ability makes it possible to explore the impacts of, for instance, building a new highway or trying different economic schemes to combat pollution (Kagho et al., 2020).

However, it is crucial to acknowledge their limitations. The efficacy of these models is inherently tied to the quality of the input data and reliant on assumptions regarding the future state of the research phenomenon and overarching trends in society (Flyvbjerg et al., 2005; Witzell, 2021). Moreover, they can be computationally demanding and require high technical expertise for their setup, operation, and interpretation (Profillidis and Botzoris, 2018).

Sampers

In my research, I have employed Sampers, the Swedish transport model, which has a proven track record in assessing various transport dynamics in Sweden (Jonsson et al., 2011). Sampers is a four-step transport model incorporating demand generation, trip generation distribution, mode choice, and route choice into a single model framework. Using this approach, the model accommodates all major transport modes: cars, public transport, walking, and cycling (Algers, 2004). Given its specific focus on Swedish transport dynamics, it offers locally relevant insights that are highly valuable for policymaking within Sweden (Trafikverket, 2020).

However, like other simulation models, Sampers has its downsides. It can be computationally intensive and requires a considerable dataset encompassing various trip purposes and geographies. Furthermore, like all simulation models, it depends on the forecaster reasonably assessing what the intended scenario would look like (Andersson et al., 2017).

Sampers is also designed to model *current* behaviours and relationships in the transport sector. As such, the model has a relatively narrow scope (e.g. all vehicles are driven by adults with a driving licence), and using it outside of these parameters (e.g. empty self-driving vehicles) could produce more unreliable results. Therefore, only overall results are generally valid, whereas details for, e.g., individual neighbourhoods tend not to be reliable.

Paper C and D (and indirectly E)

Throughout my work with Papers C and D, I used Sampers to assess the impacts of self-driving vehicle systems. Paper E did not use a simulation model per se, but it was based on results from Paper C.

In Paper C, this assessment was done by changing mainly the overall factors in the model, such as fuel price and car accessibility. Furthermore, the model had to be adjusted to simulate self-driving vehicle accessibility by changing the driving licence rate to 100 % (to indicate that anyone could drive) or changing the highway capacity to simulate potentially more effective group behaviour between vehicles. Large parts of the network were also removed and replaced by direct lines to major stops to emulate a change from line-based public transport to on-demand public transport. This paper's Sampers model was complemented with Visum ("PTV Visum," 2017) to determine public transport supply and route choice.

Meanwhile, Paper D examines the implementation of a self-driving bus line in Stockholm. This examination was simulated in Sampers by making changes to the public transport network. This examination was done mainly by changing a specific line in terms of outline, headway, and run-time between stops. To simulate changes to the value of time, which could be linked to smoother driving behaviour (Kolarova, 2021), the actual run-time on the line was changed rather than the value of time since this was not technically feasible with the Sampers model.

For a more thorough description of the Sampers model and the method applied in Papers C and D, please see Almlöf (2022).

4.2.2 Cost-benefit calculations

The typical cost-benefit calculation process involves identifying all the advantages and disadvantages of a particular phenomenon, followed by a monetisation of each aspect (Stevens, 2004). Within transport, cost-benefit calculations are commonly used in infrastructure assessment to determine, for instance, if the construction of a new highway will have a net positive impact when all societal aspects are considered (Mackie et al., 2014).

The monetisation of different values might include saving lives due to safer operations and determining how much a life is worth (or rather, what the alternative costs are) or how much people value having a shorter commute time. These monetised aspects can then be compared to infrastructure costs and give policymakers a more comprehensive understanding of whether a project has a net benefit or which course of action is the most effective (Boardman et al., 2018).

The main advantage of this methodology is its comprehensiveness since it aims to cover 'all' aspects of a given field. Second, it strives to increase transparency by clearly outlining which factors have a positive outcome and which might have adverse impacts. Third, the results of the analysis are relatively easy to understand and communicate despite the complexity of the underlying problems.

However, the method also has considerable problems associated with it. First, all factors might not be monetisable (e.g. cultural impacts or biodiversity) or have a clear-cut influence (e.g. noise, for which the impacts have not been thoroughly researched). These factors are usually labelled as 'not included' and, consequently, receive less attention than seemingly more 'scientific' numbers (Witzell, 2021). Second, the results may hide the manifold assumptions that underpin the analysis, such as the assumed price of CO_2 emissions, which are heavily contested (Mandell, 2021). Third, the phenomenon's time horizons and system boundaries might be unclear, especially given that most infrastructure has a long history and might have very long time horizons (Boardman et al., 2018).

Paper D

In Paper D, we explored three scenarios for implementing self-driving buses in southern Stockholm by using the Swedish model Samkalk (part of the Sampers model family) to perform cost-benefit calculations. These calculations were performed in several steps, as outlined below.

First, the three scenarios were designed by interviewing two vehicle manufacturers, Region Stockholm, and the Swedish Transport Administration, and discussing the scenarios within the project group and with supervisors.

Second, the scenarios were further outlined with more concrete assumptions using an iterative process together with the project group and experts at the Swedish Transport Administration.

Third, these scenarios were modelled using the Sampers model (featured in Section 4.3.1), and the results were exported to the Samkalk model. Simultaneously, manual calculations of certain aspects (such as operational or investment costs) were carried out and validated by experts at the Swedish Transport Administration and Region Stockholm, before finally being incorporated into the Samkalk model.

Fourth, the results were discussed with the project group, the experts at the Swedish Transport Administration and Region Stockholm, and in a workshop with 17 participants. This final step was carried out to establish the rigorousness of the results and to ensure that no aspects were overlooked.

4.3 Mixed methods

Mixed methods research combines qualitative and quantitative techniques into a methodological fusion that capitalises on the virtues of each paradigm to deliver a fuller, more complete understanding of the research topic (Creswell and Creswell, 2018).

The advantages of adopting a mixed-methods approach are manifold. First, the mix of qualitative insights and quantitative data yields a richer, more complete portrait, answering not only the 'how much' question but also the 'why' and 'how' (Creswell and Creswell, 2018). Second, mixed methods approaches may give the researcher increased flexibility to delve into unforeseen issues or trends that may surface during the investigative process. Lastly, strategic sequencing permits researchers to tailor the study so that one methodological approach feeds into another, thus establishing a logical sequence and hierarchy in data collection and analysis (Heyvaert et al., 2013).

However, this methodology is not without its challenges. It tends to be resource-intensive given that it entails conducting both qualitative and quantitative studies, which can be time-consuming and require more comprehensive competence on the part of the researcher (Tashakkori and Creswell, 2007). Furthermore, the contrasting nature of qualitative and quantitative data can sometimes produce conflicting results, thus warranting cautious interpretation (Heyvaert et al., 2013).

4.3.1 Language analysis

Language analysis provides an understanding of not only what texts contain explicitly but also how their content is expressed, which in turn can help unearth what is not said (Sandoval and Denham, 2021). This field spans a vast array of disciplines, from the grammatical exploration of language structure and the investigation of how sentiments are communicated to the context-dependent nature of language use (Kramsch, 2014; Sandoval and Denham, 2021).

By dissecting the language used in these contexts, researchers can uncover underlying assumptions, values, and power dynamics that influence internal decision-making and core values. Furthermore, language analysis helps scrutinise diverse communication forms, be they written, oral, or even visual, thereby widening its applicability (Sandoval and Denham, 2021).

However, the complexity of language analysis should not be underestimated. It is laborious and resource-intensive, particularly when applied to expansive datasets. Language analysis can further be affected by research bias. In fact, many argue that parts of language analysis cannot be viewed objectively (Taylor, 2013) and that the researcher's context and background heavily affect the results and must be acknowledged.

Additionally, the application of language analysis within interdisciplinary studies such as transport research highlights its potential to uncover the socio-linguistic dimensions that influence public perceptions and policy discourse in the field (Witzell, 2021). By integrating language analysis, researchers can better understand how technological advancements and policy initiatives are communicated and perceived, thus offering insights into their societal acceptance and implementation challenges.

Paper A

While language analysis has mainly been used as a qualitative tool, in Paper A, I used a method to investigate a large dataset that borders on quantitative analysis. In the paper, I explored the 500 most highly cited papers in the self-driving vehicle research field using four different techniques.

First, I qualitatively coded the texts to find explicit mentions of motivation for doing the research, using the principles described in Section 4.1.4. Second, I searched for so-called modal verbs that described probability and which were connected to how the authors described the likelihood of certain outcomes, such as, for instance, if authors wrote, 'self-driving vehicles *will* lead to', versus the more cautious 'self-driving vehicles *could* lead to'. Third, the writing style was explored to determine whether authors used informative, persuasive, or imaginative styles in their texts. Fourth, the sentiment of the text was analysed to see whether the authors described self-driving vehicle systems as positive, neutral, or negative.

