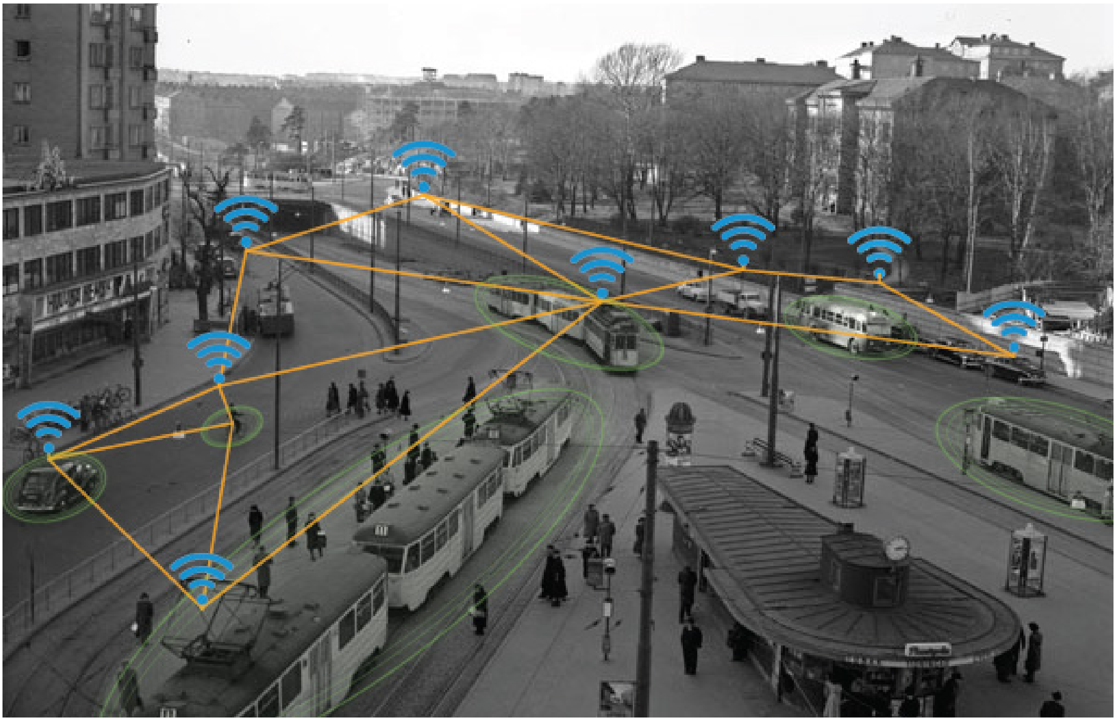
KTH ROYAL INSTITUTE
OF TECHNOLOGY

Licentiate Thesis in Machine Design

Exploring societal impacts of self-driving public transport using four-step transport models

ERIK ALMLÖF



Stockholm, Sweden 2022

Exploring societal impacts of self-driving public transport using four-step transport models

ERIK ALMLÖF

Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Licentiate of Engineering on Tuesday the 7th of June 2022, at 10:00 a.m. at the Integrated Transport Research Lab, Drottning Kristinas Väg 40, Kungliga Tekniska högskolan, Stockholm

Licentiate Thesis in Machine Design
KTH Royal Institute of Technology
Stockholm, Sweden 2022

ISBN 978-91-8040-267-5
TRITA-ITM-AVL 2022:18

Printed by: Universitetsservice US-AB, Sweden 2022

Abstract

During the last decade, self-driving technology has become increasingly visible in the news, with the vision that people would enter vehicles that drive themselves, and that people could instead rest, read the newspaper, or have a meeting. However, these visions have mainly focused on the potential for car usage, even though public transport could benefit greatly from self-driving technology. For bus traffic, the bus driver accounts for half of the cost of driving, and savings on personnel costs could, for example, be reinvested in expanded public transport service or used to lower taxes.

At the same time, more research has shown potential problems linked to self-driving technology, for example that more comfortable driving would lead to more traffic, which in turn would lead to increased emissions, higher noise levels in cities or further focus on car-centric infrastructure. For public transport, the driver's role in creating safety and acting as problem solvers has also been emphasized - who should I ask for directions if there is no knowledgeable driver on board?

Various methods have previously been used to explore the social effects of self-driving technology and in this dissertation I have used so-called "four-stage models", more specifically the Swedish transport model Sampers. Four-stage models have been used for 50 years to evaluate effects on the transport system from e.g. infrastructure changes, but these models face new challenges, handling vehicles that drive by themselves. In my research, I have adjusted the model to simulate self-driving technology and investigated what effects this has on, for example, traffic volumes and emissions.

In the three articles that are part of the dissertation, I have four main conclusions:

- Self-driving technology can mean large savings in costs for public transport, primarily for bus traffic but also to some extent for rail traffic. In addition, a smoother driving behaviour would mean more comfortable travel, which would increase the attractiveness of public transport. In addition, public transport not limited by, for example, driver schedules or current commercial conditions, could develop new types of services, such as on-demand public transport.
- Four-stage models have previously been used to model the transport system and have been shown to have good results, at least at an overall level. Within my research, I have made some adaptations of these models to mimic self-driving technology, but the models in their current form cannot consider, for example, vehicle sharing.
- It is important to point out that bus and train drivers currently perform many tasks that are not directly related to the driving of the vehicle, such as answering

questions, maintaining social order among passengers and taking care of faults that occur during the trip. Today, self-driving technology cannot fulfil these roles.

- Self-driving technology for public transport would affect people's accessibility, driving style for vehicles, safety on board, how we plan traffic and the people who currently work as drivers. In fact, a multitude of societal effects have been identified, affecting all areas of transport. In addition, the effects are generally not similar across geographies, time units or for different actors, which further emphasizes that the total effect is not easy to summarize.

Keywords: Self-driving vehicles; Public transport; Four-step transport model; Societal impacts; Sampers.

Sammanfattning

Självkörande teknik har under det senast decenniet synts allt mer i media, med målet att människor ska slippa köra själv på väg till jobbet, och istället kunna vila, läsa tidningen eller hålla ett möte. Dessa visioner har dock i huvudsak fokuserat på just bilen, trots att kollektivtrafiken skulle kunna dra stor nytta av självkörande teknik. För busstrafik står bussföraren för hälften av kostnaden för att köra trafiken, och besparingar på personalkostnader skulle t ex kunna återinvesteras i mer utökad kollektivtrafik, lägre skatter eller utökad välfärd inom andra områden.

Samtidigt så har alltmer forskning visat på potentiella problem kopplat till självkörande teknik, exempelvis att den mer bekväma körningen skulle leda till mer trafik som i sin tur leder till mer utsläpp, höjda bullernivåer i städer eller ytterligare fokus på bilcentrerad infrastruktur. För kollektivtrafiken har även förarens roll som trygghetsskapande och som problemlösare lyfts fram – vem ska jag fråga om vägen om det inte finns en kunnig förare ombord?

Olika metoder har tidigare använts för att utforska samhällseffekterna av självkörande teknik, i den här avhandlingen har jag använt mig av så kallade ”fyrstegsmodeller”, mer specifikt den svenska transportmodellen Sampers. Fyrstegsmodeller har använts i uppemot 50 år för att utvärdera effekter på transportsystemet, men har ställts inför nya krav på att hantera fordon som körs av sig själva. Inom min forskning har jag gjort anpassningar av modellen för att simulera självkörande teknik och undersökt vilka effekter detta får på t ex trafikvolymer och utsläpp.

I de tre vetenskapliga artiklarna som är del av avhandlingen har jag kommit fram till fyra huvudsakliga slutsatser:

- Självkörande teknik kan innebära stora besparingar i kostnader för kollektivtrafiken, i första hand för busstrafik men även i viss mån för spårtrafik. Därutöver skulle en mer jämn körstil innebära bekvämare resor, vilket skulle öka kollektivtrafikens attraktionskraft. Därutöver kan kollektivtrafik som inte begränsas av t ex förarscheman eller nuvarande kommersiella villkor kunna innebära nya tjänster, såsom efterfrågestyrd (”on-demand”) kollektivtrafik.
- Fyrstegsmodeller har tidigare använts för att modellera transportsystemet och visat sig ha god överenstämmelse med verkligheten, åtminstone på övergripande nivå. Inom ramen för min forskning har jag gjort anpassningar av Sampers för att efterlikna självkörande teknik, men modellerna kan i sin nuvarande form inte ta hänsyn till t ex delande av fordon.
- Det är viktigt att påpeka att förare idag utför många uppgifter som inte direkt är kopplade till framförandet av fordonet, såsom att svara på frågor, upprätthålla

ordning bland resenärer och att ta hand om fel som uppstår på fordonet. Dessa roller kan självkörande teknik idag inte uppfylla.

- De samhällseffekter som identifierats är överlag varierande och mångfaldiga. Självkörande teknik för kollektivtrafik skulle påverka människors tillgänglighet, körstilen för fordonen, tryggheten ombord, hur vi planerar trafiken och de personer som idag arbetar som förare. Dessutom är effekterna generellt sett inte likartade över geografi, tidsenhet eller för olika aktörer, vilket ytterligare understryker att effekten inte är enkel att sammanfatta.

Acknowledgements

They say that it takes a village to raise a child, and I am not sure if more or less is required to raise a PhD student, but I owe my gratitude to a large number of people. This research was not done in an ivory tower, but rather through daily discussions with co-workers and colleagues within the transport field. I think that I have discussed my research with more than 200 professionals who have provided some form of feedback, all of which has contributed to the final results of my research or to my way of thinking.

I would like to thank all my colleagues at ITRL and SL for providing guidance. All of you have helped me on my scientific journey. My managers, supervisors and fellow PhD students have been especially helpful and I owe you my gratitude.

Thank you Mia for helpful support and feedback, and interesting discussions. You really bring new perspectives, which may be difficult but that I have come to value and I look forward to our continued work.

Thank you Gabriella for your support and interest, despite my initial shocking decision to take on this project.

I'd like to thank my parents, family and friends for providing support and encouraging my studies, starting as a young child and continuing as an adult.

I think that my first year as a PhD student was especially confusing and stressful, and five people really supported me and deserve a special appreciation for the first phase of my studies.

Thank you Sophie, for encouraging me to apply for the position and saying "You gotta do this!" when I was hesitant.

Thank you Albin. I think that I have had many hours of "work therapy" with Albin, complaining about the problems of Sampers/Samgods and the regular annoyance with supervisors, editors or teachers. You also gave me support during a struggling period in my personal life, which I value dearly.

Thank you to my supervisors Anna, Mikael and Erik who helped guide me in the weekly confusion on what to focus on, what makes the difference between science and 'interesting' and for sorting out general misunderstandings.

Erik Almlöf, May 2022.

Dissertation and list of appended papers

A Licentiate of Technology is an intermediate Swedish academic degree that can be obtained halfway between the MSc and PhD. While less formal than a Doctoral Dissertation, examination for the degree includes writing a thesis and a public presentation with an invited discussion leader.

This Licentiate thesis consists of two parts. The first part gives an overview of the research with a summary of the performed work. The second part collects the following appended scientific papers, which are referred to in the text by their short version, Paper A, Paper B and Paper C.

The following papers are included within this thesis and the CRediT system (https://credit.niso.org/, accessed 2021-11-05) is used below in presenting the contributions.

Paper A

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

Contributions of the authors:

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

Paper B

Almlöf, E., Nybacka, M., Pernestål, A., Jenelius, E., n.d. *Will leisure trips be more affected than work trips by autonomous technology? Modelling self-driving public transport and cars in Stockholm, Sweden*. Rev.

Contributions of the authors:

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

Paper C

Almlöf, E., Xiaoyun, Z., Pernestål, A., Jenelius, E., Nybacka, M., n.d. *Evaluation of frameworks for assessing societal impacts of self-driving technology*. Rev.

Contributions of the authors:

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

Other publications

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

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).

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).

Nomenclature

The following abbreviations are used throughout the thesis:

- CBA – Cost-Benefit Analysis.
- OECD – Organisation for Economic Co-operation and Development.
- PKT – Person Kilometres Travelled.
- STA – The Swedish Transport Administration (Sv. Trafikverket).
- TIA – Total Impact Assessment, the STA's framework for assessing changes to the transport system (Sv. Samlad effektbedömning).
- VDF – Volume Delay Function.
- VKT – Vehicle Kilometres Travelled.
- VoTT – Value of Travel Time

Contents

1 Introduction

During the last decade, self-driving technology has arisen as a potential game-changer for the transport system. Waymo (a spinoff company of Google) was a pioneer within the field, with their public demonstration of a self-driving car in 2010, showcasing a technique that was said to soon reach technological maturity (Shladover, 2018). Investments during the 2010s exceeded 40 $ billion and a large number of companies and public institutions have done extensive trials (McKinsey & Company, 2019).

The interest is not unfounded. Transport is a large part of the world GDP spending and the prospect of attracting new user groups (e.g. children and others without a driver's license) may yield gigantic profits for the companies that realise the technology (Fagnant and Kockelman, 2015). Furthermore, many proponents envision the transition from private car usage to shared taxi services, where profit is made from transport rather than selling the product 'car', leading to a disruption of current business models (Becker et al., 2020; Marsden and Reardon, 2018).

However, the initial expectations of a quick technological breakthrough has been thwarted by the complexity of the technology, and the forecasts of expected year of technological maturity and widespread adoption ranges vastly (European Commission/Directorate General for Mobility and Transport, 2020; Martínez-Díaz and Soriguera, 2018; Tabone et al., 2021). The optimistic worldview of societal advantages has also been questioned during the last years, with opponents questioning the sustainability of self-driving technology which could lead to increased congestion, pollution and car-centric cities (Faisal et al., 2019; Marsden and Reardon, 2018; Milakis et al., 2017).

Research into the high-level impacts of the technology has almost exclusively focused on the self-driving *car* (Marsden and Reardon, 2018), but public transport could also be heavily influenced (Azad et al., 2019). This thesis tries to fill this research gap by focusing on the impacts of self-driving technology on public transport. For especially bus traffic, public transport authorities could make substantial savings as the bus driver constitutes around 50 % of the cost of operations (Bösch et al., 2018), funds that could be spent on improving public transport overall or reduce financial burdens.

The methods previously used to investigate self-driving technology has been diverse, ranging from demonstrations and driving simulators to surveys and field experiments (Harb et al., 2021b), philosophical approaches (Sparrow and Howard, 2020) or letting people use cars with drivers, freeing them of the driving task (Harb et al., 2021a; Johansson et al., 2021; Wadud and Huda, 2019). Within this thesis, I use so called four-step transport models, which have a long history of use within the transport field (Boyce and Williams, 2015; Curtis et al., 2021; Flyvbjerg et al., 2005; Johari et al., 2021). But these models are faced with new problems and may need to be adapted to new modes of transport, for example cars driving empty to pick up a passenger or several travellers sharing a vehicle (Friedrich et al., 2018).

The approach of using four-step transport models to draw conclusions of self-driving vehicles has been used extensively previously but almost exclusively for the car (Soteropoulos et al., 2019), overlooking the potential for public transport companies to increase their service offering. This thesis explores self-driving technology within the public transport sector using four-step transport models.

1.1 Terminology

This section describes the main terminology used within this thesis.

1.1.1 Self-driving, driverless, autonomous…

As noted by e.g. Kassens-Noor et al. (2021) and Shladover (2018), multiple terms are used to describe vehicles that operate to some extent without a human driver. The plethora of terms is not helpful, especially since many authors are referring to partly different mechanics. As Gandia et al. (2019) showed in the bibliometric survey, various variants of the expressions *autonomous*, *automated*, *self-driving*, *driverless* and *intelligent* are used throughout the field (Gandia et al., 2019). *Unmanned* seems to be used to some extent as well, but more in military research (Durst et al., 2018). The term intelligent is notable as it is quite broad and may also refer to other types of technology, such as anti-lock brake systems (Mauer, 1995), GPS use (Zito et al., 1995) or communication protocols (Singh and Kim, 2018), and I therefore find it to be less useful.

The terms self-driving and driverless both indicate that vehicles do not have human driver in control, i.e. a complete transfer of control to a machine. Meanwhile, the term autonomous indicates that the system is capable of functioning without outside interference, similar to the word automated. However, autonomous and automated could apply to a variety of tasks, such as automatic transmission of gears or windshield vipers autonomously reacting to rain. The terms self-driving and driverless are therefore somewhat more specifically referring to the (complete) driving task.

Within this thesis, I use the term 'self-driving' which is more commonly used (Gandia et al., 2019) rather than driverless. Furthermore, I find the term to be more easily understood by laymen, and as my research is primarily targeted towards practitioners (mainly public planners), I prefer a term that is more easily understood.

Within the field of self-driving technology research, the primary scale used for different levels of "driving automation" is the standard by SAE International (2021). This scale is divided into six levels:

- Level 0: The vehicle has no autonomy.
- Level 1: Driver assistance, such as cruise control commonly used in cars today.
- Level 2: Partial driving automation, where the vehicle is capable of handling itself, but the driver needs to continuously supervise the vehicle (this is the stage currently offered by companies offering "self-driving" capabilities).

- Level 3: Conditional driving automation, where the vehicle may be completely in control and no driver is needed. However, unanticipated events may result in the vehicle prompting a driver to take back control at any point and with short notice.
- Level 4: High driving automation, where the vehicle can handle all situations. However, one way of handling a situation may be that the vehicles stops (in a safe way) and requests a driver to take control at a time of his/her choice.
- Level 5: Full driving automation, where the vehicle can handle all road conditions and any events that may occur during driving.

In practice, a vehicle capable of SAE level 5 may never be fully achieved, as new types of events may occur for vehicles that prompt human input on how to handle the situation (Axelrod, 2019). Drivers also fulfil a large set of tasks that are not driving, such as itinerary planning (Pakusch et al., 2021) and fault handling (Flämig, 2016). Public acceptance of these vehicles (Gkartzonikas and Gkritza, 2019) and their interaction with society in general (Epting, 2019; Hopkins and Schwanen, 2018; Hultén et al., 2021; Marsden and Reardon, 2018; Sparrow and Howard, 2020) are areas of much research as well, further complicating the term self-driving.

Within this thesis, I explore vehicles of very high self-driving levels (level 4 or 5), as well as assuming a high levels of public acceptance and integration into society. At this point, the advantages to authorities are most apparent, as the cost of drivers are reduced substantially. Paper C also states more explicitly the assumed level of human interaction in the driving role.

1.1.2 First and last mile transport

One aspect of self-driving technology is the idea of the self-driving taxi, shipping people from door-to-door without the need of transfers (or walking to the nearest bus stop). Within the sub-research field of self-driving public transport, the prospect of replacing bus lines of low utilisation rates with first and last mile services has emerged as a potential for increasing the attractiveness of public transport in areas of low accessibility (Chee et al., 2020; Scheltes, 2017; Yap et al., 2016), further described in Section 3.2. This is usually referred to as “on demand transport” (Pettersson, 2019; Shen et al., 2018) or “demand responsive transport” (Azad et al., 2019). However, these names bare a resemblance of paratransit or taxi systems currently widely available. A commonly used term is also “first and last mile transport” (Zubin et al., 2021), which is the term I choose to use in this thesis, as it primarily describes the type of operational area that the service is intended for.

1.1.3 Four-step transport model

The method of inquiry within this thesis are so called four-step (or stage) transport models, however this is a term which is not universally used. The term refers to the four sub-models used, from demand generation to route choice (de Dios Ortúzar and Willumsen, 2011; McNally, 2008). Four-step transport models usually use macroscopic flow modelling as part of the last step, a term used to differentiate from two other common models – microscopic and mesoscopic (see Burghout et al. (2004), Johari et al., 2021 and van Wageningen-Kessels et al., 2015 for three overviews). Meanwhile, MATSim, a popular transport model has both macroscopic, mesoscopic and microscopic modelling options (Horni et al., 2016).

Within Section 2 I describe more in-depth the modelling framework, which more explicitly states how the models calculate transport behaviour.

1.1.4 Different levels of implications

The general research approach (Section 1.4) I have used within the papers in this thesis is to use the results of research on individuals or groups of people, or vehicles or groups of vehicles. These results are used as input to the macroscopic transport models to investigate the impacts on the transport system or societal level, see Figure 1. This is the strategy used in several research activities at the Integrated Transport Research Lab at the Royal Institute of Technology, where I have done my research so far (Integrated Transport Research Lab, 2021). The approach is similar to previously used frameworks, such as the approach of Milakis et al. (2015) who used the so-called ripple effects model. Milakis model divided implications of self-driving technology into three levels ("ripples"), with societal impacts in the outermost level (the model is mainly centred on the chronological dimension). Likewise, Taiebat et al. (2018) divided impacts into four levels – vehicle, transport system, urban system and society and tried to draw on conclusions from the vehicle level to society in general.

Within this thesis I use the two concepts 'low-level impacts' and 'high-level impacts'. These terms are not sharply defined and it may be difficult to distinguish which of the terms a specific impact should belong to.

With low-level impacts, I refer to impacts on a personal level or within a group of individuals. Or, similarly, to impacts for an individual vehicle or a group of vehicles and their interaction. These impacts can for example be the interaction between vehicles affecting the average speed possible on congested highway or how individuals perceive a bus ride when no driver is present.

With high-level impacts, I refer to overarching impacts on the general transport system or societal impacts. These impacts can for example be CO2-emissions from the entire vehicle fleet, general accessibility within a city or the total number of accidents occurring in Sweden.

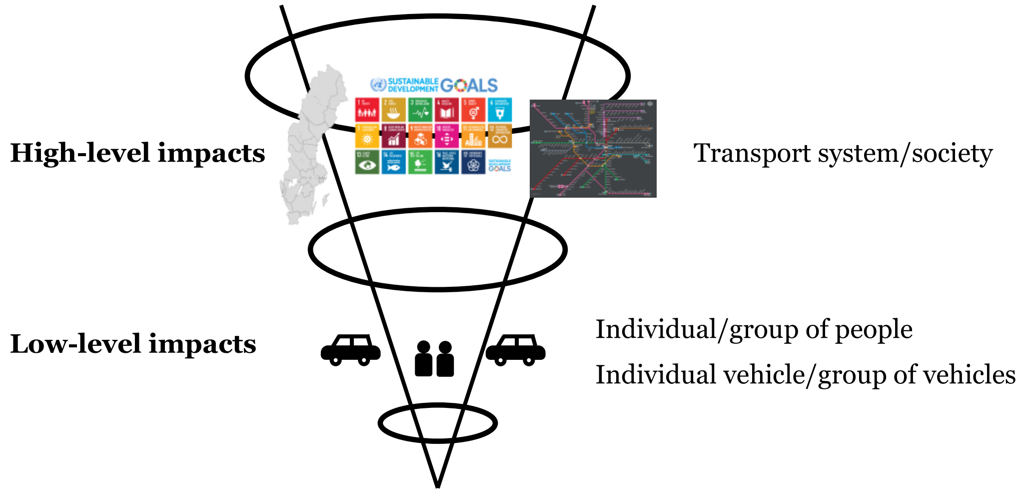


Figure 1. Illustration of high- and low-level impacts.

1.2 Research objective and research questions

The objective of the research leading up to this licentiate thesis has been to give an overview of the high-level impacts of self-driving technology for public transport, of four-step transport models and how four-step transport models can be used to increase our knowledge of what self-driving technology might entail, especially for public transport.

More specifically, during my research I have had the following research questions that have guided my work and is part of this thesis.

1. Which potentials for public transport can self-driving technology have?
2. Which parameters in four-step transport models need to be adjusted to simulate self-driving public transport?
3. Which implications would self-driving public transport have for the transport system?

In this thesis I mainly discuss impacts for passenger transport, i.e. freight transport is not within the scope. The field of self-driving technology has previously mostly been explored in the context of highly developed countries, with China as the main exception (Gandia et al., 2019). This thesis is unfortunately no exception and the conclusions within this study should be limited to explaining high-level impacts within developed countries, here referred to as OECD countries.

1.3 Reflections on the research process

My background is constituted of ten years of experience within the field of public transport, working with high-level planning and forecasting future travel demand, hence I should be considered a 'native' (Creswell and Creswell, 2018) within the transport field. Going into the work on this research during the fall of 2018, the main question I posed was related to the relevance (or even existence) of public transport in the future. Visions of taxi cars abundantly available to anyone questioned if public transport was just an outdated form of transport which would be replaced by self-driving taxis or pods with door-to-door transport.

When I began to investigate this topic, first through reviewing the existing field and later through my own experiments, it increasingly became apparent that self-driving technology held a lot of promises but that it also could lead to substantial problems. Milakis et al. (2017) was an early inspiration with their overview of societal impacts and the questions I discussed with colleagues became more nuanced, delving into how and where self-driving technology could change transport and society overall. Congestion would not be non-existent in cities (Ye and Yamamoto, 2018) and the commercial viability of upholding a taxi service in rural areas would likely be low (Meyer et al. 2017).

Furthermore, early talks with my supervisors and with professionals from MTR Nordic and SL, the Stockholm Public Transport Authority, made it apparent that public transport could make significant gains related to the implementation of self-driving technology, with the bus driver constituting about 50 % of overall costs (Mojdeh et al. 2019), and that a change in the organisational aspects of planning could lead to new types of public transport (Pernestål Brenden and Kottenhoff, 2018). This piqued my interest further into how this new technology could enhance current services. This ultimately led to the writing of Paper A and B.

After my initial study, I had become increasingly interested in understanding the 'size' of different impacts. A lot of studies investigated the effects of individual aspects of self-driving technology, e.g. the potential to reduce accident rates (Fagnant and Kockelman, 2015), technology costs (Wadud, 2017), increases in CO_2 emissions (Wadud et al., 2016) or accessibility gains (Soteropoulos et al., 2019) but I could find few studies that tried to assess the scale of different aspects, e.g. if the costs associated with CO_2 emissions would outweigh the benefits of increased accessibility. Getting conclusive results would be infeasible, but I was interested in trying to get a sense of scale for different impacts. This interest led to the writing of Paper C, where I investigated the overall impacts of a self-driving bus service. In Paper C, I could for example conclude that accident reduction would not be a major impact, even considering quite optimistic rates of accident reductions.

However, when writing Paper C, and especially the literature overview in the introduction, it became increasingly clear that only a handful of previous papers had used a comprehensive framework with the intent to investigate 'all' impacts of the introduction of self-driving technology. Hence, Paper C revolves around comparing different frameworks, and the study of the bus service is used as an example, rather than being the focal point of the paper.

1.4 Research approach

The research approach is similar in the projects that led to the three included papers, described in Figure 2. The two research projects were *Självkörande fordon och* *kollektivtrafik – hot och möjligheter* (grant number LS 2017-0585, henceforth abbreviated as the SLL SDV study) and *Självkörande eldriven stombuss på Tvärförbindelse Södertörn – en skalbar förstudie* (grant number TRV 2019/118695, henceforth abbreviated to the Södertörn project).

In each project I began by conducting a state-of-the-art of previous similar work and approaches. This process was more extensive within the SLL SDV project since I had less experience working as a researcher. This step was followed by, and was to some extent interconnected to, development of scenarios for the two projects. This step was done by conducting workshops and interviews with experts within the transportation field in Sweden to gauge the main potential and which scenarios would be deemed interesting to further investigate. See also Section 4.1 that further describes this process.

The SLL SDV project also contained a step for choosing an appropriate model to perform the study, which ultimately concluded in the use of the Sampers model. With the Södertörn project, this model was chosen early due to 1) my experience with using it, 2) its integrated cost-benefit module SamKalk and 3) due to the assistance available from the STA (e.g. availability of licenses and practical support).

For both projects, the scenarios were applied to the Sampers model, further detailed in Section 4.2. Lastly, the result was analysed (mostly using Microsoft Excel) and written up into the three papers.

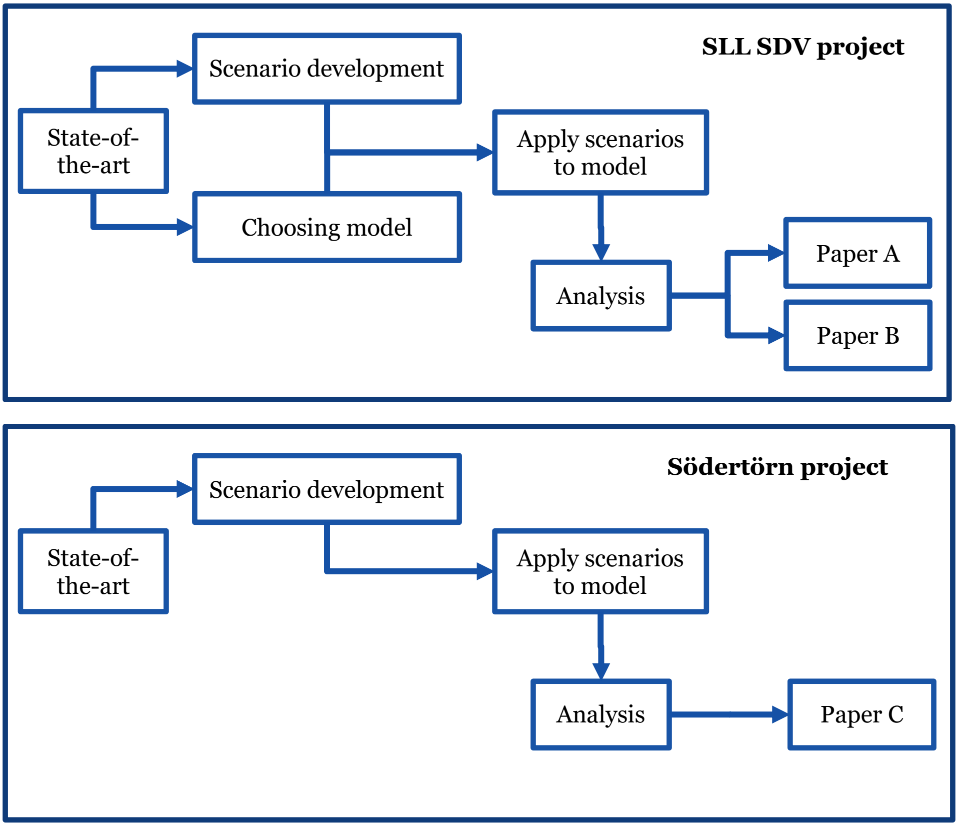


Figure 2. Research approach overview.

1.5 Outline of the thesis

Following this introduction, Section 2 outlines the history of traffic flow models, more specifically four-step transport models and a description of the Sampers model used within the included papers. Section 3 gives an overview of self-driving technology – previous research and especially previous similar attempts of using four-step transport models to investigate the high-level impacts of self-driving technology. Section 4 describes the research methods and the process I have applied to answer the research questions. Section 5 shortly summarises the papers, followed by Section 6 where I outline the key findings of the research papers in relation to the research questions. In Section 7 I discuss the limitations and point to future research needs within the field. Finally, Section 8 concludes the thesis.

2 Overview of four-step transport models

This section is an overview of four-step transport models and the different types of models used. In Section 2.1 I describe how four-step transport models work, their advantages and disadvantages and give an overview of how macroscopic models calculate transport behaviour. Section 2.2 further describes the Sampers model, used within the three papers.

There are numerous models of different types for evaluating transport or mobility, e.g. system dynamics (Shepherd, 2014), econometric models (e.g. Andersson and Ivehammar (2019) and Wadud and Mattioli (2021)), qualitative models describing people's preferences (Guo et al., 2020; Musselwhite et al., 2014; Zmud et al., 2013) or conceptual models of transportation as cultural artefacts (Holden et al., 2020; Sovacool and Axsen, 2018; Urry, 2004). Within this thesis, I focus on four-step transport models. These emulate large areas and large numbers of people and provide descriptions of their journeys and how travellers interact with each other.

The first attempts to emulate transport behaviour stems from the early 1950s and 1960s in the US from research performed Greenshields (1934), Chandler et al. (1958), Gazis et al. (1959) and Lighthill and Whitham (1955) describing drivers' behaviour in relation to other road users, named "car-following models". Since then, numerous different approaches have developed, increasingly taking advantage of the growing computer power to use more complex models (Boyce and Williams, 2015).

2.1 Four-step transport models

Four-step models emulate the transport system of whole cities or regions with the intent to capture behaviour at an aggregated level, e.g. measuring congestion on a highway, the induced demand of transport from increased accessibility, the number of expected passengers on a major metro line or the total CO_2 emissions from a region. Four-step models have been in use since the 1960s (Boyce and Williams, 2015; Weiner, 1997) and are today widespread, at least in the OECD (Cruz and Sarmento, 2020; Flyvbjerg et al., 2005; Horowitz and Farmer, 1999).

The comprehensive approach of four-step transport models comes with the need of simplifying the behaviour of individual citizens, instead aggregating individuals into groups or areas of residence. The models assume that travellers with similar background behave similarly and calculates travel behaviour through regression analysis of travel surveys made previously. Furthermore, the models usually cover a 'normal' weekday (ignoring or averaging out variation throughout the year). Therefore, four-step transport models are generally most useful for answering overarching questions regarding the system or modelling large infrastructure solutions, rather than describing how many people would traverse a certain smaller bus line in a city or the day-to-day variation over a workweek (McNally, 2008).

The four steps of the model, seen in Figure 3, are:

- Trip generation
- Trip distribution
- Mode choice
- Route choice

These four-steps roughly correspond to the questions:

- How many trips will be made?
- Where should the trips go?
- Which mode of transport will be used?
- Which route will be used?

In reality, all these questions are interrelated: for instance, choosing to make a trip depends on the routes available, and four-step transport models usually have feedback loops to incorporate congestion which affects travel times when many citizens decide to choose the same road.

The models generally have a number of exogenous factors affecting travel behaviour such as demographics (e.g. age cohorts and education levels), economy (e.g. disposable income and fuel cost), land use (e.g. where workplaces are situated) and descriptive data of the transport network (e.g. the road network and public transport services). These factors are linked to zones describing the region represented in the model (de Dios Ortúzar and Willumsen, 2011).

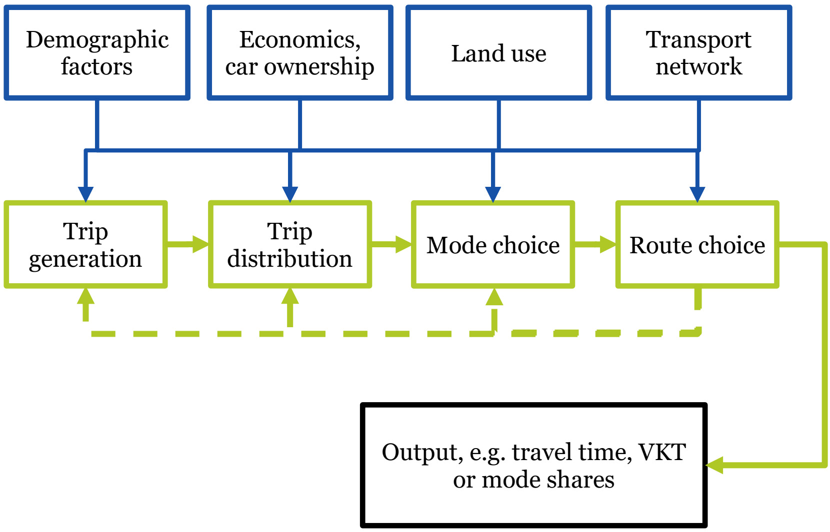


Figure 3. Overview of the four-step transport model. Dark blue are exogenous factors affecting the model, whereas green boxes indicate the core of the model with arrows indicating output affecting the next step of the model. Dotted lines are feedback loops that may exist and may be run incrementally, depending on the specific model characteristics.

2.1.1 Trip generation

The first step of a four-step transport model is generating trips, i.e. determining how many trips travellers make during the modelled time period. The demand for trips is governed by many factors, such as price of transport, accessibility to different workplaces and services, demographic factors and quality of services (Profillidis and Botzoris, 2018). Calculating the demand is usually divided into attraction and production of trips, i.e. how many trips are expected to end in the zone (e.g. a workplace) and how many trips originate within a zone (e.g. a residential area). Furthermore, this calculation of demand is usually done with different trip purposes in mind, emphasising that the number of trips to school and workplaces is mostly dependent on larger trends (McNally, 2008). In contrast, leisure trips are likely to be more dependent on the accessibility of leisure activities, which is partly stipulated by transport related policies (Burns and Golob, 1976).