The last two steps to explore writing style and sentiment were carried out using ChatGPT version 3.5 (OpenAI, 2022). The approach of using AI-assisted tools in language analysis has been only scantly explored previously and, to the best of my knowledge, not in the transport field.

However, due to the novelty of the field and heeding recommendations from AI researchers (Bowman, 2023; Srivastava et al., 2022; van Dis et al., 2023), the sentiment and writing style were validated by myself and by three colleagues independently. Furthermore, this validation was extended to the first step, the qualitative coding of explicit motivations, to establish rigour.

4.3.2 Vignettes

Vignettes, also called narratives or stories, give participants a contextual framework to create a deeper understanding of a phenomenon and elicit richer, more nuanced responses than simple interview questions (Finch, 1987). Analogous to 'probes' in design research (Sanders and Stappers, 2014) or field trials, they can be used to generate both qualitative and quantitative data (Alexander and Becker, 1978).

Among the advantages of using vignettes is their capacity for concreteness (Bloor and Wood, 2006). Vignettes encourage participants to offer more precise, grounded answers by anchoring concrete concepts in relatable narratives. Moreover, they excel at contextualising, effectively acclimatising participants to novel domains, such as self-driving vehicle systems, which have yet to be realised (Erfanian et al., 2020).

However, it is worth noting potential downsides. Crafted vignettes risk introducing response bias by guiding participants towards specific perspectives (Jenkins et al., 2010). Furthermore, maintaining the credibility of the vignettes is imperative, a challenge compounded when dealing with speculative or futuristic subject matters (Finch, 1987).

Paper E

In Paper E, I constructed two vignettes based on the findings from Paper C. The results of Paper C were transformed into a more distilled form and written into a short text describing a future in Stockholm in which self-driving vehicle systems have been introduced, and certain advantages and problems have emerged. The respondents also received a list of societal goals based on Karjalainen and Juhola (2021) and were asked to respond to the vignettes, given the societal goals, and propose different ways to achieve these goals.

Two of my colleagues assessed the vignettes and proposed several changes that were incorporated into the text. Then, one to two days before the interviews, the participants received the vignettes so that they could have time to process them.

While vignettes have mainly been used qualitatively in the past, their basis in the simulation study in Paper C makes my use of them more mixed, which is why I choose to group them as a mixed method.

4.4 Ethical considerations

Given the multifaceted methodologies employed in this research, several ethical considerations warrant discussion. These considerations span various aspects of the research, from managing human subjects in interviews and workshops to ethically handling data and using AI-assisted tools.

4.4.1 Informed consent for interviews and workshops

All the interview participants – onboard operators, white-collar professionals, and public officials – were informed of each study's overall purpose, although each interview's specific objective was not explicitly stated to avoid biased answers. Consent for recording interviews was obtained from each participant while assuring them of the confidentiality and anonymity of their contributions.

4.4.2 Handling of sensitive information

Interviews with public officials and employees from companies developing self-driving vehicle systems could yield sensitive or proprietary information. As such, statements about unnecessary technological capabilities were excluded from the appended papers. Furthermore, all the interviewees were promised anonymity to ensure their statements could not be individually identified. All the data from interviews was handled carefully to prevent information on individuals from being shared with people outside the research group.

4.4.3 Availability of articles

I have strived to include openly available reports and articles where possible for the included papers. However, since many articles are published by commercial companies that do not predominantly contain open-access journals, this has not been possible in many instances. Regardless, most researchers usually have access through their universities, somewhat mitigating the problem.

4.4.4 AI-assisted technologies in the writing process

The incorporation of artificial intelligence into the writing process in the form of ChatGPT marks a largely unprecedented change in how research is conducted. This section, therefore, aims to describe the methodological approaches taken during the writing process, particularly regarding the textual content, and improve the quality of the language.

In my work with several of the appended papers and this thesis, the Large Language Model ChatGPT 4.0 was employed to assist in developing outlines and textual content (OpenAI, 2022; Ray, 2023). While the model offers an advantage in quickly generating text, I have found that the resulting text needs ample editing and rigorous review to align it with academic standards due to the mixed to low text quality. This low quality was often manifested in unnecessarily complex language, repeated statements, and texts being either too general or too assertive.

Despite these disadvantages, I have found the model to be an excellent tool for improving my quality and productivity by refining my language and suggesting changes. Furthermore, I have used the model as a consultative tool for linguistic queries – which is excellent since English is not my native language – to query the model on the difference between, for instance, 'transport' and 'transportation'.

Additionally, I have searched for recommendations from my university and other academic institutions regarding using artificial intelligence in academic writing but have not found any helpful recommendations. Instead, the guidelines have focused on highlighting possible issues rather than providing advice on using text generation.

However, two factors do stand out when using these tools: accountability and transparency. With this section, I have tried to be transparent about using this tool. Regarding accountability, the contents of this thesis are solely my responsibility. All text generated by ChatGPT has been extensively reviewed, edited, and corroborated with appropriate sources to ensure scholarly rigour.

4.4.5 Transparency and replicability

I have strived to achieve a high level of transparency regarding the research methodologies employed to allow for the replicability of each paper. However, qualitative studies primarily rely on statements from individuals who have not been named, making replicability less feasible. Instead, I have tried to be clear about the generalisability of these studies, which tends to be lower for qualitative rather than quantitative work.

The simulation model studies face a different challenge regarding transparency since they rely on a large number of particular details that are practically impossible to document. While, for instance, Paper C has an extensive table outlining the changes in the overall parameters (e.g. the cost of driving), changes were also made to the network, such as describing how people could connect from individual zones to individual stops in a public transport network. Moreover, the simulation model used is extensive and depends on a long development history and extensive documentation, which is challenging to integrate into a single research paper (see, e.g. Algers, 2004; Beser and Algers, 2002; Trafikverket, 2020).

Therefore, rather than striving to provide all the details, I strived to give overall descriptions of the most critical parts of the model used and the key parameters. Furthermore, I stated in each paper that the changed scenarios would be available if anyone were interested in further understanding each setup.

5 Summary of the appended papers

Photo of the bus shuttle that ran in northwestern Stockholm during 2018-2023, featured in Paper B.

5 Summary of the appended papers

This section provides short summaries of each appended paper regarding their motivations, methods, primary results, and conclusions.

5.1 Paper A

This paper explores the motivations behind the academic discourse on self-driving vehicle systems. Employing both qualitative and quantitative methodologies and using ChatGPT for natural language processing, I delve into the 500 most cited papers in self-driving vehicle systems research. Specifically, Paper A examines the Introduction sections of these papers to explore the researchers' explicit and implicit motivations for studying self-driving vehicle systems. In the paper, I explore how academics frame the societal necessity for self-driving vehicle systems research, as well as the type of language they use to discuss the technology.

I find that the most frequent justification for self-driving vehicle systems research is the technology's imminent emergence; essentially, researchers argued that 'self-driving vehicles are coming, so they need to be studied'. Following this motivation, some authors also mention several benefits, including accident reduction, traffic congestion mitigation, improved onboard comfort, and environmental advantages. The papers' tones are mainly neutral or slightly positive, but in some instances, deterministic language like 'will lead to' was used instead of more cautious terms like 'can' or 'may lead to'.

I argue that academics generally adhered to norms of objectivity and cautiousness, but exceptions exist, including overly optimistic or unnuanced portrayals of the state of the art. In the paper, I emphasise researchers' vital role in shaping public opinion and policy decisions. Consequently, I call for a more critical evaluation of the motivations behind self-driving vehicle systems research and advocate for acknowledging both the potential benefits and the shortcomings, such as societal inequalities and the security vulnerabilities of the technology.

Regarding policy implications, I argue that policymakers should be offered an objective evaluation of the state of the art in self-driving vehicle systems research. This assessment should cover the potential advantages, limitations and risks involved, such as the potential for the technology to exacerbate existing social inequalities and vulnerabilities to hacking or compromise. Rather than focusing solely on regulations to facilitate the development of self-driving vehicle systems, policymakers should consider the transport ecosystem in its entirety and consider the development of self-driving technology as one among several objectives.

5.2 Paper B

In Paper B, we employ the sociotechnical systems perspective and examine the challenges faced in the real-world implementation of a self-driving vehicle system. The paper focuses on self-driving buses in northwest Stockholm, Sweden (see Figure 4), with interviews with onboard operators and stakeholders responsible for operations. In contrast to the term 'self'-driving, the paper reveals that significant human intervention is still essential for the proper functioning of these vehicles. This revelation challenges the general perception that self-driving vehicle systems can simply replace human drivers.