This step of the model is usually represented by some form of regression model based on travel survey data collected within the modelled region or based on data on e.g. traffic counts or travel behaviour. GPS data are gradually more used to increase accuracy and combat low response rates, but travel surveys are still the main form used (Huang et al., 2019; Vij and Shankari, 2015).

Trip demand is assumed to follow the general economic theory of supply and demand, where the relationship is in general non-linear, see Figure 4. This implies that e.g. a decrease in travel time by 10 % would not correspond to a fixed demand change, instead that changes to travel opportunities depend on the current travel behaviour. I.e. a person with very limited travel opportunities would likely increase their travel demand substantially by even small changes to e.g. ticket price, whereas a person who travels a lot would not make more trips.

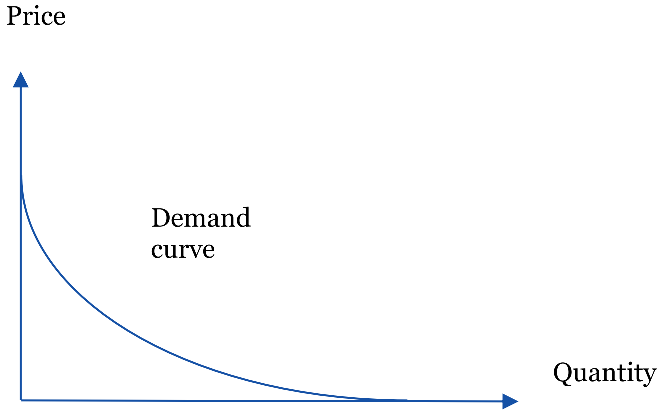


Figure 4. General demand curve within economics.

2.1.2 Trip distribution

The second step of the model revolves around determining where travellers want to go, producing so called origin-demand matrices. The process involves matching attraction and production of trips generated in the previous step, usually by measuring the 'distance' between two zones using foremost, travel impedance measured in e.g. travel time or generalised cost. The resulting pairing of attraction and production is done by the so called 'gravity model' (McNally, 2008; Voorhees, 2013), assuming that different areas will be similar to gravity fields so that travellers are pulled towards or are more likely to choose destinations that are close and/or big, thus having larger influence on the choice.

This can be exemplified by shopping for groceries. Citizens are likely to choose a convenience store close to home, but large malls also hold notable attractiveness since they may be cheaper and have a larger variety of goods. However, particular stores that are not in the direct vicinity may also attract attention due to e.g. special products. As such, all 'attraction' facilities have some probability of attracting a certain citizen.

Moreover, the trip distribution model is also subject to other types of variables than travel impedance, such as gender, age or economic income.

2.1.3 Mode choice

The third step entails distributing trips between the different modes of transport available in the model. In a passenger transport model, these usually consist of car, public transport, walking, and sometimes cycling. Some models add other modes of transport, such as boats, car-pooling, taxis or air travel, depending on the model and the context of the modelled area. For each zone-to-zone trip calculated, this step distributes how many trips are made by each travel mode. This is done through calculating the travel impedance for each mode and zone-to-zone pair and then calculating the likelihood of travellers choosing one mode or another, usually by the use of a nested logit model (McNally, 2008).

As with trip generation and trip distribution, socioeconomic and cultural factors are usually integrated into the model, accounting for differences between different travellers.

2.1.4 Route choice

The fourth and final step calculates the routes chosen by travellers for each zone pair. The primary assumption is that travellers choose the route with the least travel impedance, usually measured as generalised cost, but also taking into account factors such as a preference for walking instead of taking the bus (Bovy, 2009).

The calculation of route choice has traditionally been viewed as a problem primarily for car traffic, where congestion leads to feedback loops influencing which route is chosen (de Dios Ortúzar and Willumsen, 2011). Under the assumption that each traveller choosing the option with the least travel cost, one might expect that all travellers would choose the main streets of cities, which would lead to traffic jams. As an example, consider Figure 5, showing a simple example of two alternative routes, one with a considerably longer travel time but also higher capacity. In reality, route B would become congested and likely have substantially longer travel time than the stipulated 10 minute. Therefore, a share of the travellers would then choose Route A, and after several iterations reach an equilibrium with identical travel times for both routes.

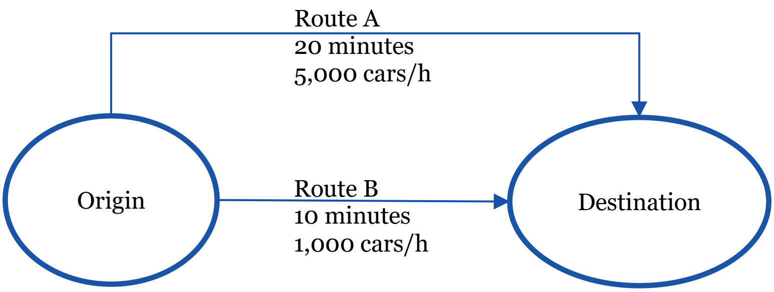


Figure 5. Example of two alternative routes, travel time and capacity.

Congestion, and the resulting travel time, is calculated differently in microscopic, mesoscopic and macroscopic traffic assignment. Microscopic transport models try to simulate the behaviour and interaction of single agents, such as cars or pedestrians, in time frames that come close to human perception (e.g. a time-step of $1/10^{th}$ of a second). These models generally have small geographic extent, for example covering a highway stretch, a train station or a small road network. Microscopic models are widely used with commercially available applications such as Vissim or Aimsun (Burghout et al., 2004).

For macroscopic traffic assignment models, congestion on links are calculated using volume delay functions (VDF), stemming from research on fundamental transport flow diagrams called the Lighthill-Whitmans-Richards model (Johari et al., 2021; Lighthill and Whitham, 1955; Richards, 1956) (See Figure 6 for an example). These describe the relationships between number of vehicles, their behaviour, flow of traffic and ultimately the travel time on the described link. The relationship is usually described using a simple equation, such as Equation 1:

$$t = t_0(1 + a * (\frac{q}{q_{max}})^b \qquad \text{(Eq. 1)}$$

Where t denotes the calculated travel time, t_o the free flow travel time, q the flow (number of vehicles), q_{max} the maximum capacity of the link and a and b denote context dependent attributes. a and b could depend on a number of factors, such as the road type, number of lanes and culturally dependent factors (e.g. that people drive slower on narrow roads).

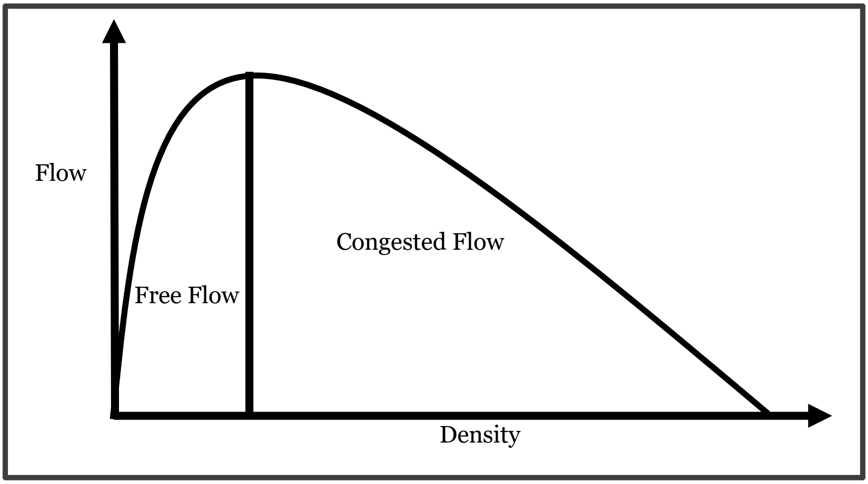


Figure 6. The relationship between density and flow and an indication of when congestion will occur.

Mesoscopic transport models use a combination of these two approaches, where individual cars are still modelled but treated as a group using VDFs on links (Burghout et al., 2004). They generally investigate the behaviour of bigger areas, e.g. the traffic behaviour of all vehicles within a larger neighbourhood, making simplification of individual agent's interaction with their surroundings. These models usually cluster individual vehicles into larger groups to reduce operational complexity (van Wageningen-Kessels et al., 2015).

2.2 Sampers

In the three papers in this thesis, I have used the Swedish National Transport Model Sampers, which is owned and developed by the Swedish Transport Administration (STA) (Beser and Algers, 2002). Sampers covers regional and national travel in Sweden, was introduced in the late 1990s and has been in continuous development during the last 20 years with new versions released every 2 or 4 years (Kristoffersson et al., 2018; Trafikverket, 2020a). The model is mainly used for assessing the impacts of various infrastructure projects for the national transport plan (Witzell, 2021) but has also been used to investigate policy changes, most notably effects of congestion charging (Börjesson et al., 2014; Eliasson, 2009; Jansson and Lang, 2009). The model is generally viewed as useful and fit for its purpose as well as modelling real world traffic in a sufficient manner (Andersson et al., 2017; Jonsson et al., 2011; Sweco Society AB, 2018), albeit with more general critique on how the model is actually used within the STA (Curtis et al., 2021; Witzell, 2021).

Sampers is based on two travel surveys from the 1994-1996 and 1998-2001, covering Swedish inhabitants over the age of 5, as well as some cross-national travel from Denmark and Norway. Additionally, international travel is added as an exogenous factor, as well as e.g. truck traffic which may impact congestion. All major roads, as well as all public transport services and large parts of sea transport is included in the model.

Sampers is divided into six sub-models. A national model covers long-distance travelling in Sweden and neighbouring areas in Norway, Finland and Denmark, while five regional models cover various areas in Sweden – Palt (northern Sweden), Skåne (the southernmost county of Sweden and its neighbouring counties), Sydost (south-eastern Sweden), Väst (the greater Gothenburg area) and Samm (Gotland and Mälaren Valley, incorporating Stockholm) (Trafikverket, 2020a). Within the three papers, I have made changes to the Samm models from 2018 (paper A and B) and 2020 (paper C) for Stockholm County.

The Samm models consists of 10,455 zones, where Stockholm County constitutes 1,364 zones. The zone layout has been designed by demographist at Statistics Sweden and generally follow street patterns, have a somewhat homogenous land use (e.g. only industrial buildings or sparsely populated area) and are somewhat similar in size of population, meaning that zones are generally small in Stockholm inner city (<0.5 km^2) and large in rural areas (>100 km^2).

Compared to a typical four-step transport model, Sampers integrates the first three steps (Trip generation, Trip distribution and Mode choice) into a nested logit model. Sampers calculates demand for five different trips purposes – work, school, social trips (e.g. visiting a relative), recreation and other. In addition, business trips are calculated in two separate ways depending on their starting location.

Non-business trips also handle trip chaining (except work trips that are not assumed to have trip chaining), such as stopping for groceries on the way home. See Figure 7 for an overview of Sampers way of calculating number of trips, their destination and mode choice.

Sampers includes five modes of transport – car, car as passenger, public transport, cycling and walking, where *car as passenger* describes a passenger in a car who is not driving and accompanying the driver to the destination (e.g. a family riding together to a destination).

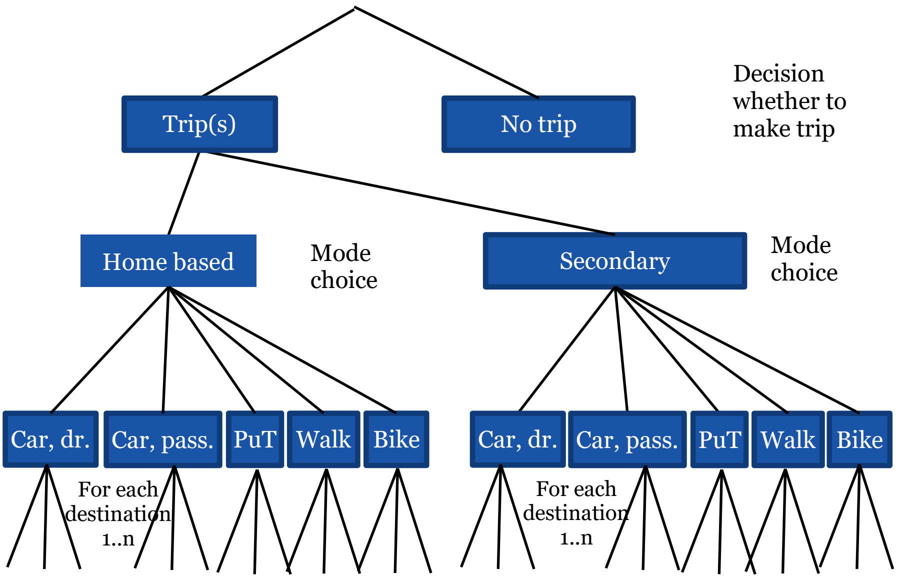


Figure 7. Description of the Sampers model for non-work trips. Image recreated from Algers (2004). The following abbreviations are used: Car, dr = Car, driver; Car, pass = Car, passenger; PuT= Public transport.

The fourth step in the four-step model, Route choice, is made separately for four time periods – morning peak hour (approx. 06:30-07:30), mid-day (approx. 09:00-15:00), afternoon peak hour (approx. 16:30-17:30) and evening (approx. 19:00-22:00). In this step, the demand for trips with the different trip purposes are integrated to capture congestion. The route choice, also called traffic assignment, is made with INRO's software Emme which calculates travel times per link. This step generates so called log-sums (de Jong et al., 2007), used as a measurement of accessibility. To capture the effect of accessibility of each zone, both to capture demand variation as well as mode choice depending on accessibility for each mode, these results feed back to the nested logit function describing the first three steps. In practice, the model is usually set at 'normal' traffic levels and then has several iterations to reach equilibrium of route choice between different routes, as well as equilibrium in overall demand.

For the different transport modes, only the public transport mode and car mode are modelled within the route choice module, whereas cycling and walking is considered to have a fixed speed and use the road network. For traffic assignment, Sampers uses INRO's software Emme, with the car mode using the Path Based Traffic Assignment method, adapted from projected-gradient method (Florian et al., 2009). This assignment method was developed to solve large-scale problems and focuses on paths between all origin-destination pairs, aiming to create equilibrium between the different paths available. Within the method, all paths are adjusted simultaneously to reach the average travel impedance (Florian et al., 2009).

For public transport, Emme uses the assignment method Standard Transit Assignment, adapted from the method Optimal Strategy (Spiess and Florian, 1989). Standard Transit

Assignment is a headway-based assignment which calculates averages for waiting times, in comparison with timetable-based assignments which calculates exact waiting times. Headway-based assignment have the advantage of not requiring detailed time-tables, making them more easy to use practically (Rydergren, 2013). The method takes travel impedance into account, e.g. transfer penalties, waiting times and walking time and distributes travellers to different paths according to probabilities calculated by their total impedance.

In addition, for Paper A and B, Visum was used for traffic assignment of public transport, using the headway-based assignment method based on the work of Hasselström (1981, as cited in Rydergren, 2013), assuming that travellers have knowledge of the entire network, in comparison to the Optimal Strategy method where the travellers have limited knowledge (Rydergren, 2013).

However, in general, these two algorithms produce similar results and seem to be more sensitive to dissimilarities in applying the network design to the model (Hildebrand and Hörtin, 2014; Trafikförvaltningen, Region Stockholm et al., 2021).

Furthermore, Sampers is connected to a separate module for computing cost-benefit calculations called SamKalk (Trafikverket, 2021), used in Paper C. SamKalk uses state-of-the-art valuation for e.g. value of time reductions, accidents costs, infrastructure maintenance and discount rate (Trafikverket, 2020b).

3 Self-driving technology – History and research overview

This section provides an overview of the history of self-driving technology development (3.1), the low-level implications that have been identified regarding the performance of the vehicle (3.2) and previous research that have used transport models (3.3).

3.1 History

As noted by (Weber, 2014), the need of constructing machines to manage the driving of vehicles arouse with the introduction of cars. Horses, the primary mode of transport, could be compared to at least a SAE level 4 capability, and sailboats used the auto-tiller or usually had plenty of people on board (Weber, 2014). Aircrafts have had autopilot features for large part of their history and automatic trains have been around since at least the 1960s with the opening of London's Victoria Line (Wikipedia, 2021). However, road transport generally presents more technological (and physical) obstacles than air, water or rail environments.

The (current) promise of self-driving car technology was initiated by Google's demonstration of their vehicle during early 2010. They showed a car that seemingly could manoeuvre in normal traffic conditions, albeit with a security driver on board at the early stage. A newspaper article in The New York Times heralded large benefits to society:

> "Robot drivers react faster than humans, have 360-degree perception and do not get distracted, sleepy or intoxicated, the engineers argue… The engineers say the technology could double the capacity of roads by allowing cars to drive more safely while closer together. Because the robot cars would eventually be less likely to crash, they could be built lighter, reducing fuel consumption."

(Markoff, 2010)

However, the public demonstrations of Google had been preceded by at least half a century of work in sensors, automatic control and computational processing. As early as the 1939 Futurama exhibition, cars running on "automatic radio control" were envisioned (Baker and Villa, 2017). General Motors and the Radio Corporation of America began experiments in the 1950s on a highway stretch with experimental cars that detected electric currents built into the highway and could keep the car in the lane. This development peaked with the design of the Firebird concept cars, but never managed to materialise to a working concept due to technological limitations (Meyer and Beiker, 2014). In Japan, researchers at the Tsubuka Mechanical Engineering Laboratory managed to build a car in 1977 that used two cameras to process images of the road and used white street markers to detect the roadway. In the 1980s and 1990s, a team led by Ernst Dickmann succeeded in having cars drive up to 100 km/h on an empty highway stretch guided by cameras, which was followed with vehicles able to manage normal traffic conditions (Bender, 1991; Brodsky, 2016; Computer History Museum, 2016).

In 2003-2007, the U.S. Defense Advanced Research Projects introduced a series of "Grand Challenges" with various competitions to develop self-driving vehicles. These competitions brought popularity into the concept of self-driving technology and managed to show that the technology may soon reach maturity. Google made especially ambitious investments into the process, attracting a lot of talent from academia and culminating in their 2010 demonstration (Brodsky, 2016; Meyer and Beiker, 2014).

Numerous companies, both manufacturers and data-driven companies, have since Google's demonstration made multi-billion euro investments into the technology (McKinsey & Company, 2019), even though the initial hype of self-driving cars seemed to have dampened somewhat (Goasduff, 2021).

3.2 Low-level implications of self-driving technology

Establishing the implications of self-driving technology has been a growing research field during the 2010s, with early research focusing on effects for car design and requirements to enable the technology (Gandia et al., 2019; Harb et al., 2021b; Milakis et al., 2017). The prospect of understanding how the technology may impact people and society in general began during the second half of the decade. Important work were made by several authors in Meyer and Beiker (2014) on summarising previous research and exploring legal, ethical, energy, emissions and driver interaction, as well as Fagnant and Kockelman's (2015) paper on policy implications for the U.S. government.

Understanding the impacts of self-driving technology may be done in various ways. As mentioned previously, Milakis et al. (2015) developed the 'ripple effects' model, with effects propagating from vehicle behaviour changes. In contrast, Taiebat et al. (2018) used the vehicle as their starting point of understanding impact, exploring vehicle operation, vehicle design, platooning and electrification. However, according to my understanding of the field of self-driving technology, there are two main areas that could be affected by self-driving technology: how the technology is perceived by people using the service; and changes in design and behaviour of the vehicle.

3.2.1 Human perception of riding in a self-driving vehicle

Self-driving technology may be lauded by media and manufacturers (Marsden and Reardon, 2018), but test subjects and the general population seem to have a more mixed view of how they would be affected. Gkartzonikas and Gkritza (2019) and Harb et al. (2021b) reviewed the current research on how self-driving services may be perceived and found substantial variation. Some respondents in experiments were positive to the prospect of not having to drive the car, instead focusing on other activities, whilst others expressed concern about safety, both the actual safety and the feeling of lack of control (Gkartzonikas and Gkritza, 2019; Harb et al., 2021b). In other research, several respondents have brought up the fact that they like driving, preferring to steer the vehicle instead of passively being toured to their destination (Hardman et al., 2019). Furthermore, it is likely that not all tasks related to driving may be automated, such as cleaning, helping travellers or fault handling (Becker et al., 2020; Flämig, 2016; Pakusch et al., 2021).

Similarly, the acceptance of the general public may not be unproblematic. In the 2020 Eurobarometer, 76 % of the respondents across the EU stated that they would not be comfortable travelling without any human supervision, and only about 61 % would be willing to travel if a human remotely supervised the journey (European Union and Kantar Belgium, 2020). Even though safety may be a key advantage proposed by advocates for self-driving technology (Marsden and Reardon, 2018), this view does not seem to be widespread among the general public.

The key findings regarding how people may perceive using a self-driving vehicle are mainly related to how they experience riding such vehicles. A key component of understanding human choice and preference for different modes of transport is the Value of Travel Time (Dubernet and Axhausen, 2020; Nordström, 2020) (VoTT), which is used in transport models to represent people's trade-offs between travel time and monetary cost.

The perception of how people would experience riding in a self-driving car has been the subject of much research (Kolarova et al., 2019; Kyriakidis et al., 2015), with proponents pointing at the reduction in mental load and the possibility for drivers to instead focus on productive activities (or reproductive activities (Cohen and Hopkins, 2019)). Some authors remark that the vehicles could have a smoother driving behaviour or that the use of vehicle-to-vehicle communication could reduce the number of stops and accelerations (Milakis et al., 2017).

However, other researchers have concluded that it might be hard to perform other tasks in a moving car, due to e.g. car-sickness (Diels and Bos, 2016; Jones, 2019; Le Vine et al., 2015) or that people who do not drive today are usually not using their time very productively (Wadud and Huda, 2019).

Similarly, travellers using public transport experience varying degrees of comfort, from train rides which most people find to be soothing, to stressed bus drivers making sharp turns and quick brakes (Hansson et al., 2019). Smoother bus behaviour could mark an attractive option for many travellers, but it is uncertain how big this effect would be, if the bus would still operate in mixed traffic (see Paper C).

In conclusion, how passengers would perceive their time in a self-driving vehicle remains uncertain.

3.2.2 Vehicle design and behaviour changes

The second area affected by self-driving technology are changes to vehicle behaviour. Google's initial attempts to driving on public roads have led to several accidents, however the majority of these seem to have been caused by other drivers who misinterpreted the behaviour of the car (Brodsky, 2016). This misinterpretation may be the legal fault of the human drivers, but it is not unproblematic with a car that does not operate as people are used to.

Within this section, I review low-level impacts identified in previous research (see also Paper C), namely changes to:

a) accident rates

b) road capacity and vehicle speed

c) energy consumption

d) the cost of the vehicle

e) type of and price of services

The behaviour of the car is subject to engineering decisions, especially on the level of security, e.g. which speed is deemed appropriate at any given time. As a consequence, various manufacturers and researchers are using different approaches which leads to heterogeneity in actual behaviour on the road (Amer et al., 2017). This heterogeneity affects accident rates (and types) and affects other vehicles speed due to congestion, thus affecting road capacity in general (Amer et al., 2017; Faisal et al., 2019). Therefore, predicting the overall outcome may be difficult.

A potential impact with connected self-driving vehicles is that they could make use of vehicle-to-vehicle or vehicle-to-infrastructure communication, e.g. anticipating that the line of cars in front will break in 0.1 seconds or optimising traffic light (Hoogendoorn et al., 2014; Le Vine et al., 2015; Shladover, 2021; Ye and Yamamoto, 2018). The concept of bus-to-infrastructure communication however is well established and used throughout the OECD, but there are substantial potential to further enhance this feature (Dadashzadeh and Ergun, 2018; Sørensen et al., 2021). Furthermore, smoother travel motions could potentially reduce travel times due to reduced stop duration (see Paper C).

The driving behaviour can also lead to reductions in energy demand, for example through the use of eco-driving or platooning (Wadud et al., 2016) or by more defensive driving behaviour with more stops and accelerations (Islam et al., 2019).

As with most new technology, self-driving vehicles are expected to be costly in their initial introduction but their mid- to long-term cost estimates vary substantially (Andersson and Ivehammar, 2019; Becker et al., 2020; Wadud and Mattioli, 2021). It is likely that the long-term costs gravitate towards the cost of just material and the process of building and maintaining the technology, but when we would arrive at this *long-term* remains uncertain (Wadud and Mattioli, 2021). The introduction of self-driving technology could also lead to reduction in insurance costs and vehicle accident costs, reducing the lifecycle costs of vehicles (Fagnant and Kockelman, 2015; Wadud, 2017).

A feature often described in relation to self-driving technology is the ability for cars to be shared effortlessly due to the vehicles' ability to drive themselves to the next traveller (Bissell et al., 2020; Epting, 2019; Meyer et al., 2017). This service could be used within a household, enabling more frequent use of the vehicle, or as free-floating taxi services that pick up any residents. Using the technology on taxis would cut costs by approximately 2/3 in the OECD (the drivers' salary) but might mean increased costs of tasks that still require human intervention such as fault handling or cleaning (Becker et al., 2020; Wadud, 2017; Wadud and Mattioli, 2021).

Bus services, being already a shared service, could still benefit from autonomous technology, as the bus driver constitutes about 50 % of costs (Bösch et al., 2018, also see paper A-C). For train services, drivers constitute a smaller share of costs (less than 5 % in Stockholm) due to the large investment and maintenance connected to infrastructure. However, drivers and on-board personnel required to increase the service when there is free infrastructure capacity account for about 50 % of the marginal cost of train service operation (i.e. assuming that the infrastructure is already built and maintained) (paper A-C).

Reducing the costs of especially bus services and eliminating the need to plan drivers' itineraries would also increase flexibility and enable the cost-efficient use of smaller routes, including first and last mile services (Paulsson, 2021; Pernestål Brenden and Kottenhoff, 2018).

3.3 High-level impacts implications of self-driving technology

Previous research into high-level impacts of self-driving technology has shown that the technology could lead to changes in emission rates (Taiebat et al., 2018), decreased accident rates (Koopman and Wagner, 2017) and increased inequality (Sparrow and Howard, 2020). In fact, the range of areas affected by self-driving technology is vast. Table 1, which has been adapted from Paper C, summarises the findings identified by previous research, conditioned on the realisation of self-driving technology on a high level.

Table 1. List of high-level impacts. Table adapted from Paper C.

Identified impact areas	Impact	Sources
Vehicle damages	Potential for decrease, albeit uncertain if realistic	(Dixit et al., 2019; Kalra and Paddock, 2016; Koopman and Wagner, 2017)
Injuries	Potential for decrease, albeit uncertain if realistic	(Dixit et al., 2019; Kalra and Paddock, 2016; Koopman and Wagner, 2017)
Vehicle technology costs	Likely high initially, then decreasing over time	(Wadud, 2017; Wadud and Mattioli, 2021)
Infrastructure cost	Uncertain, some authors assume unchanged infrastructure, others increased requirements	(Farah et al., 2018; Kulmala et al., 2019; Lu et al., 2019; Ulrich et al., 2020)

Maintenance costs	Likely increased due to increased technological requirements and tasks currently performed by drivers	(Becker et al., 2020; Kulmala et al., 2019; Nunes et al., 2020)
Operational costs (commercial actors)	Drastically reduced, however likely that new costs will arise, such as increased maintenance and remote operations support	(Andersson and Ivehammar, 2019; Fagnant and Kockelman, 2015; Faisal et al., 2019)
Energy consumption	Likely reduced per kilometre due to more eco-driving, but might increase overall due to induced travel demand and empty vehicle kilometres (cars driving between passengers)	(Taiebat et al., 2018; Wadud et al., 2016)
Greenhouse gases	Likely reduced per kilometre due to more eco-driving, but might increase overall due to induced travel demand and empty vehicle kilometres (cars driving between passengers)	(Taiebat et al., 2018; Wadud et al., 2016)
Pollution	Likely reduced per kilometre due to more eco-driving, but might increase overall due to induced travel demand and empty vehicle kilometres (cars driving between passengers)	(Taiebat et al., 2018; Wadud et al., 2016)
Noise	Likely increased due to induced travel demand and empty vehicle kilometres (cars driving between passengers)	(Horschutz Nemoto et al., 2021)
Health impacts	Likely reduced public health due to increased pollution, noise (see above) and less physical activity	(Faisal et al., 2019; Horschutz Nemoto et al., 2021; Levine et al., 2018; Milakis et al., 2015; Narayanan et al., 2020)
Travel costs for consumers	Reduced due to less costs for taxi and public transport service	(Becker et al., 2020; Bösch et al., 2018; Liu et al., 2017)
Travel time	Decreased due to increased availability to cars	(Milakis et al., 2017; Soteropoulos et al., 2019)
Congestion levels	Mixed, self-driving vehicles are expected to increase road capacity but number of trips increase substantially, increasing congestion. Likely large geographic variation.	(Cohen and Cavoli, 2019; Maciejewski and Bischoff, 2018)
Land use	Self-driving vehicles could reduce the need for parking, likely freeing up space in urban areas. Increased car accessibility would promote more disperse land use.	(Carrese et al., 2019; Gelauff et al., 2019; Hawkins and Nurul Habib, 2019; Kim et al., 2020)
Users' perception	Likely heterogeneous, with some users perceiving the lack of driver as disturbing and less safe.	(European Union and Kantar Belgium, 2020; Gkartzonikas and Gkritza, 2019; Johansson et al.,

	Additionally, would lead to lack of authority presence and ad hoc-problem solving.	2021; Kyriakidis et al., 2015; Paulsson, 2021; Piao et al., 2016)
Cybersecurity	Increased risks due to reliance on IT systems	(Gkartzonikas and Gkritza, 2019; Horschutz Nemoto et al., 2021; Taeihagh, 2021; Taeihagh and Lim, 2019)
Employment	Negative, many workers in the transport industry would be unemployed.	(Alonso Raposo et al., 2018; Smit et al., 2020; Taiebat et al., 2018)
Wider economic impacts	Likely positive due to increased overall productivity	(Hibberd et al., 2018; Innamaa et al., 2018; Smith et al., 2015)
Costs/benefits, different socio-economic groups	Uncertain, largely unexplored. May lead to increased economic inequality and problems for travellers in need of assistance.	(Bissell et al., 2020; Nahmias-Biran et al., 2021; Sparrow and Howard, 2020)

Many of the impacts stem from an overall increased demand for travel, linked to an overall increased accessibility (Soteropoulos et al., 2019). This in turn leads to e.g. increased congestion, pollution, emissions and demand for infrastructure. Even though self-driving technology could lead to e.g. energy savings per kilometre driven (Wadud et al., 2016), the overall induced demand would likely overshadow these positive impacts (Pernestål et al., 2019).

3.4 Previous research of self-driving technology using transport modelling

After the (current) vision of widespread self-driving vehicles, research using large-scale modelling tools began during the first half of the 2010s with mainly white papers or conference papers (Soteropoulos et al., 2019), such as Burns et al. (2012), Burghout et al. (2014) and the series of reports presented by the International Transport Forum (International Transport Forum, 2017a, 2017b, 2016, 2015) describing possible impacts for Lisbon, Auckland and Helsinki. Following this initial work, some early peer-reviewed published papers was done by e.g. Fagnant and Kockelman (2014), Fagnant et al. (2016), Zhang et al. (2015), Bischoff and Maciejewski (2016), Boesch et al. (2016), Azevedo et al. (2016) and Meyer et al. (2017), simulating mainly medium and large U.S. and European cities. The studies also mainly centred on various types of taxi services substituting previous car and/or public transport demand (Pernestål and Kristoffersson, 2019).

The assumptions generally centred around the availability of cars (e.g. assuming that all citizens would use a self-driving car), the road capacity and the value of travel time (Pernestål and Kristoffersson, 2019; Soteropoulos et al., 2019). The price of the service and waiting times were sometimes treated as exogenous assumptions or results from the model (e.g. Azevedo et al. (2016), Boesch et al. (2016) and Liu et al. (2017).

The studies generally showed increased car traffic (Milakis et al., 2017; Pernestål and Kristoffersson, 2019) and more dispersed land use (Carrese et al., 2019; Gelauff et al., 2019; Hawkins and Nurul Habib, 2019), especially if self-driving cars would not also be used together with trip-sharing services. In the case of shared car use, the car fleet could decrease to less than 10 % of the current need due to the increased usage rates (Bischoff and Maciejewski, 2016; Boesch et al., 2016; Fagnant et al., 2016). However, as shown by more recent studies, the results varied substantially by geography (Gelauff et al., 2019; Meyer et al., 2017). Finally, it should be stressed that the results seemed to be largely conditional on assumptions made by the researchers and results varied substantially (Pernestål and Kristoffersson, 2019; Soteropoulos et al., 2019).

Only a handful of previous studies have explored the prospect of self-driving public transport (Azad et al., 2019; Gelauff et al., 2019; International Transport Forum, 2017a, 2015; Meyer et al., 2017), while the majority of previous studies have assumed no changes to the public transport service (Azad et al., 2019; Pernestål and Kristoffersson, 2019; Soteropoulos et al., 2019).

Most previous studies focus on the two last steps of the four-step model – the mode choice and route choice, with especially the route choice model being the main subject of research (Pernestål and Kristoffersson, 2019; Soteropoulos et al., 2019). A variety of models have been used, mainly microscopic and mesoscopic route assignment models using agents-based models with fixed travel demand (Pernestål and Kristoffersson, 2019) where individual vehicles are modelled to show e.g. the demand for parking (e.g. Zhang et al., 2015), kilometres driven with empty cars (between customers, or to parking facilities) (e.g. Dia and Javanshour, 2017) or needs for fleet size to meet demand, in relationship to waiting time or the rate of sharing (e.g. Azevedo et al., 2016).

The majority of studies used agent-based modelling where individual vehicles and/or travellers are seen as agents moving throughout the network. This approach makes it possible to simulate e.g. vehicle sharing which is not available in traffic flow based models, such as Sampers (Pernestål and Kristoffersson, 2019). Furthermore, Sampers works with fixed time demand segments, virtually emulating a single point in time rather than a more dynamic flow of vehicles throughout the network. Furthermore, as links in traffic flow models are not directly dynamically linked to each other, congestion issues on an individual link does not propagate throughout the network (Samuelsson and Wang, 2020). However, the majority of previous papers assumed a fixed demand for each mode or an overall fixed demand, not taking into account changes such as induced demand due to increased accessibility or people choosing the car instead of public transport, which is a major advantage of Sampers.

4 Investigating self-driving technology using the Sampers model

To investigate the impacts of self-driving technology using the Sampers model, certain adaptions have been required. This section describes two different parts of the research methods applied within the papers. Section 4.1 describes how the scenarios used within each project was made, and Section 4.2 describes the changes made to the Sampers model to emulate the scenarios.

4.1 Scenario development

All three papers included in this thesis rely on scenarios, where possible future transport systems are investigated. The scenarios were developed through a series of steps, described in Figure 8. The steps are not entirely separately distinguished, especially the first and second step (Scenario development and Scenario interpretation) were formed together, and the following steps also have lighter feedback loops.

The first step, Scenario development, was mainly done by reviewing previous work and through workshops with stakeholder or experts within the field. The scenarios were intended to be mutually exclusive and describe a vast variable space, taking inspiration from morphological analysis (Johansen, 2018). Furthermore, the scenarios were intended to be explorative (‘what *can* happen?’) rather than likely (‘what *will* happen?’), taking inspiration from Börjeson et al. (2006) and Vanston et al. (1977). Furthermore, the scenarios were intended to be simple, to increase the comprehensibility.

The second step, interpretation and adjustment to the model, incorporates making the scenarios more concrete and feasible to include in a four-step model, in this case Sampers. This step was done partly concurrently with the first step as not all scenarios were possible to simulate within the Sampers framework due to limitations of the model (see Section 7.1).

The third step, Parameter change appraisal, further concretized the scenarios into quantitative numbers, e.g. valuation of exactly how road capacity or maintenance costs would change. This step was, according to my experience, the most controversial one as some parameter values were highly contested or dependent on assumptions without universal consensus in the research community.

Finally, the fourth and fifth steps were the most labour-intensive and required considerable time. The implementation part of a four-step model also requires small design details (e.g. setting an exact time between two bus stops).