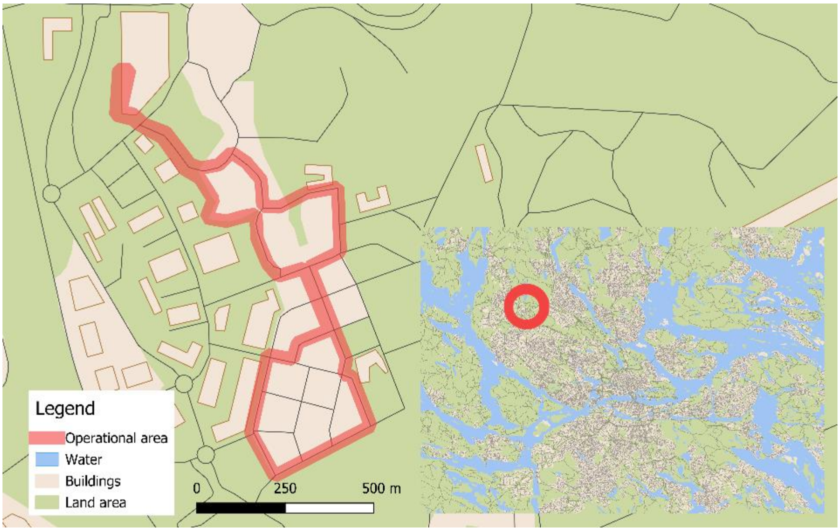


Figure 4. Overview of the Barkarby area, where the shuttle featured in Paper B operated. The red overlay shows the operational area of the bus. Down to the right is an overview of Stockholm, with a red circle indicating Barkarby.

In the paper, we point out that the existing legal framework poses significant challenges to incorporating self-driving vehicles into mainstream transport systems. Not only do we state that current laws need to be adapted to the lack of a human driver, but we also emphasise that self-driving vehicle systems require a different way of thinking about risk in driving.

Furthermore, we argue that human drivers possess a complex and tacit understanding of contextual elements, such as behaviour and norms that are challenging to code into a machine. If self-driving vehicle systems are to be integrated into the transport system, these traffic norms would need to change, which might have a negatively impact the traffic flow.

In addition, one of the striking findings is the technological gap in the vehicle's ability to understand context. Current self-driving technologies utilise specialised, driving-only intelligence, but we argue that a form of general intelligence might be necessary to achieve comprehensive self-driving vehicle operation. This necessity implies that achieving genuine autonomy may require engineering efforts far beyond the current state of technology.

In conclusion, we emphasise the need for a cautious approach towards implementing self-driving vehicle systems. Policymakers should maintain stringent legal requirements, irrespective of whether the driver is human or machine. Relaxing legal standards could compromise safety and disrupt overall traffic flow. Therefore, the findings of this paper serve as a roadmap for future research and policy formulation while advocating for a balanced approach that addresses the technical and societal impacts of self-driving vehicle systems.

5.3 Paper C

This paper investigates the impacts of self-driving vehicle systems on public transport and cars, focusing on Stockholm, Sweden. Four scenarios are presented, developed using input from 130 transport, academic, and government professionals, and evaluated using Sampers, the Swedish national demand model.

Overall, introducing self-driving vehicle systems leads to minor changes to public transport than to the car mode, which experiences dramatic changes, especially in a scenario where privately driven cars are replaced by a self-driving taxi system. However, the most dramatic change in mode use regarded walking and cycling, which decreased substantially. This change questions the sustainability of self-driving vehicle systems, and their introduction could lead to a drop in overall public health due to less physical exercise.

Geographically, inner-city areas showed a dramatic increase in person-kilometres travelled in car-based scenarios, especially those featuring a self-driving taxi service. In contrast, the outer regions of the county exhibited less drastic changes. These geographical disparities are attributable to cost and accessibility parameters, among other factors.

In the paper, we also delved into the purpose of trips, finding that self-driving vehicle systems influence 'other' trips, such as leisure trips and errands, to a greater extent than work-related travel. However, this impact varies geographically and particularly influences non-commuting trips in inner-city areas. The paper reveals that this impact is primarily due to the flexibility in demand for these kinds of trips compared to work trips.

Furthermore, a sensitivity analysis on the running cost of the car mode revealed significant impacts on person-kilometres travelled, thus emphasising the sensitivity of the results to cost assumptions.

In summary, we suggest that the transformative impact of self-driving vehicle systems is likely to be complex and will affect leisure travel more than commuting. This notion raises questions about the sustainability of widespread self-driving vehicle systems and emphasises the need for geographically and temporally specific policy interventions.

5.4 Paper D

In Paper D, we introduce the Total Impact Assessment (TIA) framework developed by the Swedish Transport Administration and apply it to evaluate three scenarios for self-driving bus services in Stockholm. Furthermore, we comprehensively examine existing frameworks for assessing self-driving vehicle systems' societal impacts.

The three scenarios were part of a pre-study to explore the possibilities of introducing a self-driving bus line in southern Stockholm (Sjöström et al., 2021). In the first scenario, we imagined a partially self-driven bus, akin to a SAE Level 4 vehicle, which could run driverless on parts of the network while a bus driver would resume control on other parts. In the second scenario, we imagined a bus capable of running without any personnel onboard while aided by a predominantly physical infrastructure, i.e. a separate road lane. In the third scenario, we presumed the bus could run without personnel onboard while guided by mainly digital infrastructure, e.g. high-speed broadband connectivity for the entire network.

In the paper, we find the second scenario to be extremely costly and not likely profitable from a societal perspective, although this result might not hold under all assumptions. Furthermore, we find digital infrastructure costs to be comparably small, although these requirements had significant uncertainties.

The most significant net societal benefit from the three scenarios is associated with a potential for better, smoother driving behaviour of the buses, which accrues substantial positive impacts even with modest improvement assumptions. In contrast, the often highlighted positive impact of accident rate reduction has almost no impact in our case study due to the already low rates of bus accidents in Sweden.

Second, reviewing current societal impact frameworks, we find that previous frameworks have largely overlooked critical areas such as cybersecurity and biodiversity as possible impacts related to self-driving vehicle systems. Moreover, most frameworks tend to assume that the impacts of self-driving vehicle systems are uniformly experienced across society, neglecting the variations in, for instance, perceived security.

Although the TIA framework had primarily been used for infrastructure investments, we find that it could be a robust model for evaluating self-driving vehicle systems. While the framework is not without limitations – it tends to prioritise quantifiable impacts, and underlying assumptions can significantly influence the results – it presents several advantages. Two significant strengths are its ability to capture a broad range of societal impacts and its comprehensive ambition. It also allows for comparisons of the scale of impacts, thereby offering a sense of proportion that many other frameworks lack.

Despite the various frameworks' capabilities, we conclude that no existing framework, including the TIA framework, adequately covered all the potential impacts related to self-driving vehicle systems. Critical areas like general well-being, economic impacts, and social sustainability are generally not addressed. Therefore, while the TIA framework contributes to a deeper understanding of the societal impacts of self-driving vehicle systems, it needs further refinement to include neglected aspects such as cybersecurity and employment impacts.

5.5 Paper E

Paper E addresses the challenge of effectively communicating complex research findings – such as self-driving vehicle systems – to non-experts, particularly those in public planning. The paper employs a somewhat novel approach in the form of vignettes to present quantitative results concerning the impact of self-driving vehicle systems on transport systems.