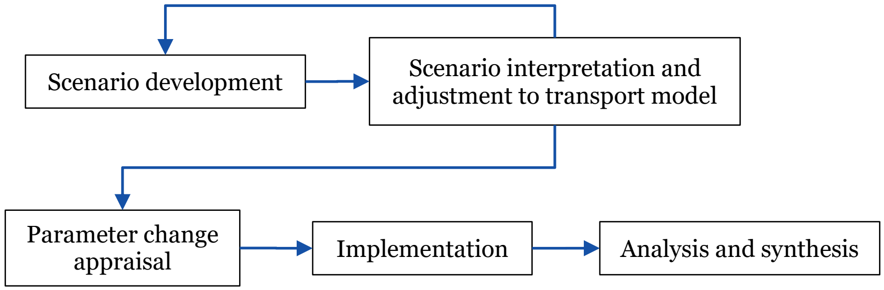


Figure 8. Outline of the method used for the papers in this thesis.

For paper A and B, the main inspiration for scenarios were from Pernestål et al. (2019) which had two axes for possible futures related to self-driving technology. The two axes were 1) the rate of governmental engagement and 2) the rate of sharing, which together formed four separate ‘extreme’ scenarios. These scenarios were then compared to similar scenario development by e.g. Gelauff et al. (2017), Richter (2018) and Tillema et al. (2015) and workshops were conducted with a total number of 130 transport industry professionals. Together, this formed an iterative process where the scenarios were reviewed and then further evaluated based on input from the industry professionals.

This process led to a final set of six scenarios with two axes - changes to the public transport and changes to the car system. The public transport axis explored potential changes in the organization of the public transport system, especially the possibility to increase service levels due to decreased costs for on-board personnel. The car axis explored possibilities to share the car resource due to the car’s new ability to transport itself to a new passenger without the need for a driver. Two of the scenarios, involving shared taxis, were removed due to technical limitations in the model and are discussed more within Section 7.1.

Regarding paper C, the process was somewhat similar but instead of workshops, interviews with select groups of industry professionals were made, and the scenarios were more outlined as per the research objective for the project. The main dimensions investigated were the requirements for digital and physical infrastructure related to self-driving transport, and thus three scenarios were developed varying these requirements.

4.2 Applying the scenarios to the Sampers model

Due to the structure of four-step models, the application of self-driving technology was divided into the car mode and the public transport mode with changes done separately to the modes. In Section 3.2 I identified the following parameters that might be affected by self-driving technology: VoTT; accident rate; road capacity; energy consumption; the cost of the vehicle; and the type of service available to citizens.

In the SLL SDV project, reported in Paper A and B, I made changes to the parameters road capacity, the cost of the vehicle and the type of service. The value of time was deemed to be infeasible to change due to technical reasons and not all types of services were included.

Road capacity was modelled using the VDFs, namely to double the maximum capacity of the major roads in the area.

The introduction of self-driving cars was deemed to mean that additional population groups would have access to the car, i.e. those without a drivers' license. To model this, drivers' license availability was set to 100 % in the region. However, the number of cars were still limited, meaning that the 'competition' for using the car within households increased. Two of the scenarios in Paper A and B entailed a replacement of private car use with a taxi service, which would increase the availability of the car mode, thus the car availability was set to 100 % in these scenarios. However, the shift from privately owned cars to taxi services would mean that the business model for paying for the car mode shifts as well. Therefore, the cost of 'driving' was simultaneously increased to account for capital costs for vehicles, which are usually treated as non-existent by most drivers (Becker et al., 2020), resulting in an increased cost of use from approximately 0.2 €/km to 0.5 €/km.

Regarding public transport in Paper A and B, it has previously been identified that the driver constitutes a substantial share of the cost of operations (see Section 3.2.2) and the assumption was set that the reduction in cost would be used to increase the levels of service. This was done by decreasing the headway for public transport in the model. However, similar to the car mode, a new form of public transport was modelled, namely on-demand public transport servicing last and first mile trips. This was done by removing all minor bus lines (minor was defined by routes having more than 10 minutes of headway outside of peak hours) and replacing these by on-demand public transport connecting passengers to the nearest major bus or train station, except for the inner city where this was deemed unfeasible due to congestion. Practically, this was done by adding new access and egress connections with a speed of 25 km/h, assuming that this would be an average service speed across geographies (compare to Burghout et al. (2014) who used 20 km/h for taxi services but also included the inner city).

Paper C only concerned changes to the public transport system, assuming a similar increase in service levels due to reduction of costs. Furthermore, assumptions about the value of travel time was made, likening a new bus service to the comfort levels of train services. Practically, this was accomplished by changes to the time between stops (as Sampers has no separate value for value of travel time that may be more easily changed). Additionally, assumptions of increased service speeds were made, further limiting the time between stops.

5 Summary of appended papers

5.1 Paper A: Will public transport be relevant in a self-driving future? A demand model simulation of four scenarios for Stockholm, Sweden

The paper uses the Sampers model to investigate impacts of self-driving technology for Stockholm, Sweden, with self-driving technology used for both cars and public transport. Four scenarios are presented, exploring two possible transport alternatives for car transport and two for public transport, together forming a matrix, see Figure 9.

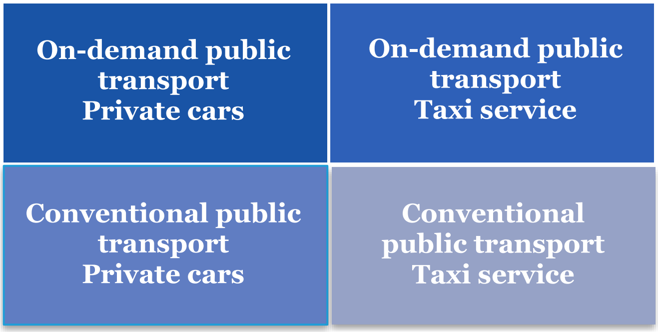


Figure 9. Scenarios in Paper A.

For car traffic, the car was assumed to be either 1) privately owned (which is most prevalent currently) but with the change that anyone within the household can use the car (not only those who hold a drivers' license), or 2) used as a taxi service, available to anyone. The major difference, other than accessibility to the car mode, is that in the first case, the cost of driving is unchanged from today (reflecting mainly the cost of fuel and maintenance), whereas the cost of using the car is heavily increased in the second case. This reflects that travellers would need to pay for the vehicle as part of the marginal cost of use, instead of a large up-front purchase to acquire the car. Still, the cost of this taxi service would be dramatically reduced compared to the current cost of taxi services.

For public transport, 1) a conventional public transport service and 2) an On-demand service were investigated. The conventional public transport case assumed that public transport was similarly organised as today, with fixed routes and time schedules, but with dramatic increases in service level (i.e. reduced headway between trips) for mainly bus traffic, but also for rail based traffic during off-peak hours. In the second case, fixed routes assumed to have been replaced by On-demand shuttles driving passengers to bigger stops where trunk lines would operate (like currently planned systems, but with increased service levels as the first case).

During the analysis of the results, I concluded that the increased service levels for public transport had remarkably low impacts on overall travel. Instead, a transition to self-driving cars would be associated with a transition to car use from public transport, walking and cycling. However, these results were largely dependent on assumptions of cost of car use.

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

The second paper is a continuation of the first, with more thorough analysis of results and the impacts of the results. Within the paper, we analyse the results based on differences between different trip purposes and geography, as well as sensitivity analysis of variation in price as well as analysing each modelled factor separately.

We find moderate changes to work travel but that leisure trips increase dramatically. This may be due to the inelasticity of work trips (i.e. the number of work trips is mostly associated with population size, economy and cultural factors, rather than accessibility), whereas people would make more trips to e.g. sports activities or visit grandparents if their transport accessibility would increase.

Geographic changes were also substantial for both car and public transport use. In the scenarios with taxi services replacing privately owned cars, rural car traffic decreased, likely connected to the price of the service whereas the increased overall accessibility to the car mode (i.e. that no drivers' license or ownership of the car was required) likely had little impact in areas where 'everyone' already has a car. In the inner city, results indicated large increases in car use, but we question the feasibility of the results there as congestion is not properly modelled within the Sampers model. Furthermore, the increased accessibility in the inner city is likely small due to a public transport network with high frequencies. Instead, areas most likely to be affected are the suburbs where current public transport is lacking and where car ownership is moderately high, with excess demand for transport is not currently satisfied.

Further analysis of the public transport option showed that the increased service, and especially the On-demand solution, could be especially attractive for rural areas. Here, stops are generally a long walk from home, and may only have one trip per hour or similar, making it a poor option at present. An On-demand solution, even with low average speed, could be a feasible solution for a lot of residents.

5.3 Paper C: Evaluation of frameworks for assessing societal impacts of self-driving technology

The third paper has two parts, one regarding frameworks to assess societal impacts of self-driving technology, and one part evaluating the impacts of a self-driving bus service in southern Stockholm, Sweden.

The first part summarises previous frameworks that have been made to assess the societal impacts of self-driving technology, out of which several are white papers. The list of potential impacts listed vary largely, with 24 factors identified and no framework that covers all aspects. The previous frameworks use various methods of assessing impacts: conceptual, mostly using qualitative analysis; mathematical, with ‘simple’ quantitative relationships between variables; system dynamics, a technique focusing on feedback loops and identifying causalities on a holistic level; and finally state-of-the-art which mainly investigate previous research and groups the result into an overall framework of understanding. Furthermore, the scope and motivation also vary widely.

The second part highlights the findings from the Södertörn project (Sjöström et al., 2021), which evaluates three scenarios for self-driving bus services with various levels of self-driving capabilities. The project evaluated a bus line with

1) Self-driving capability but with a bus driver on-board who would take over in areas where the bus could not drive by itself,

2) Self-driving capabilities facilitated by heavy investments into physical infrastructure (e.g. a dedicated highway lane) and remote steering when needed,

3) And finally self-driving capabilities facilitated by digital development where the bus could drive in mixed traffic and only occasionally in need of remote guidance.

The assessment was done by using the Total Impact Assessment (Sv. ‘Samlad effektbedömning’), developed by the STA, a framework previously used for infrastructure assessment which uses a mix of quantitative and qualitative assessment and a procedure for peer-review of results with experts within various field (e.g. biologists or accessibility experts). The Sampers model was used to model impacts on ridership and indirect effects, such as people switching from car travel to the bus as an effect of a more attractive service.

We concluded that the use of the framework made it possible to compare the scale of different effects, such as comparing reduction in cost of vehicle injuries to infrastructure costs of digital infrastructure. Furthermore, the framework also made it clear that costs and benefits would not affect different actors (such as the STA, bus operators or the different groups of travellers) evenly, necessitating further discussion of how public infrastructure and service is funded.

6 Key findings

This section of the thesis summarises the contributions of the papers in relation to the research questions posed in Section 1.2.

6.1 Which potentials for public transport can self-driving technology have?

In Paper A-C we showed that self-driving technology would mean a substantial reduction in costs for especially bus traffic. The bus driver constitutes about half of the cost of operations in the OECD and about half of the marginal cost of operations for train traffic (i.e. not accounting for infrastructure costs) (Paper A and B). However, costs of purchasing these vehicles would be high, at least initially and new costs could arise, such as remote operations and increased maintenance (Paper C). Self-driving technology may also require infrastructure investments which could be substantial in relation to cost savings (Paper C). The costs could also be shifted onto different actors than during current operations (Paper C).

A major finding of Paper C was that increased comfort for bus rides could be the largest benefit, outshining the reduced cost of operations. As stated in the article, these findings were likely overoptimistic, but could still be large. The realisation of them depends on 1) if the technology would be realisable and 2) if this increased comfort would be perceived as similar to train travel.

Decreased accident and injury rates have usually been heralded as the major benefits of self-driving technology (Fagnant and Kockelman, 2015; Kalra and Paddock, 2016; Koopman and Wagner, 2017). However, as we have shown in Paper C, even an optimistic reduction in injuries for public transport (by 90 %) would account for only small increases in overall benefit of public transport, as accidents are (fortunately) already uncommon.

The change in cost structure of public transport would open up new possibilities for public transport offerings previously deemed difficult due to cost and organisational practices. A reduction in cost of public transport would make it possible for authorities to offer public transport in areas with low utilisation levels (Pernestål Brenden and Kottenhoff, 2018). Indirectly, this could also contribute to the use of smaller vehicles than full-sized buses, further opening up for new possibilities. As we showed in Paper C, the size of buses limits their operational areas due to 1) restrictions in roadways allowed (with bearing capacity in mind or due to turning radius) and 2) noise levels.

Furthermore, an important constraint on current bus operations is the requirements of itineraries of bus drivers, which limits flexibility both legally as drivers need breaks at certain intervals and practically to ensure efficient scheduling (Paulsson, 2021). Removing this constraint would open up for new possibilities for e.g. on-demand services, explored in Paper A and B.

6.2 Which parameters in four-step transport models need to be adjusted to simulate self-driving public transport?

To emulate the expected implications of self-driving technology, the following changes were deemed necessary to change in four-step models: road capacity and congestion behaviour; increased public transport service levels; the modelling of first- and last-mile services; changes to the value of time; and increased availability of the car mode.

Road capacity is modelled by VDFs in macroscopic traffic assignment models and the changed behaviour of individual vehicles would lead to differences at an aggregated level. Within Paper A and B, a simple assumption was made that doubled the capacity of the road, but more elaborate changes to the functions are likely needed to capture the complex behaviour (Sonnleitner et al., 2021).

The reduction in costs of public transport was assumed in Paper A-C to be used to increase service levels, especially during off-peak hours which would limit the need for additional vehicles. This was modelled by decreasing the headway of the public transport lines, which should be a suitable way of emulating this. However, this increase in service levels did not account for e.g. congestion issues that may occur in the roadways or additional requirements for bus terminals.

First and last mile public transport services were modelled in Paper A and B as direct links between zones and major stops or stations, with the assumption that travellers would have an average travel speed of 25 km/h considering waiting times, transfer times and the non-direct path (i.e. not a beeline). These assumptions were simplifications and individual travel routes from each zone to the major stops or stations would have been a more realistic simulation of the service. There has been considerable work done in this field by e.g. Scheltes (2017), Shen et al. (2018), Zhang et al. (2019) and Badia and Jenelius (2020) which could be further incorporated into four-step models.

Changes to the value of travel time was done by a multitude of previous transport model studies (Pernestål et al., 2019; Soteropoulos et al., 2019), usually by changing the value within the model. This was not feasible in the Sampers model, instead changes to the travel times themselves were made, which however does not show the variation in value of time for different travellers.

The increased availability of the car mode was represented by increasing the car availability and drivers' license availability, both treated as exogenous factors in the Sampers model. This approach posed a drastic change to the model, outside the 'normal' range of availability, thus such an increased availability was outside the scope of the model. Still, the resulting effects were deemed to be reasonable (see Section 7.1).

6.3 Which implications would self-driving public transport have for the transport system?

As found by previous researchers and confirmed in Paper A-C, the bus driver accounts for about 50 % of the total cost of operations for bus traffic. Furthermore, in Paper A and B, I found that for rail-based traffic, on-board personnel constitute a large portion of the marginal cost. Put in simple terms, once the infrastructure has been built and trains purchased, the driver is currently a large part of operational costs, and therefore it makes fiscal sense to use the vehicles to the furthest extent. Therefore, the reduced costs of operations for operators would lead to large cost savings. In Paper A-C, we found that professionals from the transport sector thought that a potential use of these savings could go into increasing service levels, which might attract more passengers and reduce car use.

In Paper A and B, we found this drastic increase in service levels to have a limited impact on ridership for Stockholm. Therefore, the reduction in costs of operation could probably be better spent by e.g. lowering taxes or using funds for other welfare areas. However, in Paper B we showed that the effect of the increased service had varied impacts in different parts of the region. In rural areas, the current public transport service is currently poorly accustomed to travellers, with few trips per day and long distances to stops. Whereas in more central parts, public transport is already the dominating mode of transport with buses and metro trains wait times being marginal. An increase in service therefore did not lead to substantial time savings and therefore had limited impact on ridership.

This variability in impact due to geography likely points to the difficulty of generalising the results – it is likely that my results may be transferable to cities of similar size with a similar layout, i.e. Western European cities. But for more rural areas, the overall results are likely quite different. Furthermore, not all countries have a similar wage levels as Sweden, and the cost of the driver is not a dominating factor (Becker et al., 2020).

Paper C delved into other possible effects rather than ridership and operating costs, with a comprehensive framework listing impacts to various areas. In Paper C, we showed that the greatest effect of self-driving technology was more comfortable trips, due to ‘smoother’ driving behaviour. This impact was similar to claims from previous research on car ridership, where the value of travel time (VoTT) would be lowered, leading to more productive trips where one could work or take a nap. In Paper C, we showed that this effect could be possible for public transport as well, comparing bus rides to train rides, where the latter is much more comfortable. However, it was hard to know how much smoother a bus ride using self-driving technology would be perceived, and therefore gauge the total value of this effect.

Furthermore, in Paper C we showed that gains from reducing personnel cost seem to outweigh infrastructure costs, unless a separate road lane would be required. This conclusion was of course heavily dependent on scale, in the study there was a singular bus line (albeit with high frequency), and choosing links with high utilisation would have been preferable.

In contrast to car traffic, where accident reduction have been seen as one of the major benefits of self-driving technology (Koopman and Wagner, 2017), we found limited merits for public transport, mainly since bus traffic seems to be relatively safe already.

In addition, in Paper C we showed that experts at the Swedish Transport Administration stressed that the experience of riding in a self-driving bus could be perceived very differently by different groups of people, for example those with physical disabilities who need hands-on help from a driver, or by women who prefer to have a driver on board to ensure safety. Several additional effects with uncertain scale were also identified, such as increased noise levels due to the increased frequency, or that the buses could constitute local barriers as parents would not trust self-driving vehicles to 'see' children who would need to cross the road. The experts also highlighted possible effects for biodiversity and pollution, especially during construction of new infrastructure.

Finally, in Paper C we also showed that benefits and costs were not uniformly distributed amongst the different organisations. For example, infrastructure requirement would likely be the responsibility of the road operator, while the public transport authorities would reap the benefits of reduced driver costs. This uneven distribution of costs and benefits would stress the need for new models for financing e.g. infrastructure needed to facilitate self-driving technology.

7 Discussion

7.1 Limitations

7.1.1 General limitations

This thesis has only covered impacts on personal transport, with a focus on public transport implications. Impacts for e.g. goods transport or the potential for air or sea transport has not been investigated.

A major drawback of the current field of research is the English-centric bibliography. I have only considered research published in English or Swedish (the latter mainly governmental reports). Out of the published work in English, almost all research has been done in western Europe, the U.S. and Canada, with some papers originating in East Asia as well (Gandia et al., 2019). This limits the universality of the thesis (and the field in general) and results may not hold for other parts of the world.

One of my major assumptions is that self-driven vehicles will be treated as a 'normal' mode, which is not culturally different than current modes of transport, which may not be the case. Furthermore, the papers assume that people accept the technology, which is far from certain. Comparing the introduction of this new technology to the initial hesitance of using train which has since receded (Milne-Smith, 2016) might not be correct. An alternative comparison could be with airplanes, which far from everyone are comfortable using, despite their century-long existence.

7.1.2 Four-step transport models

I have identified four main limitations with four-step transport models.

First, as the models are quantitative in their nature, they can only depict changes that are numerical and force modellers to quantify unknown or uncertain implications (Witzell, 2021). The value of time, much debated within the field of self-driving technology (Kolarova, 2021; Singleton, 2019) is a good example of this. How people value their time is uncertain, heterogeneous and there are large difference depending on total value of time and the marginal value of time (Mokhtarian, 2018; Nordström, 2020; Wardman, 1998) and modelling this with an exact value may be misleading. In fact, it may be that our models of time valuation do not apply to riding in a vehicle without a driver (Mokhtarian, 2018).

Second, many other factors affect society apart from self-driving technology and may in fact pose as greater influences on e.g. CO_2 emissions. Demographic changes have a large impact on transport behaviour (Hoque et al., 2021; Lemp et al., 2021) and the COVID-19 pandemic is a direct testament to changes unanticipated by most forecasters, myself included.

Third, four-step transport models are complex (albeit still simplifications of reality) and effectively 'black boxes', with changes and impacts being hard to overlook and explain (Curtis et al., 2021; Jonsson et al., 2011). Changes to the model may have unintended consequences due to the interaction of various variables and issues such as failure to reach equilibrium in the route choice model and in the overall model may create problems in assessing the results (Curtis et al., 2021; Sweco Society AB, 2018)

Fourth, the computational time of four-step transport models is high (Johari et al., 2021). A single run of Sampers on a high-end modern computer is more than a full day. It is possible to run four-step models on supercomputers, but this option is often unpractical, making it difficult to have more of a 'trial-and-error' approach to modelling. This limits the ability to interact with e.g. practitioners and discuss model results incrementally.

7.2 Alternative models – agent-based models

Understanding the high-level impacts of self-driving technology could be done through a multitude of methods, e.g. interviews with experts, surveying the general population through analytical and deductive reasoning. The most common approach when modelling autonomous vehicles on a larger scale have however been by using agent-based models using microscopic or mesoscopic traffic assignment methods (Pernestål and Kristoffersson, 2019), most notably the MATSim model.

Microscopic or mesoscopic models have multiple advantages – they emulate the interaction between vehicles more accurately and are in general more flexible for introducing new types of interaction patterns than the volume-delay functions of macroscopic models (Burghout et al., 2004). Agent-based models also use individuals rather than groups, more accurately simulating the behaviour of individuals and explaining the complexity of mobility patterns. This approach may also extend to vehicles – individual vehicles may be modelled – which makes it possible to e.g. share vehicles between travellers throughout the day or more easily model vehicle kilometres travelled between customers in the case of self-driving taxi services (Feil, 2010; Kagho et al., 2020).

However, agent-based models also come with disadvantages. First, they are a relatively new type of model that have not been used extensively beyond the academy and have not been extensively validated to real world observations (Kagho et al., 2020). In contrast, Sampers has been in constant development since the 1990s and each release of the Sampers model is joined by a technical report outlining how well the model represents actual traffic data (Samuelsson and Wang, 2020). They should therefore generally be better at modelling our current transport system.

To the best of my understanding, agent-based models also have a severe disadvantage compared to four-step transport models regarding computational time (Kagho et al., 2020). The use of individual agents is more time-consuming, and the use of microscopic or mesoscopic modelling is associated with many hours of computation, making them generally more difficult to handle and this is usually counteracted by reducing the complexity of the model (Feil, 2010; Kagho et al., 2020). MATSim, the most commonly used agent-based model, is generally run with a fixed demand and only has rudimentary demand- and destination-choice models (Horni et al., 2016).

In summary – agent-based microscopic models may be a better option for modelling all aspects of self-driving vehicles, but still have considerable associated difficulties, most notably their lack of validation to real world data and inability to model changes to overall demand, making four-step transport models a feasible option.

7.3 Future work

Four major areas of future research areas have been identified within this thesis.

Continued model development. The Sampers model used within this thesis may be a suitable model for modelling current transportation behaviour, but it is not equipped with e.g. the possibility to model extensive taxi use and sharing of cars. Agent-based simulation is likely the most attractive option, but as stated in Section 7.2, these models are still in development and seem to have been mostly used in academic settings so far.

Continued impact investigation. Reviews of past research, as well as the papers included in this thesis, show that impacts from self-driving technology are still uncertain and needs to be further explored. Furthermore, as Paper C showed, several areas of importance have been only marginally explored, such as impacts for infrastructure requirements or noise levels that might stem from both changes in overall traffic levels as well as changes in vehicle behaviour.

Developing frameworks to understand impacts. Furthermore, the impacts from self-driving technology are still lacking a comprehensive framework for our shared understanding of what they may entail. Paper C showed that various frameworks identify different affected areas, but that no framework succeeds in capturing them all, moreover in a clear and understandable way.

Heterogeneous impact assessment. The three papers included showed that the effects of self-driving technology are not uniformly distributed, yet previous research has mainly showed overall impact, not showing differences across e.g. geographic areas, socioeconomic groups or between men and women. Paper C moreover identified that past frameworks only to a small degree included variations in impacts – instead only showing overall impacts. Further research needs to be done to include variations in impacts, not assuming that impacts are uniformly distributed.

8 Conclusions

Within this thesis, I have explored how four-step transport models can be used to investigate the impacts of self-driving technology for public transport. These models have considerable disadvantages, such as their narrow focus on quantitative impacts, opaque model configuration and considerable computational time which limits the usability and analysis possible. Still, they have proven to be quite capable of modelling transport behaviour changes in the past, at least on a larger scale. In the papers, I have emulated self-driving technology in the models and explored the effects on e.g. accessibility, CO_2 emissions and pollution on the Stockholm region.

In the Introduction, I outlined three research questions: how self-driving technology can enhance public transport; how self-driving transport can be modelled using four-step models; and what impacts self-driving public transport would have for the transport system.

In conclusion, self-driving technology could lead to significant cost-savings for public transport, foremost for bus traffic but also to a large extent for rail-based traffic. Furthermore, removing the drivers and changing the cost structure of bus traffic could lead to new possibilities in planning public transport which is not limited to driver itineraries and the use of public transport in areas currently not deemed suitable for operation. This potential could lead to increased public transport travelling, especially in areas with poor public transport service today. Additionally, more smooth driving behaviour could lead to more comfortable travel which could lead to more people using public transport.

To model self-driving public transport with four-step models, I have concluded that they may be adjusted to fit into the new “features” of the technology, such as increased availability to the car mode, changes to the value of travel time or through changes to road capacity. Still, these models hold considerable limitations in their current state, such as the inability to account for sharing of vehicles.

Regarding the impacts of self-driving technology on public transport, the potential to reduce costs for drivers is substantial. In the appended papers, I assumed that this reduced cost would be re-invested into increased service level, which would mean increased accessibility for travellers, especially those living in more rural areas. However, the drivers perform several other tasks than explicit driving tasks, such as answering questions from passengers, fault mitigation and real-time re-planning in case of unexpected events. Furthermore, the driver has an authoritative role, making passengers feel safe and enacting norms on social control, e.g. telling off loud teenagers disturbing other passengers.

In addition, Paper C concluded that effects from self-driving technology are likely to be unevenly distributed, meaning e.g. increased accessibility for some and decreased mobility for others due to e.g. safety issues. Likewise, the effects for different organisations are likely not evenly distributed, stressing the need for new models for e.g. financing of public infrastructure and services.

9 References

Algers, S., 2004. Regional Trips. URL https://www.trafikverket.se/contentassets/d7cf7d727fb2488aab9fa9d24387c7c8/externa-rapporter/2021/2a_regmodeller21.pdf (accessed 2021-05-21).

Alonso Raposo, M., Grosso, M., Després, J., Fernández Macías, E., Galassi, C., Krasenbrink, A., Krause, J., Levati, L., Mourtzouchou, A., Saveyn, B., Thiel, C., Ciuffo, B., 2018. An analysis of possible socio-economic effects of a Cooperative, Connected and Automated Mobility (CCAM) in Europe (No. EUR 29226 EN). Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/777

Amer, N.H., Zamzuri, H., Hudha, K., Kadir, Z.A., 2017. Modelling and Control Strategies in Path Tracking Control for Autonomous Ground Vehicles: A Review of State of the Art and Challenges. J. Intell. Robot. Syst. 86, 225–254. https://doi.org/10.1007/s10846-016-0442-0

Andersson, M., Brundell-Freij, K., Eliasson, J., 2017. Validation of aggregate reference forecasts for passenger transport. Transp. Res. Part Policy Pract. 96, 101–118. https://doi.org/10.1016/j.tra.2016.12.008

Andersson, P., Ivehammar, P., 2019. Benefits and Costs of Autonomous Trucks and Cars. J. Transp. Technol. 09, 121–145. https://doi.org/10.4236/jtts.2019.92008

Axelrod, C.W., 2019. Autonomous Vehicles Meet Inhospitable Roadways, in: 2019 IEEE Long Island Systems, Applications and Technology Conference (LISAT). Presented at the 2019 IEEE Long Island Systems, Applications and Technology Conference (LISAT), IEEE, Farmingdale, NY, USA, pp. 1–6. https://doi.org/10.1109/LISAT.2019.8816825

Azad, M., Nima, H., Candace, B., Christopher R., C., Lee D., H., 2019. Fully Autonomous Buses: A Literature Review and Future Research Directions. J. Adv. Transp. 2019, 16. https://doi.org/10.1155/2019/4603548

Azevedo, C.L., Marczuk, K., Raveau, S., Soh, H., Adnan, M., Basak, K., Loganathan, H., Deshmunkh, N., Lee, D.-H., Frazzoli, E., Ben-Akiva, M., 2016. Microsimulation of Demand and Supply of Autonomous Mobility On Demand. Transp. Res. Rec. J. Transp. Res. Board 2564, 21–30. https://doi.org/10.3141/2564-03

Badia, H., Jenelius, E., 2020. Feeder Transit Services in Different Development Stages of Automated Buses: Comparing Fixed Routes versus Door-to-Door Trips. Transp. Res. Procedia 47, 521–528. https://doi.org/10.1016/j.trpro.2020.03.127

Baker, D.R., Villa, L., 2017. Self-driving cars: The road from fantasy to fruition. San Franc. Chron. URL https://www.sfchronicle.com/drivingthefuture/timeline/ (accessed 2021-11-25).

Becker, H., Becker, F., Abe, R., Bekhor, S., Belgiawan, P.F., Compostella, J., Frazzoli, E., Fulton, L.M., Guggisberg Bicudo, D., Murthy Gurumurthy, K., Hensher, D.A., Joubert, J.W., Kockelman, K.M., Kröger, L., Le Vine, S., Malik, J., Marczuk, K., Ashari Nasution, R., Rich, J., Papu Carrone, A., Shen, D., Shiftan, Y., Tirachini, A., Wong, Y.Z., Zhang, M., Bösch, P.M., Axhausen, K.W., 2020. Impact of vehicle automation and electric propulsion on production costs for mobility services worldwide. Transp. Res. Part Policy Pract. 138, 105–126. https://doi.org/10.1016/j.tra.2020.04.021

Bender, J.G., 1991. An overview of systems studies of automated highway systems. IEEE Trans. Veh. Technol. 40, 82–99. https://doi.org/10.1109/25.69977

Beser, M., Algers, S., 2002. SAMPERS — The New Swedish National Travel Demand Forecasting Tool, in: Lundqvist, L., Mattsson, L.-G. (Eds.), National Transport Models. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 101–118. https://doi.org/10.1007/978-3-662-04853-5_9

Bischoff, J., Maciejewski, M., 2016. Simulation of City-wide Replacement of Private Cars with Autonomous Taxis in Berlin. Procedia Comput. Sci. 83, 237–244. https://doi.org/10.1016/j.procs.2016.04.121
Bissell, D., Birtchnell, T., Elliott, A., Hsu, E.L., 2020. Autonomous automobilities: The social impacts of driverless vehicles. Curr. Sociol. 68, 116–134. https://doi.org/10.1177/0011392118816743
Boesch, P.M., Ciari, F., Axhausen, K.W., 2016. Autonomous Vehicle Fleet Sizes Required to Serve Different Levels of Demand. Transp. Res. Rec. J. Transp. Res. Board 2542, 111–119. https://doi.org/10.3141/2542-13
Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., Finnveden, G., 2006. Scenario types and techniques: Towards a user's guide. Futures 38, 723–739. https://doi.org/10.1016/j.futures.2005.12.002
Börjesson, M., Brundell-Freij, K., Eliasson, J., 2014. Not invented here: Transferability of congestion charges effects. Transp. Policy 36, 263–271. https://doi.org/10.1016/j.tranpol.2014.09.008
Bösch, P.M., Becker, F., Becker, H., Axhausen, K.W., 2018. Cost-based analysis of autonomous mobility services. Transp. Policy 64, 76–91. https://doi.org/10.1016/j.tranpol.2017.09.005
Bovy, P.H.L., 2009. On Modelling Route Choice Sets in Transportation Networks: A Synthesis. Transp. Rev. 29, 43–68. https://doi.org/10.1080/01441640802078673
Boyce, D.E., Williams, H.C.W.L., 2015. Forecasting Urban Travel : Past, Present and Future. Edward Elgar Publishing Limited, ProQuest Ebook Central. URL https://ebookcentral-proquest-com.focus.lib.kth.se/lib/kth/detail.action?docID=1997057&pq-origsite=primo (accessed 2020-10-15).
Brodsky, J.S., 2016. Autonomous Vehicle Regulation How an Uncertain Legal Landscape May Hit the Brakes OnSelf-Driving Cars. Berkeley Technol. Law J. 31, 851–878. URL https://www.jstor.org/stable/26377774 (accessed 2021-11-25)
Burghout, W., Rigole, P.-J., Andreasson, I., 2014. Impacts of Shared Autonmous Taxis in a Metropolitan Area. Proc. 94th Annu. Meet. Transp. Res. Board Wash. DC 2015 14.
Burghout, W., 2004. Hybrid microscopic-mesoscopic traffic simulation. KTH Royal Institute of Technology, Stockholm. URL: http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A14700&dswid=1625 (accessed 2022-05-10)
Burns, L.D., Golob, T.F., 1976. The role of accessibility in basic transportation choice behavior. Transportation 5, 175–198. https://doi.org/10.1007/BF00167272
Burns, L.D., Jordan, W.C., Scarborough, B.A., 2012. Transforming personal mobility. The Earth Institute, New York. URL http://wordpress.ei.columbia.edu/mobility/files/2012/12/Transforming-Personal-Mobility-Aug-10-2012.pdf (accessed 2021-12-01).
Carrese, S., Nigro, M., Patella, S.M., Toniolo, E., 2019. A preliminary study of the potential impact of autonomous vehicles on residential location in Rome. Res. Transp. Econ. 75, 55–61. https://doi.org/10.1016/j.retrec.2019.02.005
Chandler, R.E., Herman, R., Montroll, E.W., 1958. Traffic Dynamics: Studies in Car Following. Oper. Res. 6, 165–184. https://doi.org/10.1287/opre.6.2.165
Chee, P.N.E., Susilo, Y.O., Wong, Y.D., 2020. Determinants of intention-to-use first-/last-mile automated bus service. Transp. Res. Part Policy Pract. 139, 350–375. https://doi.org/10.1016/j.tra.2020.06.001
Cohen, S.A., Hopkins, D., 2019. Autonomous vehicles and the future of urban tourism. Ann. Tour. Res. 74, 33–42. https://doi.org/10.1016/j.annals.2018.10.009

Cohen, T., Cavoli, C., 2019. Automated vehicles: exploring possible consequences of government (non)intervention for congestion and accessibility. Transp. Rev. 39, 129–151. https://doi.org/10.1080/01441647.2018.1524401
Computer History Museum, 2016. Ernst Dickmanns' VaMoRs Mercedes Van, 1986-2003. URL https://youtu.be/I39sxwYKlEE (accessed 2021-11-25).
Creswell, J.W., Creswell, J.D., 2018. Research design : qualitative, quantitative, and mixed methods approaches, Fifth edition. ed. SAGE Publications, Inc., Bell and Bain Ltd, Glasgow, Great Britain.
Cruz, C.O., Sarmento, J.M., 2020. Traffic forecast inaccuracy in transportation: a literature review of roads and railways projects. Transportation 47, 1571–1606. https://doi.org/10.1007/s11116-019-09972-y
Curtis, C., McLeod, S., Hultén, J., Pettersson-Lofstedt, F., Paulsson, A., Hedegaard Sørensen, C., 2021. Knowledge for policy-making in times of uncertainty: the case of autonomous vehicle model results. Transp. Rev. 41, 478–498. https://doi.org/10.1080/01441647.2020.1857885
Dadashzadeh, N., Ergun, M., 2018. Spatial bus priority schemes, implementation challenges and needs: an overview and directions for future studies. Public Transp. 10, 545–570. https://doi.org/10.1007/s12469-018-0191-5
de Dios Ortúzar, J., Willumsen, L.G., 2011. Modelling Transport. John Wiley & Sons, Incorporated. URL https://onlinelibrary-wiley-com.focus.lib.kth.se/doi/book/10.1002/9781119993308 (accessed 2021-11-12).
de Jong, G., Daly, A., Pieters, M., 2007. The logsum as an evaluation measure: Review of the literature and new results, Transp. Res. Part A. https://doi:10.1016/j.tra.2006.10.002
Dia, H., Javanshour, F., 2017. Autonomous Shared Mobility-On-Demand: Melbourne Pilot Simulation Study. Transp. Res. Procedia 22, 285–296. https://doi.org/10.1016/j.trpro.2017.03.035
Diels, C., Bos, J.E., 2016. Self-driving carsickness. Appl. Ergon. 53, 374–382. https://doi.org/10.1016/j.apergo.2015.09.009
Dixit, V., Xiong, Z., Jian, S., Saxena, N., 2019. Risk of automated driving: Implications on safety acceptability and productivity. Accid. Anal. Prev. 125, 257–266. https://doi.org/10.1016/j.aap.2019.02.005
Dubernet, I., Axhausen, K.W., 2020. The German value of time and value of reliability study: the survey work. Transportation 47, 1477–1513. https://doi.org/10.1007/s11116-019-10052-4
Durst, P.J., Anderson, D.T., Bethel, C.L., Carruth, D.W., Monroe, G., 2018. A history and overview of mobility modeling for autonomous unmanned ground vehicles, in: Dudzik, M.C., Ricklin, J.C. (Eds.), Autonomous Systems: Sensors, Vehicles, Security, and the Internet of Everything. Presented at the Autonomous Systems: Sensors, Vehicles, Security and the Internet of Everything, SPIE, Orlando, United States, p. 17. https://doi.org/10.1117/12.2309570
Eliasson, J., 2009. A cost–benefit analysis of the Stockholm congestion charging system. Transp. Res. Part Policy Pract. 43, 468–480. https://doi.org/10.1016/j.tra.2008.11.014
Epting, S., 2019. Transportation Planning for Automated Vehicles—Or Automated Vehicles for Transportation Planning? Essays Philos. 20, 189–205. https://doi.org/10.7710/1526-0569.1635
European Commission/Directorate General for Mobility and Transport, 2020. Study on the effects of automation on road user behaviour and performance: final report. Publications Office of the European Union, Luxembourg. https://doi.org/10.2832/431870