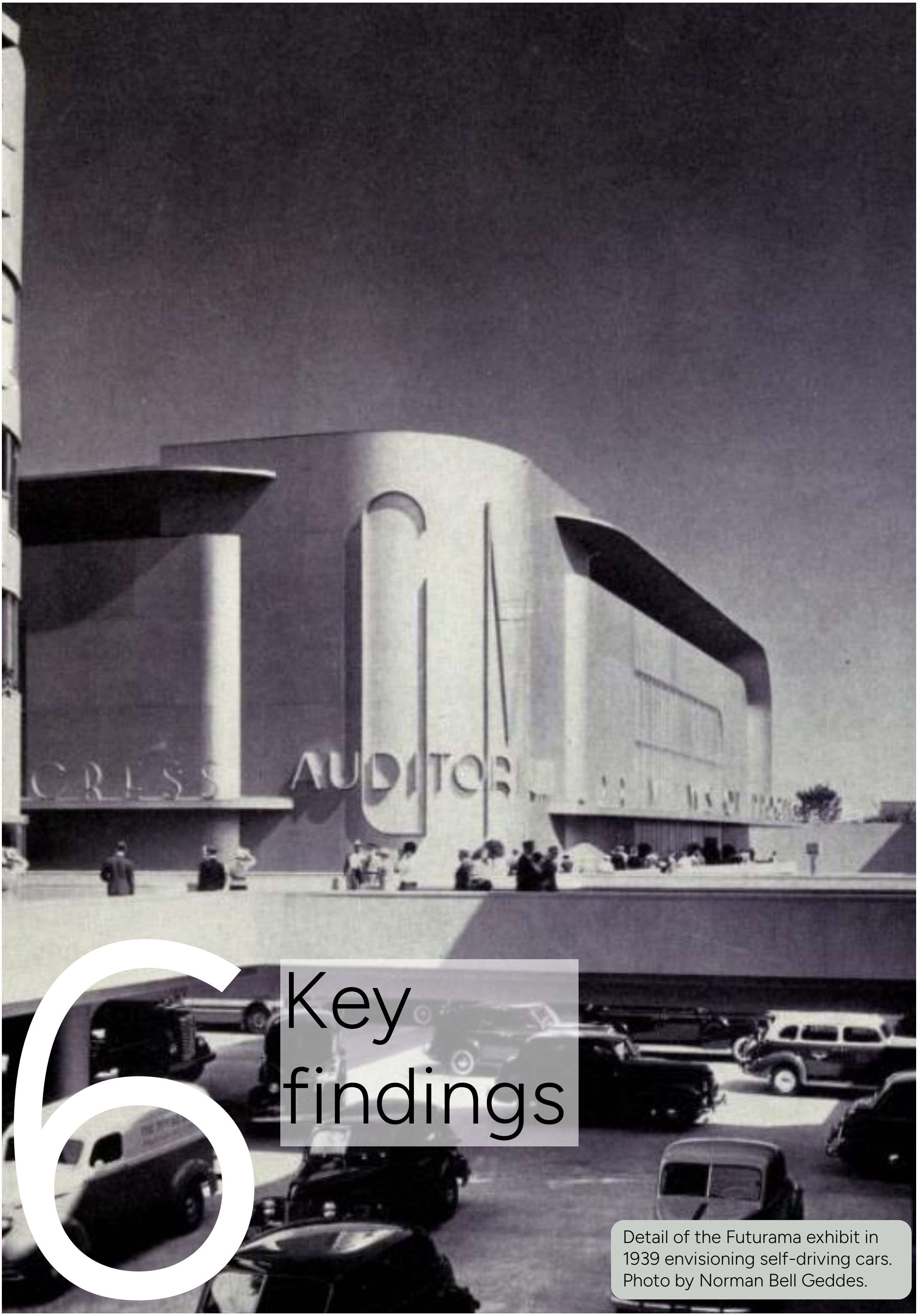
Historically, vignettes have been constructed using qualitative methods like the Delphi method, but this paper differed by sourcing its vignettes from a quantitative simulation model. This method allowed the public planners to think critically about the societal impacts of self-driving vehicle systems and facilitate the identification of a range of policy tools to steer transport systems toward sustainability goals.

The findings reveal that policymaking cannot rely on a single policy tool but needs a holistic approach considering the context. The planners emphasise the role of zonal planning, electrification, public transport development and the sharing of resources as pivotal for the sustainable implementation of self-driving vehicle systems.

Furthermore, the paper focuses on the effectiveness of using vignettes as a research method, which the participants found helpful in visualising an abstract and unknown future. Therefore, vignettes serve as an effective stimulus for further discussion and critical thinking.

In summary, I argue for the increased use of vignettes as a research tool, especially for complex subjects like the impacts of self-driving vehicle systems on public planning and policymaking. While pointing out that single policy tools are inadequate for addressing the complex impacts of such technology, a multi-faceted policy approach might be more effective.

6 Key findings



Detail of the Futurama exhibit in 1939 envisioning self-driving cars. Photo by Norman Bell Geddes.

6 Key Findings

In this section, I delve into the five research questions and show how the findings in the appended papers answer each question.

6.1 How is the development of self-driving vehicle systems motivated?

This research question is explored in Paper A, which investigates how the 500 most highly cited articles within the field express the need for their research, both explicitly and implicitly, by using the text's tone.

In the Paper, I find that a large portion of research articles fail to provide any motivation at all. Furthermore, many articles only include vague descriptions of 'emerging' technology, i.e. researching self-driving vehicle systems, because they are either being researched or since they are being introduced.

About half of the articles list one or several reasons for doing the research: accident mitigation, congestion relief, environmental benefits, energy reduction, or increased onboard productivity. However, as I show in the Paper, several of these outcomes are heavily disputed and depend on many different assumptions.

While about half of the included articles adhered to academic standards of objectivity and cautiousness, about 10% present a rosy view of self-driving vehicle systems, and about half have a slightly optimistic view of self-driving vehicle systems. In contrast, only a tiny share of the included articles question impacts or sustainability issues.

In conclusion, in Paper A, I show that much research into self-driving vehicles lacks a clear motivation for why it is actually needed. While researchers should be free to explore subjects without preconceived notions of the outcomes, it is still problematic that the research topic is not scrutinised better.

6.2 Given the currently known technical limitations, what adaptations would be needed to fully implement self-driving vehicle systems?

This research question is addressed in Papers B and D, with the former encompassing multiple areas and the latter concentrating on infrastructure requirements. Paper B posits that the necessary adaptations for self-driving vehicle systems extend beyond technological adaptations, requiring a comprehensive view of the entire sociotechnical system in which they operate. These adaptations are delineated into four principal areas, which add a layer of complexity, as depicted in Figure 5.

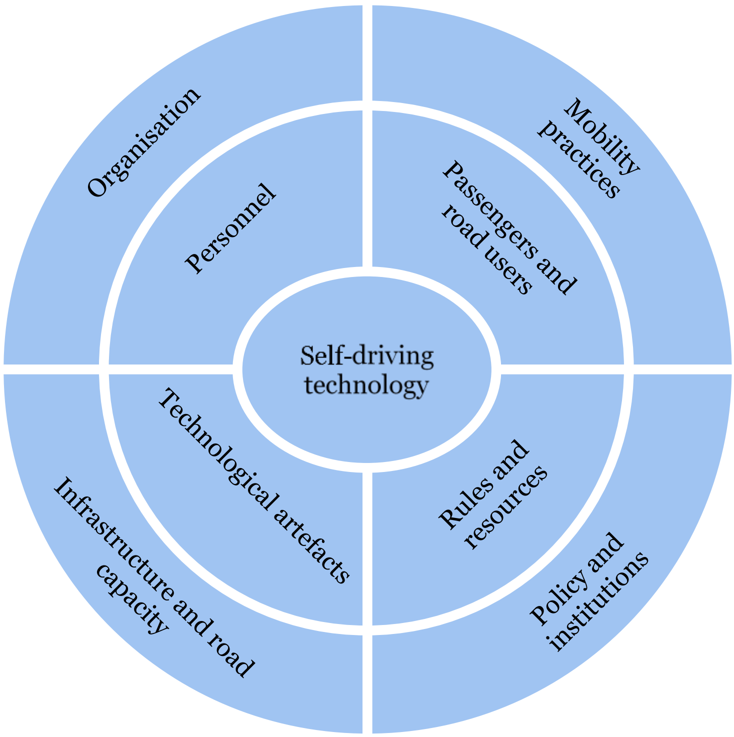


Figure 5. Changes to the sociotechnical system, as featured in Paper B.

First, new routines are essential for personnel engaged with self-driving vehicle systems. Their focus will shift from driving tasks to becoming ambulatory fault-handlers, addressing practical issues as they arise. Additionally, self-driving vehicle systems require broader organisational support beyond the tangible vehicle, thus requiring the active involvement of vehicle suppliers in operations, which runs contrary to their current, more passive role as suppliers of a finished product.

Second, removing operators from buses, as one operator suggested, implies that passengers might face extended delays or must resolve issues themselves, similar to managing basic computer problems or seeking remote assistance. This change requires altering the behaviour of other road users, such as human drivers and pedestrians, who must adapt their interactions with self-driving vehicles within the road space.

This shift underscores broader challenges in mobility practices. As I demonstrate in Paper B, self-driving vehicle systems are currently ill-equipped to interpret and mimic the complex behaviours people exhibit in the transport system. Instead, driving involves ongoing spatial negotiation and rule adaptation to specific contexts. Consequently, new driving and mobility practices are fundamental and may include digital protocols between vehicles and novel communication protocols and practices in the non-digital realm.

Third, previous studies have identified the need for regulatory changes. In Paper B, this is illustrated by showing apparent problems with the current legislation, such as requiring alcohol tests for all drivers.

However, introducing these systems also exposes more profound philosophical questions about risk. As highlighted in Paper B, the accepted risk levels associated with human driving, an unfortunate yet inevitable aspect of societal mobility, and contrast with the risk-averse approach of self-driving vehicle systems. The shift from individual, decentralised risk in human driving to centrally managed driving behaviour by an accountable organisation could lead to more defensive driving practices, potentially slowing down traffic and reducing overall accessibility.

Fourth, the integration of self-driving vehicle systems requires that adaptations be made to various technological artefacts within the road system, as explored in both Papers B and D. For instance, these systems currently depend on pre-rendered high-resolution 3D maps, high-precision localisation tools (such as NRTK, odometers, distance counters and object recognition technologies), and continuous communication with other systems such as the on-demand bus hailing software from the Barkarby trial in Paper B.

These requirements will intensify in a future devoid of onboard personnel and will need robust communication channels with traffic managers or emergency services. Challenges such as maintaining high-bandwidth broadband for continuous network communication will therefore arise.