European Union, Kantar Belgium, 2020. Eurobarometer - Expectations and concerns of connected and automated driving (No. 496), Special Eurobarometer. https://doi.org/10.2760/494496
Fagnant, D.J., Kockelman, K., 2015. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. Transp. Res. Part Policy Pract. 77, 167–181. https://doi.org/10.1016/j.tra.2015.04.003
Fagnant, D.J., Kockelman, K.M., 2014. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. Transp. Res. Part C Emerg. Technol. 40, 1–13. https://doi.org/10.1016/j.trc.2013.12.001
Fagnant, D.J., Kockelman, K.M., Bansal, P., 2016. Operations of Shared Autonomous Vehicle Fleet for Austin, Texas, Market. Transp. Res. Rec. J. Transp. Res. Board 2563, 98–106. https://doi.org/10.3141/2536-12
Faisal, A., Yigitcanlar, T., Kamruzzaman, Md., Currie, G., 2019. Understanding autonomous vehicles: A systematic literature review on capability, impact, planning and policy. J. Transp. Land Use 12. https://doi.org/10.5198/jtlu.2019.1405
Farah, H., Erkens, S.M.J.G., Alkim, T., van Arem, B., 2018. Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions, in: Meyer, G., Beiker, S. (Eds.), Road Vehicle Automation 4, Lecture Notes in Mobility. Springer International Publishing, Cham, pp. 187–197. https://doi.org/10.1007/978-3-319-60934-8_16
Feil, M., 2010. Choosing the daily schedule: Expanding activity based travel demand modelling. ETH Zurich. https://doi.org/10.3929/ETHZ-A-006200573
Flämig, H., 2016. Autonomous Vehicles and Autonomous Driving in Freight Transport, in: Maurer, M., Gerdes, J.C., Lenz, B., Winner, H. (Eds.), Autonomous Driving. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 365–385. https://doi.org/10.1007/978-3-662-48847-8_18
Florian, M., Constantin, I., Florian, D., 2009. A New Look at Projected Gradient Method for Equilibrium Assignment. Transp. Res. Rec. J. Transp. Res. Board 2090, 10–16. https://doi.org/10.3141/2090-02
Flyvbjerg, B., Skamris Holm, M.K., Buhl, S.L., 2005. How (In)accurate Are Demand Forecasts in Public Works Projects?: The Case of Transportation. J. Am. Plann. Assoc. 71, 131–146. https://doi.org/10.1080/01944360508976688
Friedrich, M., Hartl, M., Magg, C., 2018. A modeling approach for matching ridesharing trips within macroscopic travel demand models. Transportation 45, 1639–1653. https://doi.org/10.1007/s11116-018-9957-5
Gandia, R.M., Antonialli, F., Cavazza, B.H., Neto, A.M., Lima, D.A. de, Sugano, J.Y., Nicolai, I., Zambalde, A.L., 2019. Autonomous vehicles: scientometric and bibliometric review. Transp. Rev. 39, 9–28. https://doi.org/10.1080/01441647.2018.1518937
Gazis, D.C., Herman, R., Potts, R.B., 1959. Car-Following Theory of Steady-State Traffic Flow. Oper. Res. 7, 499–505. https://doi.org/10.1287/opre.7.4.499
Gelauff, G., Ossokina, I., Teulings, C., 2019. Spatial and welfare effects of automated driving: Will cities grow, decline or both? Transp. Res. Part Policy Pract. 121, 277–294. https://doi.org/10.1016/j.tra.2019.01.013
Gelauff, G., Ossokina, I., Teulings, C., 2017. Spatial effects of automated driving: dispersion, concentration or both?
Gkartzonikas, C., Gkritza, K., 2019. What have we learned? A review of stated preference and choice studies on autonomous vehicles. Transp. Res. Part C Emerg. Technol. 98, 323–337. https://doi.org/10.1016/j.trc.2018.12.003
Goasduff, L., 2021. The 4 Trends That Prevail on the Gartner Hype Cycle for AI, 2021. Gartner. URL https://www.gartner.com/en/articles/the-4-trends-that-prevail-on-the-gartner-hype-cycle-for-ai-2021 (accessed 2021-11-25).

Greenshields, B.D., 1934. The photographic method of studying traffic behavior. Proc. 13th Annu. Meet. Highw. Res. Board 382–399.
Guo, J., Susilo, Y., Antoniou, C., Pernestål Brenden, A., 2020. Influence of Individual Perceptions on the Decision to Adopt Automated Bus Services. Sustainability 12, 6484. https://doi.org/10.3390/su12166484
Hansson, J., Pettersson, F., Svensson, H., Wretstrand, A., 2019. Preferences in regional public transport: a literature review. Eur. Transp. Res. Rev. 11, 38. https://doi.org/10.1186/s12544-019-0374-4
Harb, M., Malik, J., Circella, G., Walker, J., 2021a. Glimpse of the Future: Simulating Life with Personally Owned Autonomous Vehicles and Their Implications on Travel Behaviors. Transp. Res. Rec. J. Transp. Res. Board 036119812110525. https://doi.org/10.1177/03611981211052543
Harb, M., Stathopoulos, A., Shiftan, Y., Walker, J.L., 2021b. What do we (Not) know about our future with automated vehicles? Transp. Res. Part C Emerg. Technol. 123, 102948. https://doi.org/10.1016/j.trc.2020.102948
Hardman, S., Berliner, R., Tal, G., 2019. Who will be the early adopters of automated vehicles? Insights from a survey of electric vehicle owners in the United States. Transp. Res. Part Transp. Environ. 71, 248–264. https://doi.org/10.1016/j.trd.2018.12.001
Hawkins, J., Nurul Habib, K., 2019. Integrated models of land use and transportation for the autonomous vehicle revolution. Transp. Rev. 39, 66–83. https://doi.org/10.1080/01441647.2018.1449033
Hibberd, D., Louw, T., Aittoniemi, E., Brouwer, R., Dotzauer, M., Fahrenkrog, F., Innamaa, S., Kuisma, S., Merat, N., Metz, B., Neila, N., Penttinen, M., Puente Guillen, P., Rösener, C., Silla, A., Streubel, T., Tango, F., van den Boom, B., Weber, H., Woerle, J., Zerbe, A., 2018. From Research Questions to Logging Requirements: L3Pilot Deliverable D3.1. URL https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ba8f036d&appId=PPGMS (accessed 2021-10-12).
Hildebrand, C., Hörtin, S., 2014. A comparative study between Emme and Visum with respect to public transport assignment (Master). Linköping university. URL https://www.diva-portal.org/smash/get/diva2:772068/FULLTEXT01.pdf (accessed 2022-04-14).
Holden, E., Banister, D., Gössling, S., Gilpin, G., Linnerud, K., 2020. Grand Narratives for sustainable mobility: A conceptual review. Energy Res. Soc. Sci. 65, 101454. https://doi.org/10.1016/j.erss.2020.101454
Hoogendoorn, R., van Arerm, B., Hoogendoom, S., 2014. Automated Driving, Traffic Flow Efficiency, and Human Factors: Literature Review. Transp. Res. Rec. J. Transp. Res. Board 2422, 113–120. https://doi.org/10.3141/2422-13
Hopkins, D., Schwanen, T., 2018. Automated Mobility Transitions: Governing Processes in the UK. Sustainability 10, 956. https://doi.org/10.3390/su10040956
Hoque, J.M., Erhardt, G.D., Schmitt, D., Chen, M., Wachs, M., 2021. Estimating the uncertainty of traffic forecasts from their historical accuracy. Transp. Res. Part Policy Pract. 147, 339–349. https://doi.org/10.1016/j.tra.2021.03.015
Horni, A., Nagel, K., Axhausen, K.W. (Eds.), 2016. The Multi-Agent Transport Simulation MATSim. Ubiquity Press. https://doi.org/10.5334/baw
Horowitz, A.J., Farmer, D.D., 1999. Statewide Travel Forecasting Practice: A Critical Review. Transp. Res. Rec. J. Transp. Res. Board 1685, 13–20. https://doi.org/10.3141/1685-03

Horschutz Nemoto, E., Issaoui, R., Korbee, D., Jaroudi, I., Fournier, G., 2021. How to measure the impacts of shared automated electric vehicles on urban mobility. Transp. Res. Part Transp. Environ. 93. https://doi.org/10.1016/j.trd.2021.102766
Huang, H., Cheng, Y., Weibel, R., 2019. Transport mode detection based on mobile phone network data: A systematic review. Transp. Res. Part C Emerg. Technol. 101, 297–312. https://doi.org/10.1016/j.trc.2019.02.008
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 2021-11-02).
Innamaa, S., Smith, S., Barnard, Y., Rainville, L., Rakoff, H., Horiguchi, R., 2018. Trilateral Impact Assessment Framework for Automation in Road Transportation. URL https://www.connectedautomateddriving.eu/wp-content/uploads/2018/03/Trilateral_IA_Framework_April2018.pdf (accessed 2021-10-07).
Integrated Transport Research Lab, 2021. Our Research [Webpage]. URL https://www.itrl.kth.se/research (accessed 2021-11-29).
International Transport Forum, 2017a. Shared Mobility Simulations for Helsinki. OECD/International Transport Forum. URL https://www.itf-oecd.org/sites/default/files/docs/shared-mobility-simulations-helsinki.pdf (accessed 2018-10-01).
International Transport Forum, 2017b. Shared Mobility Simulations for Auckland. OECD/International Transport Forum. URL https://www.itf-oecd.org/sites/default/files/docs/shared-mobility-simulations-auckland.pdf (accessed 2018-09-28).
International Transport Forum, 2016. Shared Mobility - Innovation for Liveable Cities. OECD/International Transport Forum. URL https://www.itf-oecd.org/sites/default/files/docs/shared-mobility-liveable-cities.pdf (accessed 2020-01-27).
International Transport Forum, 2015. Urban mobility system upgrade - How shared self-driving cars could change city traffic. OECD/International Transport Forum. URL https://www.itf-oecd.org/sites/default/files/docs/15cpb_self-drivingcars.pdf (accessed 2020-04-28).
Islam, E.S., Moawad, A., Kim, N., Rousseau, A., 2019. Vehicle Electrification Impacts on Energy Consumption for Different Connected-Autonomous Vehicle Scenario Runs. World Electr. Veh. J. 11, 9. https://doi.org/10.3390/wevj11010009
Jansson, K., Lang, H., 2009. Models for competition between public transport routes and modes. 11th Conf. Compet. Ownersh. Land Passeng. Transp. 20.
Johansen, I., 2018. Scenario modelling with morphological analysis. Technol. Forecast. Soc. Change 126, 116–125. https://doi.org/10.1016/j.techfore.2017.05.016
Johansson, M., Ekman, F., Strömberg, H., Karlsson, M., Bligård, L.-O., 2021. Capable and considerate: Exploring the assigned attributes of an automated vehicle. Transp. Res. Interdiscip. Perspect. 10, 10. https://doi.org/10.1016/j.trip.2021.100383
Johari, M., Keyvan-Ekbatani, M., Leclercq, L., Ngoduy, D., Mahmassani, H.S., 2021. Macroscopic network-level traffic models: Bridging fifty years of development toward the next era. Transp. Res. Part C Emerg. Technol. 131, 103334. https://doi.org/10.1016/j.trc.2021.103334
Jones, M.L.H., 2019. A Testbed for Motion Sickness in Driverless Vehicles. URL https://mcity.umich.edu/wp-content/uploads/2019/08/mcity-whitepaper-motion-v6.pdf (accessed 2021-11-26).

Jonsson, D., Berglund, S., Almström, P., Algers, S., 2011. The Usefulness of Transport Models in Swedish Planning Practice. Transp. Rev. 31, 251–265. https://doi.org/10.1080/01441647.2010.537100
Kagho, G.O., Balac, M., Axhausen, K.W., 2020. Agent-Based Models in Transport Planning: Current State, Issues, and Expectations. Procedia Comput. Sci. 170, 726–732. https://doi.org/10.1016/j.procs.2020.03.164
Kalra, N., Paddock, S.M., 2016. Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability? Transp. Res. Part Policy Pract. 94, 182–193. https://doi.org/10.1016/j.tra.2016.09.010
Kassens-Noor, E., Wilson, M., Cai, M., Durst, N., Decaminada, T., 2021. Autonomous vs. Self-Driving Vehicles: The Power of Language to Shape Public Perceptions. J. Urban Technol. 28, 5–24. https://doi.org/10.1080/10630732.2020.1847983
Kim, S.H., Mokhtarian, P.L., Circella, G., 2020. Will autonomous vehicles change residential location and vehicle ownership? Glimpses from Georgia. Transp. Res. Part Transp. Environ. 82, 102291. https://doi.org/10.1016/j.trd.2020.102291
Kolarova, V., 2021. Measuring, analysing and explaining the value of travel time savings for autonomous driving (Doctoral). Humboldt Universität. URL https://edoc.hu-berlin.de/handle/18452/24281 (accessed 2021-12-08).
Kolarova, V., Cyganski, R., Lenz, B., 2019. Activities while travelling? Travel time perception and travel time use in an era of automated driving, in: Advances in Transport Policy and Planning. Elsevier, pp. 171–206. https://doi.org/10.1016/bs.atpp.2019.07.002
Koopman, P., Wagner, M., 2017. Autonomous Vehicle Safety: An Interdisciplinary Challenge. IEEE Intell. Transp. Syst. Mag. 9, 90–96. https://doi.org/10.1109/MITS.2016.2583491
Kristoffersson, I., Berglund, S., Samuelsson, S., Almström, P., Algers, S., 2018. Sampers4 - Skattning av regionala efterfrågemodeller. URL https://www.diva-portal.org/smash/get/diva2:1269692/FULLTEXT01.pdf (accessed 2021-04-20).
Kulmala, R., Jääskeläinen, J., Pakarinen, S., 2019. The impact of automated transport on the role, operations and costs of road operators and authorities in Finland (No. 6/2019). Traficom Research Reports. URL https://www.traficom.fi/sites/default/files/media/publication/EU_EIP_Impact_of_Automated_Transport_Finland_Traficom_6_2019.pdf (accessed 2020-12-16).
Kyriakidis, M., Happee, R., de Winter, J.C.F., 2015. Public opinion on automated driving: Results of an international questionnaire among 5000 respondents. Transp. Res. Part F Traffic Psychol. Behav. 32, 127–140. https://doi.org/10.1016/j.trf.2015.04.014
Le Vine, S., Zolfaghari, A., Polak, J., 2015. Autonomous cars: The tension between occupant experience and intersection capacity. Transp. Res. Part C Emerg. Technol. 52, 1–14. https://doi.org/10.1016/j.trc.2015.01.002
Lemp, J., Rossi, T., Newman, J., Copperman, R., 2021. Uncertainty in Travel Forecasting: Exploratory Modeling and Analysis TMIP-EMAT: A Desk Reference (No. FHWA-HEP-21-032). Federal Highway Administration, Washington, D.C.
Levine, J., Zellner, M., Arquero de Alarcón, M., Shiftan, Y., Massey, D., 2018. The impact of automated transit, pedestrian, and bicycling facilities on urban travel patterns. Transp. Plan. Technol. 41, 463–480. https://doi.org/10.1080/03081060.2018.1468968
Lighthill, M.J., Whitham, G.B., 1955. On kinematic waves II. A theory of traffic flow on long crowded roads. Proc. R. Soc. Lond. Ser. Math. Phys. Sci. 229, 317–345. https://doi.org/10.1098/rspa.1955.0089
Liu, J., Kockelman, K.M., Boesch, P.M., Ciari, F., 2017. Tracking a system of shared autonomous vehicles across the Austin, Texas network using agent-based

simulation. Transportation 44, 1261–1278. https://doi.org/10.1007/s11116-017-9811-1
Lu, X., Madadi, B., Farah, H., Snelder, M., Annema, J.A., Arem, B.V., 2019. Scenario-Based Infrastructure Requirements for Automated Driving, in: CICTP 2019. Presented at the 19th COTA International Conference of Transportation Professionals, American Society of Civil Engineers, Nanjing, China, pp. 5684–5695. https://doi.org/10.1061/9780784482292.489
Maciejewski, M., Bischoff, J., 2018. Congestion effects of autonomous taxi fleets. Transport 33, 971–980. https://doi.org/10.3846/16484142.2017.1347827
Markoff, J., 2010. Google Cars Drive Themselves, in Traffic. N. Y. Times. URL https://www.nytimes.com/2010/10/10/science/10google.html (accessed 2021-11-25).
Marsden, G., Reardon, L., 2018. Governance of the Smart Mobility Transistion, Emerald Points. Emerald Publishing.
Martínez-Díaz, M., Soriguera, F., 2018. Autonomous vehicles: theoretical and practical challenges. Transp. Res. Procedia 33, 275–282. https://doi.org/10.1016/j.trpro.2018.10.103
Mauer, G.F., 1995. A fuzzy logic controller for an ABS braking system. IEEE Trans. Fuzzy Syst. 3, 381–388. https://doi.org/10.1109/91.481947
McKinsey & Company, 2019. The future of mobility is at our doorstep. URL https://www.mckinsey.com/~/media/McKinsey/Industries/Automotive%20and%20Assembly/Our%20Insights/The%20future%20of%20mobility%20is%20at%20our%20doorstep/The-future-of-mobility-is-at-our-doorstep.pdf (accessed 2020-11-19).
McNally, M.G., 2008. The Four Step Model. EScholarship Univ. Calif. 19. URL https://escholarship.org/uc/item/0r75311t (accessed 2021-11-17).
Meyer, G., Beiker, S. (Eds.), 2014. Road Vehicle Automation, Lecture Notes in Mobility. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-05990-7
Meyer, J., Becker, H., Bösch, P.M., Axhausen, K.W., 2017. Autonomous vehicles: The next jump in accessibilities? Res. Transp. Econ. 62, 80–91. https://doi.org/10.1016/j.retrec.2017.03.005
Milakis, D., van Arem, B., van Wee, B., 2017. Policy and society related implications of automated driving: A review of literature and directions for future research. J. Intell. Transp. Syst. 21, 324–348. https://doi.org/10.1080/15472450.2017.1291351
Milakis, D., van Arem, B., van Wee, B., 2015. The ripple effect of automated driving. Presented at the BIVEC-GIBET Transport Research Day, Eindhoven, The Netherlands, p. 3.
Milne-Smith, A., 2016. Shattered Minds: Madmen on the Railways, 1860–80. J. Vic. Cult. 21, 21–39. https://doi.org/10.1080/13555502.2015.1118851
Mokhtarian, P.L., 2018. The Times They Are A-Changin': What Do the Expanding Uses of Travel Time Portend for Policy, Planning, and Life? Transp. Res. Rec. J. Transp. Res. Board 2672, 1–11. https://doi.org/10.1177/0361198118798602
Musselwhite, C., Avineri, E., Susilo, Y.O., 2014. Legitimising risk taking: articulating dangerous behaviour on the road. Transp. Plan. Technol. 37, 62–82. https://doi.org/10.1080/03081060.2013.844905
Nahmias-Biran, B., Oke, J.B., Kumar, N., 2021. Who benefits from AVs? Equity implications of automated vehicles policies in full-scale prototype cities. Transp. Res. Part Policy Pract. 154, 92–107. https://doi.org/10.1016/j.tra.2021.09.013