Moreover, as discussed in Paper D, self-driving vehicle systems will demand higher-quality physical infrastructure, including more distinct road markings, enhanced snow removal, and real-time information about road conditions.

All these requirements show that the idea of infrastructure for transport must be broadened to encompass not only traditional, mainly physical infrastructure, but also digital artefacts.

In conclusion, I argue that any adaptation to facilitate self-driving vehicle systems would require drastic changes to the overall sociotechnical transport system and not just the simple addition of a new mode or minor changes to transport.

6.3 What societal impacts will fully implemented self-driving vehicle systems have, given a laissez-faire approach?

While this issue has received much attention (see Section 3.2), I have contributed to the understanding of the societal impacts of self-driving vehicle systems through my work presented in Papers B, C, and D.

6.3.1 Paper C

Paper C explores the impacts of a self-driving vehicle system in Stockholm using the Sampers model. While similar studies had been done previously, the Sampers model has two main advantages that have not been explored extensively: geography and trip purposes. Furthermore, only a handful of studies had previously explored the impacts of introducing self-driving vehicle systems in *both* cars and public transport. Instead, the focal point for most previous research had been on cars in the form of various taxi services.

In this paper, I find that the introduction of self-driving vehicle technology in public transport seems to have a limited impact on overall ridership, likely due to Stockholm's already high level of service. However, the geographical variation is considerable, with public transport becoming notably more attractive in rural areas since such areas currently have poor services.

Likewise, the impacts of self-driving cars have substantial geographical variations. Since cars currently dominate rural areas, introducing this new technology seems only somewhat to affect the overall usage of cars. However, the findings in Paper C suggest that changing the car ownership model by transitioning from individually owned family cars to shared, on-demand taxi services could result in extended waiting times and, potentially, increased user costs for rural areas.

Conversely, owning a car is currently a poor choice for more densely populated areas as parking prices are high and managing a car in a city environment is cumbersome. Therefore, providing access to a cheap taxi service would likely be an attractive alternative in dense cities, increasing car usage markedly in more central parts of the city.

However, two results from Paper C. are especially noteworthy. First, differences in self-driving car use depend mainly on a trip's purpose. While the public image of self-driving cars is that of more comfortable work trips, throughout the paper, I show that self-driving cars would have a considerable impact on leisure trips. While work trips could become more convenient, people typically only make one trip per day, limiting any increase in work trips. Meanwhile, having a more accessible car option would likely result in more trips to the store, football practice, and grandma's house, which would affect the transport system more than slightly increases during peak business hours.

Finally, I show in the paper that introducing self-driving vehicle systems leads to drastic decreases in walking and cycling, which could result in diminished public health for citizens. Thus, I question the sustainability impacts of self-driving vehicle systems.

6.3.2 Paper D

In Paper D, we review the current state of the art for understanding the societal impacts of self-driving vehicle systems. The main conclusion from this review is that the current frameworks vary substantially in their comprehensiveness, and no single framework managed to cover all potential outcomes. Furthermore, several aspects are largely overlooked, such as cybersecurity, cultural impacts, biodiversity, and the users' perspectives. Additionally, most frameworks fail to consider that impacts might differ for different societal and income groups.

Paper D also uses the Swedish Transport Administration's cost-benefit analysis framework to explore the societal impacts of introducing self-driving buses on a proposed new line in southern Stockholm. Using this framework, I draw upon three main conclusions regarding the impacts of self-driving vehicle systems.

First, even a partial introduction of self-driving buses with a driver onboard could lead to considerable benefits connected to smoother vehicle driving, which outweigh all other benefits.

Second, while accident mitigation is often highlighted as a considerable potential for self-driving cars, the same cannot be said for self-driving buses. Despite excessive assumptions on accident reduction, the gains barely show in the cost-benefit calculation. While this might sound surprising, it can be entirely attributed to buses already being extremely safe, at least within the Swedish context, compared to cars.

Third, infrastructure costs could vary drastically depending on physical versus digital infrastructure needs, and requiring self-driving vehicles to have their own road lane would likely be very expensive.

6.3.3 Paper B

Paper B takes a somewhat different approach to understanding societal impacts and investigates a self-driving pilot project rather than simulations on assumptions, as in Papers C and D.

The paper's results point to the fact that societal impacts stemming from self-driving vehicle systems cannot be seen in isolation since they would profoundly impact society. These impacts are exemplified by those concerning safety, where accident rates would not only simply increase or decrease; self-driving vehicle systems could also create new safety issues, such as cybersecurity-related incidents.

More profoundly, in Paper B, we show that self-driving vehicle systems would lead to new forms of transport behaviour in the road space. This behaviour could essentially eliminate certain types of accidents, such as those created by not paying attention to what is in front of the vehicle. However, the introduction of a new mode of transport could simultaneously lead to failed communication between actors on the road. For instance, the buses featured in Paper B strictly adhered to traffic rules, whereas car drivers in the area were more flexible and adapted to the local context.

This more inflexible behaviour would, therefore, lead to less efficient traffic due to the adherence to the explicitly stated rules. This efficiency loss is because current traffic norms increase flexibility, and drivers immediately seize opportunities that arise in front of them instead of strictly obeying the rules.

Throughout the paper, I show that the introducing self-driving vehicle systems forces an 'explicitisation' of driving, i.e. a larger focus on explicit rules rather than implicit and flexible handling. Currently, driving could be likened to somewhat of an art form where drivers use their intuition and evaluate every unique situation independently. Conversely, machines demand simple instructions that hold in all situations within a category and are universally applicable.

Furthermore, a director at the vehicle manufacturer stated that they viewed accident prevention as a calculation of the sensors' abilities to detect objects versus the vehicle's braking distance. While the capabilities of sensors and the 'intelligence' of the technology are likely to increase, decision-making relative to vehicle behaviour is moved away from the vehicle's actual location to a more centralised location, presumably under the control of an engineer. This relocation would change transport behaviour in the transport system from a human-centred activity to something centrally decided.

In conclusion, I show in Paper B that self-driving vehicle systems would not only lead to minor changes to the transport system but would usher in a new sociotechnical regime which would affect all other venues of human activity related to the transport system.

6.4 Given fully implemented self-driving vehicle systems, what policy tools would steer Stockholm towards current transport sustainability goals?

All the research papers somewhat answer this research question, but Paper E addresses this aspect more thoroughly by describing the results of interviews with public officials on the governance of self-driving vehicle systems. Therefore, in this section, I begin by briefly describing the overall conclusions of the four first papers before addressing the research question more directly using the findings from Paper E.

In Paper A, I show that researchers' discourse relative to the state-of-the-art of self-driving vehicle systems fails to nuance the impacts on society. Therefore, I argue that policymakers should not only focus on implementing self-driving vehicle systems but also consider the drawbacks of the technology’s impacts. This conclusion is further emphasised in Paper B, where I show that self-driving vehicle systems would affect many parts of society and not only the vehicles themselves. A laissez-faire approach would, therefore, have unintended consequences impacting many aspects of sustainability.

Furthermore, in Paper C, I show the need for well-considered policies that take time and geographical variations into consideration since impacts are likely to be homogeneously distributed. Similarly, the findings in Paper D show that the benefits of self-driving vehicle systems are mainly individual, while financing infrastructure is a public task requiring specific business models for financing.

While these findings in Paper A-D indicate certain aspects required for governance, Paper E answers the research question more directly. In the paper, I find that changes to governance tools might be less pronounced than expected despite the new capabilities and impacts of self-driving vehicle systems. Four areas of governance were identified: zonal planning, electrification, public transport, and increased sharing of resources.

Zonal planning is the area dealing with how cities are built, and it largely dictates the requirements of the transport system. More precisely, active zonal planning could facilitate the construction of new residential areas close to current public transport or prioritise between road space and parks or other areas that promote active mobility.

The participants saw electrification as an obvious solution to many problems in the transport sector that would not diminish in value due to the introduction of self-driving vehicle systems. For instance, electrification policies could be promoted by taxes on carbon emissions, allowing only zero-emission vehicles in certain parts of the city, or permitting electric vehicles to drive in bus lanes.

The use of public transport alternatives is further identified as a policy tool that could alleviate many problems with self-driving cars. Public transport alternatives increase transport efficiency since space and energy needs are substantially reduced compared to car traffic. These alternatives would thus alleviate the city's energy needs, emissions, congestion, and road space requirements. In practice, public transport could be further subsidised, extensive infrastructure projects could be funded, or the service could be enhanced by better cooperation between road administrators and public transport authorities.

The participants featured in Paper E stressed that sharing resources is generally essential and represents a solution with few downsides. This sharing could be in the form of public transport, which would reduce the extensive use of single-occupancy vehicles, or economic policies to make driving more expensive, which would encourage groups of people to share costs.

7 Discussion

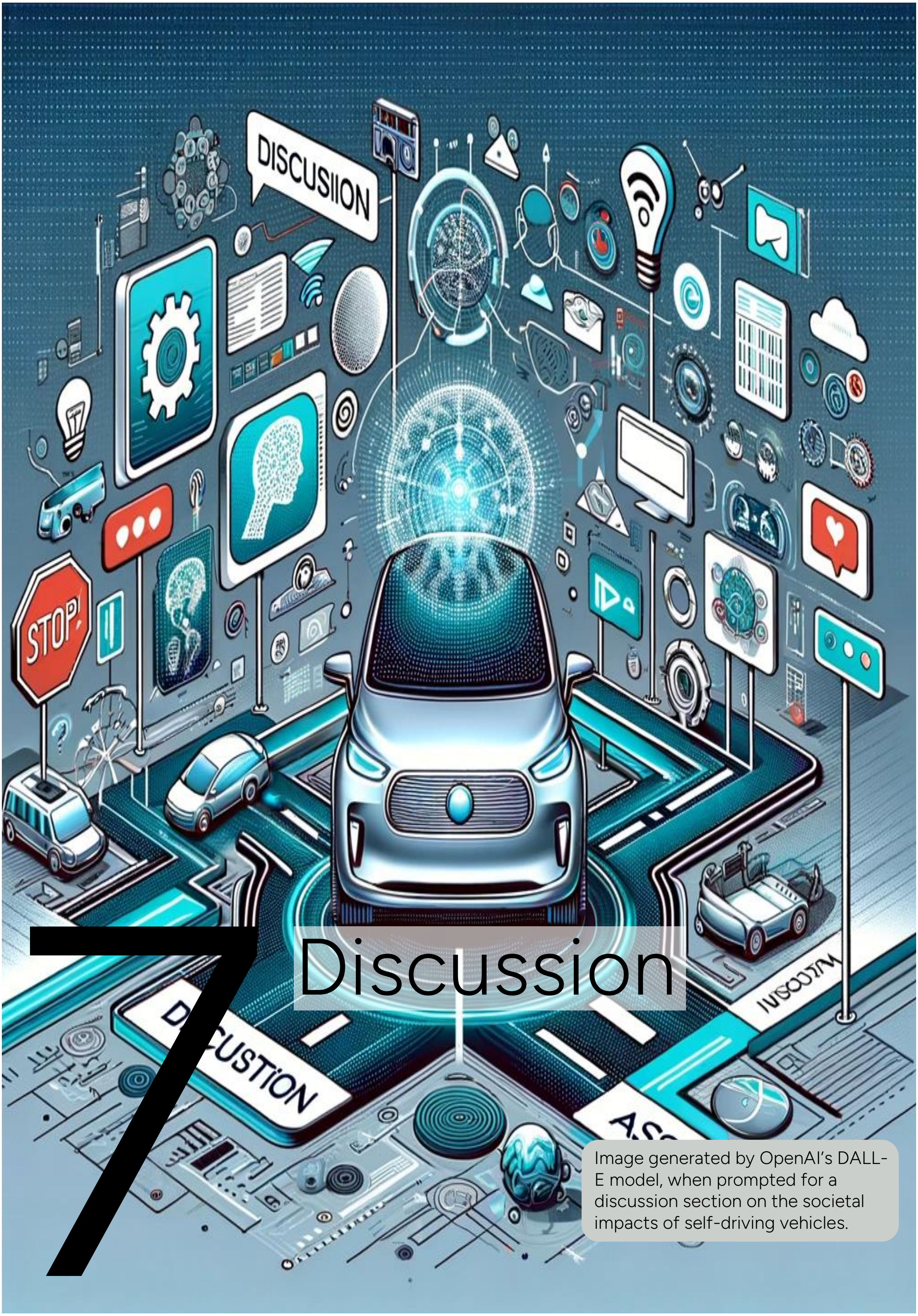


Image generated by OpenAI's DALL-E model, when prompted for a discussion section on the societal impacts of self-driving vehicles.

7 Discussion

In the previous section, I showed how the appended papers answer each research question. In this section, I elaborate on how these findings relate to previous research in the field, how the overall objectives are addressed and, finally, the overall aim of understanding the impacts of self-driving vehicle systems.

7.1 Exploring the motivations of self-driving vehicle system development

The motivations driving the research and development of self-driving vehicle systems are multifaceted and often ambiguous. Marsden and Reardon (2018) highlighted this through various case studies and suggested that the clarity of motivations in this field is not always evident. These motivations seem to have changed over time; as Kroesen et al. (2023) noted, perceptions and motivations regarding self-driving vehicle systems have evolved and adopted a more pessimistic view of the outcomes associated with these technologies.

Investigations into the portrayal and perception of self-driving vehicle systems reveal a complex narrative. Martin (2021) delved into the advertising strategies of self-driving vehicle manufacturers, thus shedding light on these technologies' optimistic and sometimes over-simplified portrayal. Similarly, Jelinski et al. (2021) examined media representations, which often mirror technological enthusiasm without necessarily addressing the underlying challenges. Furthermore, Du et al. (2022) explored public misconceptions about self-driving vehicle systems, indicating that a gap exists between public understanding and technological realities.

The findings of this thesis, explored in Paper A, reveal a lack of clear motivation in a significant portion of self-driving vehicle systems research. Many articles in the field do not explicitly state their motivation, while others offer vague descriptions of self-driving vehicles as 'emerging' technologies; this suggests a trend to conduct research simply because it is a current topic. Approximately half of the reviewed articles provided specific motivations, such as accident mitigation or environmental benefits. Yet I show that these are often based on heavily debated assumptions that depend on various factors. This analysis thus indicates a disparity in the field; a notable proportion of research lacks motivation, which could potentially lead to an unbalanced and overly optimistic portrayal of self-driving vehicle systems.

In light of these findings, I argue that the discussion needs to shift towards adapting self-driving vehicle systems to societal needs rather than moulding society to fit the advent of self-driving vehicle systems. Epting (2019) emphasises this viewpoint, arguing that transport planning should not be overly focused on just the self-driving vehicle systems; instead, they should be incorporated into broader urban mobility plans that prioritise human development, sustainability, and transport justice. This stance is echoed by Bissell et al. (2020), who criticise the prevalent technologically deterministic narratives surrounding self-driving vehicle systems. They advocate for a more nuanced approach concentrating on aspects beyond mere regulation, safety, or efficiency while acknowledging self-driving vehicle systems' broader social scientific impacts.

In conclusion, this research underscores the necessity for a more critical and comprehensive understanding of the motivations behind self-driving vehicle systems research and development. The field must move beyond a narrow technological focus and consider these advances' broader societal, ethical, and environmental impacts. Only then can the development of self-driving vehicle systems be aligned with the overarching goals of sustainable and equitable transport systems.

7.2 Investigating how self-driving vehicle systems are realised

As explored in my research, the realisation of self-driving vehicle systems in practical settings presents a landscape markedly different from the prevailing narratives in existing literature. The findings, particularly in Papers B and D, reveal the multifaceted and often underappreciated complexities of bringing self-driving vehicle systems from concept to reality.

The research conducted on the Barkarby self-driving bus trial (Paper B) starkly contrasts with the technical-centric view predominant in current literature (Gandia et al., 2019; Lou et al., 2022). While most previous research focuses on technical advancements like localisation and image detection algorithms, the findings highlight the significant hands-on effort and collaboration required even in limited-scale operations. The necessity for safety operators to perform tasks like route approvals, passenger management, and ad-hoc problem-solving illustrates a reality far more grounded in hands-on intervention than is often acknowledged in technical research.

The legislative aspects, as discussed by Tennant et al. (2021), Hansson (2020), and Shladover and Nowakowski (2019), gain new significance in light of my findings. The practical challenges faced in the Barkarby trial underscore the need for adjustments to the legal framework and broader philosophical discussions on risk. Similarly, the business model impacts discussed, for instance, by Lang and Mohnen (2019) and Yun et al. (2016), resonate with my observations of the need for car manufacturers and transport authorities to adapt to the changing dynamics introduced by self-driving vehicle systems.

As detailed in Paper B and D, self-driving vehicles would need not only investments in more physical infrastructure and more maintenance efforts but also an extension of the digital infrastructure since this infrastructure is paramount to these systems (see also Austroads, 2022; Manivasakan et al., 2021; Wang et al., 2022).

Furthermore, the realisation of self-driving vehicles requires a dramatic change to the broader sociotechnical system. This view contrasts with the often narrow focus of current self-driving vehicle research, which predominantly addresses technological advancements without fully grappling with the wider societal, legislative, and infrastructural impacts and often downplays the transition to self-driving vehicle systems (Farah et al., 2023; Marsden and Reardon, 2018). My findings instead indicate that a comprehensive and integrated approach is crucial due to the technological capabilities of self-driving vehicles and how they would fit into the existing social fabric.