Narayanan, S., Chaniotakis, E., Antoniou, C., 2020. Shared autonomous vehicle services: A comprehensive review. Transp. Res. Part C Emerg. Technol. 111, 255–293. https://doi.org/10.1016/j.trc.2019.12.008
Nordström, M., 2020. Is time money? Philosophical perspectives on the monetary valuation of travel time (Licentiate). KTH Royal Institute of Technology, Stockholm, Sweden. URL http://kth.diva-portal.org/smash/get/diva2:1452346/FULLTEXT01.pdf (accessed 2021-03-02).
Nunes, A., Harper, S., Hernandez, K.D., 2020. The Price Isn't Right: Autonomous Vehicles, Public Health, and Social Justice. Am. J. Public Health 110, 796–797. https://doi.org/10.2105/AJPH.2020.305608
Pakusch, C., Boden, A., Stein, M., Stevens, G., 2021. The Automation of the Taxi Industry – Taxi Drivers' Expectations and Attitudes Towards the Future of their Work. Comput. Support. Coop. Work CSCW. https://doi.org/10.1007/s10606-021-09408-1
Paulsson, A., 2021. Självkörande bussar: om arbete, teknologi och en oviss framtid. Arbetsmarknad Arbetsliv 27, 60–75. URL https://journals.lub.lu.se/aoa/article/view/21613 (accessed 2021-10-01).
Pernestål, A., Kristoffersson, I., 2019. Effects of driverless vehicles – Comparing simulations to get a broader picture. Eur. J. Transp. Infrastruct. Res. 19, 23.
Pernestål, A., Kristoffersson, I., Mattsson, L.-G., 2019. Where will self-driving vehicles take us? Scenarios for the development of automated vehicles with Sweden as a case study, in: Autonomous Vehicles and Future Mobility. Elsevier, pp. 17–32. https://doi.org/10.1016/B978-0-12-817696-2.00002-0
Pernestål Brenden, A., Kottenhoff, K., 2018. Self-driving shuttles as a complement to public transport – a characterization and classification. Proc. 7th Transp. Res. Arena TRA2018.
Pettersson, F., 2019. An international review of experiences from on-demand public transport services (No. 2019:5), K2 Working papers. K2. URL http://www.k2centrum.se/sites/default/files/fields/field_uppladdad_rapport/on-demand_pt.pdf?utm_campaign=unspecified&utm_content=unspecified&utm_medium=email&utm_source=apsis-anp-3 (accessed 2019-06-20).
Piao, J., McDonald, M., Hounsell, N., Graindorge, M., Graindorge, T., Malhene, N., 2016. Public Views towards Implementation of Automated Vehicles in Urban Areas. Transp. Res. Procedia 14, 2168–2177. https://doi.org/10.1016/j.trpro.2016.05.232
Profillidis, V.A., Botzoris, G.N., 2018. Modeling of Transport Demand. Elsevier. https://doi.org/10.1016/B978-0-12-811513-8.01001-3
Richards, P.I., 1956. Shock Waves on the Highway. Oper. Res. 4, 42–51. https://doi.org/10.1287/opre.4.1.42
Richter, V., 2018. Transport Choices and Vehicle Ownership with Autonomous Vehicles (Master). KTH Royal Institute of Technology. URL http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1243246&dswid=-7581 (accessed 2020-09-16).
Rydergren, C., 2013. Comparison of headway-based public transport models: Numerical experiments for Stockholm. Public Transp. 5, 177–191. https://doi.org/10.1007/s12469-013-0071-y
SAE International, 2021. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles (No. J3016). URL (accessed 2021-05-17).
Samuelsson, S., Wang, Q., 2020. PM Region Öst, Validering Sampers, Basprognos 2020-06-15. URL

https://www.trafikverket.se/contentassets/ca21d4a110814f23a794c2a6ebb87979/2020/pm_region_ost_validering_sampers_20_06.pdf (accessed 2021-12-22).
Scheltes, A., 2017. Exploring the use of automated vehicles as last mile connection of train trips through an agent-based simulation model: An application to Delft, Netherlands 15. Int. J. of Trans. Sci. and Tech. https:// http://dx.doi.org/10.1016/j.ijtst.2017.05.004
Shen, Y., Zhang, H., Zhao, J., 2018. Integrating shared autonomous vehicle in public transportation system: A supply-side simulation of the first-mile service in Singapore. Transp. Res. Part Policy Pract. 113, 125–136. https://doi.org/10.1016/j.tra.2018.04.004
Shepherd, S.P., 2014. A review of system dynamics models applied in transportation. Transp. B Transp. Dyn. 2, 83–105. https://doi.org/10.1080/21680566.2014.916236
Shladover, S.E., 2021. Opportunities and Challenges in Cooperative Road Vehicle Automation. IEEE Open J. Intell. Transp. Syst. 2, 216–224. https://doi.org/10.1109/OJITS.2021.3099976
Shladover, S.E., 2018. Connected and automated vehicle systems: Introduction and overview. J. Intell. Transp. Syst. 22, 190–200. https://doi.org/10.1080/15472450.2017.1336053
Singh, M., Kim, S., 2018. Branch based blockchain technology in intelligent vehicle. Comput. Netw. 145, 219–231. https://doi.org/10.1016/j.comnet.2018.08.016
Singleton, P.A., 2019. Discussing the “positive utilities” of autonomous vehicles: will travellers really use their time productively? Transp. Rev. 39, 50–65. https://doi.org/10.1080/01441647.2018.1470584
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 2021-08-11).
Smit, G., Flickenschild, M., Verkennis, N., Martino, A., De Stasio, C., Fiorello, D., Schade, W., Scherf, C., Berthold, D., Stich, M., Öörni, R., Fougeyrollas, A., Dreher, S., Giro, C., Tozzi, M., Saeidizand, P., 2020. Study on exploring the possible employment implications of connected and automated driving. ECORYS, Rotterdam, Netherlands. URL http://www.astra-model.eu/pubblication/CAD_Employment_Impacts_Main_Report.pdf (accessed 2021-06-02).
Smith, S., Bellone, J., Bransfield, S., Ingles, A., Noel, G., Reed, E., Yanagisawa, M., 2015. Benefits Estimation Framework for Automated Vehicle Operations (No. FHWA-JPO-16-229). U.S. Department of Transportation. URL https://rosap.ntl.bts.gov/view/dot/4298 (accessed 2020-11-20).
Sonnleitner, J., Friedrich, M., Richter, E., 2021. Impacts of highly automated vehicles on travel demand: macroscopic modeling methods and some results. Transportation. https://doi.org/10.1007/s11116-021-10199-z
Sørensen, C.H., Pettersson, F., Hansson, J., 2021. Planning for Bus Priority. Int. Encycl. Transp. URL https://www.sciencedirect.com/science/article/pii/B978008102671710692X (accessed 2021-12-06).
Soteropoulos, A., Berger, M., Ciari, F., 2019. Impacts of automated vehicles on travel behaviour and land use: an international review of modelling studies. Transp. Rev. 39, 29–49. https://doi.org/10.1080/01441647.2018.1523253
Sovacool, B.K., Axsen, J., 2018. Functional, symbolic and societal frames for automobility: Implications for sustainability transitions. Transp. Res. Part Policy Pract. 118, 730–746. https://doi.org/10.1016/j.tra.2018.10.008

Sparrow, R., Howard, M., 2020. Make way for the wealthy? Autonomous vehicles, markets in mobility, and social justice. Mobilities 15, 514–526. https://doi.org/10.1080/17450101.2020.1739832
Spiess, H., Florian, M., 1989. Optimal strategies: A new assignment model for transit networks. Transp. Res. Part B Methodol. 23, 83–102. https://doi.org/10.1016/0191-2615(89)90034-9
Sweco Society AB, 2018. Validering av nuläge för Sampers Basprognos 2018. URL https://www.trafikverket.se/contentassets/ca21d4a110814f23a794c2a6ebb87979/2018/validering_sampers_basprognos_nulagesar_2018_trv_reg_sthlm.pdf (accessed 2019-02-22).
Tabone, W., de Winter, J., Ackermann, C., Bärgman, J., Baumann, M., Deb, S., Emmenegger, C., Habibovic, A., Hagenzieker, M., Hancock, P.A., Happee, R., Krems, J., Lee, J.D., Martens, M., Merat, N., Norman, D., Sheridan, T.B., Stanton, N.A., 2021. Vulnerable road users and the coming wave of automated vehicles: Expert perspectives. Transp. Res. Interdiscip. Perspect. 9, 100293. https://doi.org/10.1016/j.trip.2020.100293
Taeihagh, A., 2021. Governance of artificial intelligence. Policy Soc. 40, 137–157. https://doi.org/10.1080/14494035.2021.1928377
Taeihagh, A., Lim, H.S.M., 2019. Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks. Transp. Rev. 39, 103–128. https://doi.org/10.1080/01441647.2018.1494640
Taiebat, M., Brown, A.L., Safford, H.R., Qu, S., Xu, M., 2018. A Review on Energy, Environmental, and Sustainability Implications of Connected and Automated Vehicles. Environ. Sci. Technol. acs.est.8b00127. https://doi.org/10.1021/acs.est.8b00127
Tillema, T., Berveling, J., Gelauff, G., van der Waard, J., Harms, L., Derriks, H., 2015. Driver at the wheel. KiM - Netherlands Institute for Transport Policy Analysis. URL https://english.kimnet.nl/binaries/kimnet-english/documenten/documents-research-publications/2015/10/14/driver-at-the-wheel/driver-at-the-wheel.pdf (accessed 2022-05-10)
Trafikförvaltningen, Region Stockholm, Trafikverket, Stockholms stad, 2021. Trafikprognoser och scenarier för Stockholms län (No. TN 2018-1597). URL https://bransch.trafikverket.se/contentassets/ab2b717bc619425280126edb6e725188/2021/trafikprognoser-och-scenarier-for-stockholms-lan_uppdatering_20220517.pdf (accessed 2022-04-14).
Trafikverket, 2021. Effektberäkning och samhällsekonomi (Samkalk) [Webpage]. URL https://www.trafikverket.se/tjanster/system-och-verktyg/Prognos--och-analysverktyg/Sampers/samkalk--effektberakning-och-samhallsekonomi/ (accessed 2021-02-19).
Trafikverket, 2020a. Sampers [Webpage]. URL https://www.trafikverket.se/tjanster/system-och-verktyg/Prognos--och-analysverktyg/Sampers/ (accessed 2021-02-19).
Trafikverket, 2020b. Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7.0 (No. 7.0). URL https://www.trafikverket.se/contentassets/4b1c1005597d47bda386d81dd3444b24/asek-7-hela-rapporten_210129.pdf (accessed 2021-04-15).
Ulrich, S., Kulmala, R., Reisenbichler, D., Aigner, W., 2020. ODD requirements and other consequences of automated vehicles to physical and digital infrastructure. Proc. 8th Transp. Res. Arena TRA 2020 11.
Urry, J., 2004. The 'System' of Automobility. Theory Cult. Soc. 21, 25–39. https://doi.org/10.1177/0263276404046059

van Wageningen-Kessels, F., van Lint, H., Vuik, K., Hoogendoorn, S., 2015. Genealogy of traffic flow models. EURO J. Transp. Logist. 4, 445–473. https://doi.org/10.1007/s13676-014-0045-5
Vanston, J.H., Frisbie, W.P., Lopreato, S.C., Boston, D.L., 1977. Alternate scenario planning. Technol. Forecast. Soc. Change 10, 159–180. https://doi.org/10.1016/0040-1625(77)90043-9
Vij, A., Shankari, K., 2015. When is big data big enough? Implications of using GPS-based surveys for travel demand analysis. Transp. Res. Part C Emerg. Technol. 56, 446–462. https://doi.org/10.1016/j.trc.2015.04.025
Voorhees, A.M., 2013. A general theory of traffic movement: The 1955 ITE past presidents' award paper. Transportation 40, 1105–1116. https://doi.org/10.1007/s11116-013-9487-0
Wadud, Z., 2017. Fully automated vehicles: A cost of ownership analysis to inform early adoption. Transp. Res. Part Policy Pract. 101, 163–176. https://doi.org/10.1016/j.tra.2017.05.005
Wadud, Z., Huda, F.Y., 2019. Fully automated vehicles: the use of travel time and its association with intention to use. Proc. Inst. Civ. Eng. - Transp. 1–15. https://doi.org/10.1680/jtran.18.00134
Wadud, Z., MacKenzie, D., Leiby, P., 2016. Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. Transp. Res. Part Policy Pract. 86, 1–18. https://doi.org/10.1016/j.tra.2015.12.001
Wadud, Z., Mattioli, G., 2021. Fully automated vehicles: A cost-based analysis of the share of ownership and mobility services, and its socio-economic determinants. Transp. Res. Part Policy Pract. 151, 228–244. https://doi.org/10.1016/j.tra.2021.06.024
Wardman, M., 1998. The Value of Travel Time: A Review of British Evidence. J. Transp. Econ. Policy 32, 285–316.
Weber, M., 2014. Where to? A history of autonomous vehicles. Comput. Hist. Mus. URL https://computerhistory.org/blog/where-to-a-history-of-autonomous-vehicles/?key=where-to-a-history-of-autonomous (accessed 2021-11-25).
Weiner, E., 1997. Urban Transportation Planning in the United States: An Historical Overview (fifth edition) (No. DOT-T-97-24). US Department of Transportation, Washington, D.C. URL http://www.bv.transports.gouv.qc.ca/mono/1087135.pdf (accessed 2021-11-17).
Wikipedia, 2021. Victoria line. Wikipedia. URL https://en.wikipedia.org/wiki/Victoria_line (accessed 2021-11-25).
Witzell, J., 2021. Approaching Transformative Futures. KTH Royal Institute of Technology. URL http://kth.diva-portal.org/smash/get/diva2:1512322/FULLTEXT01.pdf (accessed 2021-08-25).
Yap, M.D., Correia, G., van Arem, B., 2016. Preferences of travellers for using automated vehicles as last mile public transport of multimodal train trips. Transp. Res. Part Policy Pract. 94, 1–16. https://doi.org/10.1016/j.tra.2016.09.003
Ye, L., Yamamoto, T., 2018. Modeling connected and autonomous vehicles in heterogeneous traffic flow. Phys. Stat. Mech. Its Appl. 490, 269–277. https://doi.org/10.1016/j.physa.2017.08.015
Zhang, W., Guhathakurta, S., Fang, J., Zhang, G., 2015. Exploring the impact of shared autonomous vehicles on urban parking demand: An agent-based simulation approach. Sustain. Cities Soc. 19, 34–45. https://doi.org/10.1016/j.scs.2015.07.006
Zhang, W., Jenelius, E., Badia, H., 2019. Efficiency of Semi-Autonomous and Fully Autonomous Bus Services in Trunk-and-Branches Networks. J. Adv. Transp. 2019, 1–17. https://doi.org/10.1155/2019/7648735

Zito, R., D'Este, G., Taylor, M.A.P., 1995. Global positioning systems in the time domain: How useful a tool for intelligent vehicle-highway systems? Transp. Res. Part C Emerg. Technol. 3, 193–209. https://doi.org/10.1016/0968-090X(95)00006-5
Zmud, J., Lee-Gosselin, M., Munizaga, M., Carrasco, J.A. (Eds.), 2013. Transport Survey Methods: Best Practice for Decision Making: Best Practice for Decision Making. Emerald Group Publishing Limited. https://doi.org/10.1108/9781781902882
Zubin, I., Van Oort, N., Van Binsbergen, A., Van Arem, B., 2021. Deployment Scenarios for First/Last-Mile Operations With Driverless Shuttles Based on Literature Review and Stakeholder Survey. IEEE Open J. Intell. Transp. Syst. 2, 322–337. https://doi.org/10.1109/OJITS.2021.3106164