In conclusion, the realisation of self-driving vehicle systems, as evidenced by my empirical research, calls for a more nuanced and comprehensive approach that transcends technical aspects and addresses the practical, legislative, societal, and infrastructural facets of self-driving vehicle systems implementation. Furthermore, my conclusion corroborates that of the European Commission et al. (2020), which stated that self-driving vehicle systems need to conform to society rather than society conforming to self-driving vehicles.

7.3 Analysing societal impacts of self-driving vehicle systems

The finding in Paper C, that self-driving vehicle systems would lead to a notable reduction in walking and cycling, has been noted by several previous studies (Soteropoulos et al., 2019) and is a likely outcome echoed by the development during the last century of increased general accessibility due to technological development (Grübler, 1990).

Furthermore, through Paper C, I showed that the impacts of self-driving vehicle systems are unevenly distributed in terms of geography and trip purpose, further adding to the complexity of impacts. This uneven distribution contrasts with previous case studies, which have mainly reported overall results (Narayanan et al., 2020). The findings in Paper C can be compared to Bösch et al. (2018b), Meyer et al. (2017), and Gelauff et al. (2019), who showed large variations depending on geography. The individual findings in each paper are somewhat different; however, they are likely attributed to local contexts and variations of assumptions. Unfortunately, to the best of my knowledge, no prior studies have investigated variations in impacts due to trip purposes. Still, as is shown in Paper C, it is evident that this topic deserves more attention.

The results of Paper D, which focuses on self-driving buses in southern Stockholm, reveal a new facet to the benefits provided by self-driving vehicle systems, similar to that of value-of-time savings often envisioned as important for self-driving cars (Kolarova, 2021). The findings contradict those of Zhang et al. (2019), who identified only minor benefits from partial self-driving capabilities and overlooked the smoother ride experience. This perspective aligns with that of Gelauff et al. (2019), who noted that the benefits of public transport are frequently overlooked, thus affirming the need for a diversified view when assessing the impact of self-driving vehicle systems.

Interestingly, while Abe (2019) and Azad et al. (2019) highlight safety as a critical benefit of self-driving buses, the findings in Paper D indicate minimal safety gains in the context of Swedish public transport due to the buses' already high safety standards. These contradictory results suggest that the advantages of self-driving vehicle systems, particularly for buses, may be context-dependent, with specific benefits like safety improvements being less pronounced in regions with established transport safety protocols.

Moreover, I argue that the impacts of self-driving vehicles must be understood as representing more than simple increases in capacity on the roadway or travellers having to learn to trust self-driving vehicles. Instead, as shown in Paper B, self-driving vehicles would bring about a more profound change in society's behaviour and relationship vis-à-vis transport.

Urry (2004) provides a foundational perspective on the social entanglement of transport, arguing that car culture is deeply embedded in human society. This ingrained aspect of transport underscores the transformative potential of self-driving vehicle systems, which may disrupt long-standing cultural norms. Hind (2022) adds a crucial dimension to this discussion by illustrating how self-driving vehicles alter people's relationship with cars. While relieving individuals of certain tasks, the shift from active driving to passive travelling also introduces new challenges in service reliability and decision-making. This decentralisation of decisions from a single driver to a collective of operators and systems resonates with the changes in organisation and mobility practices identified in Paper B.

Brodersen et al. (2023) delve into the transition of transport from a social activity to a technological endeavour, particularly relevant in the context of public transport. This individualisation of the transport experience reflects a broader societal shift towards technology-centric solutions, often at the expense of social interaction and communal experiences. Bissell et al. (2020) further reviewed the dominant discourse regarding self-driving vehicle systems and emphasised the need to consider their broader societal impacts beyond utilitarian aspects like safety and efficiency. Their insight into travel as a transitional phase and a space for work and leisure activities challenges conventional assumptions about transport utility.

Bissell et al. (2020) also raised concerns about the 'black box' nature of self-driving vehicle systems, wherein the driving process becomes opaque and less understandable to users, corroborated by the findings in Paper B. This obscurity could have significant impacts on how people perceive and interact with transport systems. Sparrow and Howard (2020) highlight another critical aspect: the potential for increased inequality. They caution against a future where mobility is monetised, thus creating disparities in access and quality of transport based on economic status.

In sum, these perspectives suggest that implementing self-driving vehicle systems is not just a technological upgrade but also a catalyst for broader societal changes. It necessitates a re-evaluation of not only how we travel but also how transport systems are structured and governed. The insights from Paper B, alongside other scholars' viewpoints, underscore the need for a holistic approach to understanding and integrating self-driving vehicle systems that comprehensively considers the societal, cultural, and ethical dimensions of this emerging technology.

7.4 Exploring how self-driving vehicle systems should be governed to fulfil sustainability goals

The governance of self-driving vehicle systems presents a complex intersection of technology, policy, and sustainability.

Governments have produced varied responses to the adaptation of self-driving vehicle systems. Taeihagh and Lim (2019) identified a spectrum of governance strategies ranging from no-response to adaptation-oriented reflecting the diverse governmental approaches to the advent of self-driving vehicle systems. Cohen and Cavoli (2019) offered a critique of what they perceived as a laissez-faire approach by many governments, highlighting potential issues that could arise, particularly concerning increased inequalities and accessibility challenges.

My research, particularly in Paper E, explores the potential policy tools that could steer Stockholm towards sustainability amid the widespread adoption of self-driving vehicle systems. Interviews with public officials reveal four primary areas of governance: zonal planning, electrification, public transport, and resource sharing. While not necessarily new, these areas are crucial for integrating self-driving vehicle systems into a sustainable urban framework. Similarly, Fraedrich et al. (2019) found self-driving vehicle systems to be a potential way to promote public transport. Furthermore, D’Agostino et al. (2021) emphasised the importance of sharing vehicles and electrification as necessary governance tools.

Governance of self-driving vehicle systems is crucial since, as Emory et al. (2022) highlighted, self-driving vehicle systems could lead to possible adverse impacts on social equity, particularly for disadvantaged groups. Similarly, Hopkins and Schwanen (2018) critiqued the UK's approach to governing self-driving vehicle system innovation as lacking inclusivity and diversity and called for more comprehensive and democratic governance models.

Despite the potential benefits of self-driving vehicle systems, there is a critical need for governance that prioritises overall sustainability rather than merely accommodating self-driving vehicle systems. The findings in Paper E and other studies indicate that while self-driving vehicle systems may introduce new dynamics, many of the existing policy instruments remain relevant and crucial. Policymakers must not lose sight of overarching sustainability goals and ensure that integrating self-driving vehicle systems into the urban fabric enhances, rather than detracts from, the pursuit of sustainable, equitable, and accessible urban mobility. Further, policy must be adapted to local context, which may vary substantially (Skill et al., 2023). Research into governance of self-driving vehicle systems remains underexplored, thus necessitating a more focused and comprehensive approach to self-driving vehicle system governance that aligns with long-term sustainability goals.

7.5 Contributions

In this section, I outline the main contributions of this thesis and the appended papers, divided into scientific contributions and contributions related to policy and practice. In the first, I focus mainly on the contributions to methods and the aspects that have not been explored previously, while in the latter, I provide more practical recommendations on how the results should affect policy regarding self-driving vehicle systems.

7.5.1 Scientific contributions

In this section, I outline the explicit scientific contributions of my appended papers. They are divided into four parts, each corresponding to one of the four objectives. Finally, I explain the overall contribution of this thesis.

First, in Paper A, I conduct a novel quantitative exploration of the motivations driving research on self-driving vehicle systems. I show that many researchers fail to provide a rigorous motivation for why this research is needed and that many of the motivations provided are superficial and optimistic interpretations of the societal impacts of self-driving vehicle systems.

As shown through Papers B and D, several requirements would need to be met to implement self-driving vehicle systems in practice. While the research field of self-driving vehicle systems is vast, investigations into actual implementation seem to be few; Paper B, in particular, provides valuable insight into how this technology is realised. Furthermore, in Paper B, I show that such implementation would require multifaceted societal changes beyond simple technological adaptations.

Third, in Papers B, C, and D, I show that the societal impacts of self-driving vehicles are multifaceted and may create surprises. Paper C is the first large-scale simulation of a transport system with both self-driving cars and public transport in which the transport demand is dynamic. In the paper, I show that impacts depend not only on geographic differences but also on the type of trip being carried out. Paper D is one of the first cost-benefit calculations of a self-driving vehicle system, thus showing that this method can provide many new insights. In Paper D, I also show the full spectrum of frameworks for analysing self-driving vehicle systems and highlight that no single framework covers all aspects. Moreover, the sociotechnical systems perspective used in Paper B shows that self-driving vehicles must be understood as more expansive systems whose impacts would be far-reaching.

Fourth, Paper E provides an initial exploration into how self-driving vehicle systems can be governed, which has only been explored in a handful of other studies in other geographies. While the findings from Paper E largely corroborated past work, I managed to explicitly find more concrete tools for governance, whereas previous research mainly explored overarching governance themes. Furthermore, I used the vignette method, which had hardly been used previously, to show that it is a valuable tool to investigate an abstract phenomenon which has yet to materialise, such as self-driving vehicle systems.

Moreover, in this thesis, I show that self-driving vehicle systems affect many different aspects of society and that multiple methods are necessary to explore this vast area. In addition, I show that self-driving vehicles cannot be seen as independent of the wider society. Rather, they must be treated as sociotechnical systems affecting many aspects of human behaviour and the wider society.

7.5.2 Implications for policy and practice

The advent of self-driving vehicle systems presents a new intersection of technology with societal and environmental impacts. While self-driving vehicle systems promise several potential benefits, they also pose significant challenges and implications for urban mobility, public health, and overall sustainability. This section explores these implications and provides insights into how policymakers can navigate this emerging landscape.

Self-driving vehicle systems have the potential to dramatically transform urban mobility by increasing accessibility or reducing accident rates. However, as shown in Paper C, their introduction raises critical questions about public health and sustainability. There is a risk that increased reliance on self-driving vehicle systems could lead to reduced physical activity and thus affect public health due to less walking and cycling. To counteract this risk, policies must emphasise walkability and promote more active forms of travel.

Integrating self-driving vehicles into urban settings extends beyond technological advancements, as explored in Papers B and D. Instead, they must be viewed as parts of a sociotechnical system. For instance, the urban infrastructure must evolve to support new types of infrastructure, such as digital connectivity or advanced traffic management systems. Additionally, societal adjustments in how individuals interact with and perceive self-driving vehicle systems are crucial, as discussed in Paper B. Policymakers must develop strategies that facilitate these changes to focus on creating environments wherein self-driving vehicle systems complement existing transport systems and enhance overall urban mobility.

The economic impacts of self-driving vehicle systems are also profound. Governments and municipalities might bear substantial costs in adapting existing infrastructure. However, the direct advantages often benefit individual users through improved commute times and reduced transport costs, as shown in Paper D. This mismatch requires rethinking the transport business models. Policymakers should explore innovative financing models to ensure that the economic benefits of self-driving vehicle systems are broadly distributed and align with public investment.

Equity and accessibility remain central concerns in adopting self-driving vehicle systems, as discussed by Epting (2019) and Sparrow and Howard (2020). Policymakers must ensure that the benefits of self-driving vehicle systems do not bypass underserved or disadvantaged communities. These policies must address digital divides, ensure affordable access, and design inclusive systems that cater to diverse needs. Policies should aim to leverage self-driving vehicle systems to enhance accessibility for all urban residents, thereby contributing to more equitable urban environments.

7.6 Limitations

The limitations of this research are multifaceted due to its focus and context. Conducted within Sweden, which is a member of the OECD, the thesis inherently assumes a socioeconomic and infrastructural framework that may not represent non-OECD countries. This geographical and developmental specificity potentially limits the generalisability of the findings since societal impacts, infrastructure, and policy responses in different global contexts might vary substantially.

Furthermore, the rapidly evolving nature of self-driving technology presents a challenge to ensuring the long-term applicability of the conclusions drawn. As new technologies emerge and societal attitudes towards self-driving vehicle systems evolve, some of the findings and assumptions made in this thesis could become outdated. The dynamic nature of this field underscores the need for continuous research and a re-evaluation of the conclusions.

A significant focus of the research, particularly in Papers B and D, is on self-driving bus systems. While this provides valuable insights into this segment, it may overlook broader impacts for other types of self-driving vehicle systems, such as passenger cars. This narrower scope potentially limits the comprehensiveness of the societal impact assessment.

The speculative nature of the research on the future societal impacts of self-driving vehicle systems is another crucial limitation. Since these vehicles are not yet fully realised, the papers operate on assumptions and predictions about their future form and societal role. The actual realisation of self-driving vehicle systems could differ significantly from current expectations. Additionally, the Sampers model, used in Papers C and D, is inherently designed to model current behaviour, not only people’s behaviour but also the possibilities of current modes of transport. Introducing changes to the model beyond its scope, therefore, limits the representativeness of the results. However, I would argue that while the exact results may not be accurate, the general direction of change should still be correct, and the overall conclusions should, therefore, be reliable.

Additionally, the variability and unpredictability of public perception and acceptance of self-driving vehicle systems constitute significant limitations. These factors can influence societal impacts and remain challenging to predict accurately, especially over the longer term. The public's acceptance and perceptions are dynamic and can significantly shape the integration of technology into society.

A critical aspect of the technological focus in the research is the examination of buses in Paper B, which utilise relatively basic technology. These buses primarily rely on LIDAR for object detection and lack the dynamic driving behaviour or image detection capabilities seen in more advanced prototypes developed by companies like Waymo. While this technological simplicity limits the scope of the paper, I argue that many of the challenges identified would persist even with more advanced technologies. However, this highlights a limitation in fully capturing the potential societal impacts of more dynamic and technologically sophisticated self-driving vehicle systems.

Lastly, the absence of a comparative analysis with regions outside the OECD limits understanding how self-driving vehicle systems might affect societies with different socioeconomic and infrastructural backgrounds. This gap points to a potential area for future research and suggests the need to explore a broader range of global contexts to understand the societal impacts of self-driving vehicle systems fully.

7.7 Recommendations for future research

Future research in the field of self-driving vehicle systems needs to be multifaceted and address both the technological and societal aspects. First, there is a pressing need for more in-depth studies into the organisation and perception of practical self-driving vehicle systems testing. As discussed in Section 7.2, previous research has focused on technical aspects like image detection algorithms and fleet management. Less attention has been paid to how these tests are practically orchestrated, who is involved in their implementation, and how they are perceived by those working hands-on with the vehicles, such as safety drivers. Understanding these elements can provide valuable insights into the real-world challenges and opportunities of implementing self-driving vehicle systems.

A broader exploration of peoples' perceptions of self-driving vehicle systems is also crucial. Future research should investigate how different sociodemographic groups and cultures perceive and interact with self-driving vehicle systems. These investigations should embrace diverse viewpoints to understand the potential acceptance and resistance across various segments of society.

Moreover, the heterogeneity of the impacts and perceptions relative to self-driving vehicle systems warrants further investigation. My research in Paper C, which explores rural versus urban settings and different trip purposes, suggests there are significant impact variations based on context. Future studies should expand on this by examining how different socioeconomic groups, along with economic status, age, and gender, are impacted by the advent of self-driving vehicle systems.

Furthermore, as highlighted in Paper D, several areas remain underexplored and require attention. These include the impacts of self-driving vehicle systems on areas such as biodiversity, land use, and cybersecurity. Each area presents unique challenges and opportunities critical to the holistic understanding and implementation of self-driving vehicle systems. For instance, understanding how self-driving vehicle systems could affect biodiversity and land use can guide sustainable urban planning while exploring cybersecurity ensures the safety and reliability of these vehicles.

Finally, as discussed in Paper E, the governance of self-driving vehicle systems needs significant examination that should include developing new policies and regulatory frameworks to address sustainability issues and societal goals. Developing these governance mechanisms is crucial to ensure that integrating self-driving vehicle systems into society aligns with broader sustainability and equity goals.

These recommendations aim to guide future research towards areas pivotal for the holistic understanding and successful implementation of self-driving vehicle systems to ensure that technological advancements align with societal needs and goals.

8 Conclusion

A photo from the Dutch 'ParkShuttle', a self-driving bus service in operation since the late 1990s. The bus has a separate roadway but interacts with other road users at intersections.

8 Conclusion

This thesis has delved into the motivations behind the development of self-driving vehicle systems, their potential implementation, the broad spectrum of their impacts, and the importance of governance to achieve sustainability goals. I have shown that the motivation for research into self-driving vehicle systems is opaque, often lacking a clear rationale, and tends towards an overly optimistic and simplistic view of their benefits.

The realisation of self-driving vehicle systems may not only be distant but also likely require profound societal transformations beyond mere adjustments to road capacity and legislation. Rather, self-driving vehicle systems would mean a fundamental shift in mobility practices and a philosophical re-examination of acceptable risks.

A critical finding is that although self-driving vehicle systems promise certain advantages, they could also lead to adverse outcomes. A balanced perspective is crucial to temper the predominantly positive narrative surrounding self-driving vehicle systems. As illustrated in the papers, introducing self-driving vehicle systems will not merely adjust existing systems. Rather, it will likely usher in new forms of accidents and require redefined mobility practices and human-machine communication protocols.

Governance of self-driving vehicle systems must be robust and forward-thinking, focus on equity, tackle climate change, and address health concerns arising from pollution and potentially reduced physical activities. The framework governing self-driving vehicle systems must align with broader societal goals to ensure that their integration contributes positively to a sustainable future.

In conclusion, our approach towards self-driving vehicle systems should not be about adapting our society to accommodate them but rather understanding how this technology can be harnessed to serve us and enhance our quality of life.

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