Frameworks for assessing societal impacts of automated driving technology

Erik Almlöf, Xiaoyun Zhao, Anna Pernestål, Erik Jenelius & Mikael Nybacka

To cite this article: Erik Almlöf, Xiaoyun Zhao, Anna Pernestål, Erik Jenelius & Mikael Nybacka (2022): Frameworks for assessing societal impacts of automated driving technology, Transportation Planning and Technology, DOI: 10.1080/03081060.2022.2134866

To link to this article: https://doi.org/10.1080/03081060.2022.2134866
Frameworks for assessing societal impacts of automated driving technology

Erik Almlöf, Xiaoyun Zhao, Anna Pernestål, Erik Jenelius and Mikael Nybacka

ABSTRACT
Numerous studies have studied the impacts of automated driving (AD) technology on e.g. accident rates or CO₂ emissions using various frameworks. In this paper we present an overview of previous frameworks used for societal impacts and review their advantages and limitations. Additionally, we introduce the Total Impact Assessment (TIA) framework developed by the Swedish Transport Administration and use this framework to evaluate three scenarios for AD bus services in Stockholm. We conclude that the reviewed frameworks cover different aspects of AD technology, and that e.g. cybersecurity and biodiversity are areas largely neglected. Furthermore, most frameworks assume effects to be homogenous, when there may be large variation in e.g. perceived security. The TIA framework does not manage to include all societal aspects of AD technology, but has great benefits and manages to provide important insights of the societal impacts of AD technology, especially how effects may vary for different actors.

ARTICLE HISTORY
Received 20 January 2022
Accepted 6 October 2022

KEYWORDS
Automated driving; autonomous vehicles; framework; review; societal impacts

Introduction
Since Waymo’s first trials of automated cars during the early years of the 2010s, interest in automated driving (AD) technology has increased dramatically. Since this new research field has emerged, the majority of research has focused on how to achieve AD capability (Gandia et al. 2019), with promises of accident-free cars with napping drivers, heralding large societal gains (Marsden and Reardon 2018). These promises have been nuanced during the last years by researchers focusing on societal impacts of AD vehicles, who have revealed both advantages such as increased accessibility, as well as disadvantages, e.g. increased emissions due to higher demand (Milakis, Van Arem, and van Wee 2017).
Still, investigations of societal impacts remain a small share of research concerning AD (Gandia et al. 2019), with only a few studies comprehensively trying to evaluate all impacts of the technology (Narayanan, Chaniotakis, and Antoniou 2020).

The aim of this paper is two-fold. First, we provide an overview of previously used frameworks for evaluating AD technology. We compare and discuss the scope and motivation for each framework, the dimensions covered and the advantages and disadvantages of the different approaches.

Second, we introduce the Total Impact Assessment (TIA) framework as a potential candidate for evaluating AD technology. The framework has been developed by the Swedish National Transport Administration with the intent to comprehensively list all impacts of transport interventions and has previously been used mainly for infrastructure investments. Within this paper, we exemplify the use of the framework for AD technology evaluation with an appraisal case study of an AD bus service and three possible scenarios related to infrastructure requirements.

We show that no framework, including the TIA framework, addresses all impacts of AD technology and that this hinders the understanding of the technology. The lack of a complete understanding of societal impacts leads to less effective policy making and further work is needed to develop frameworks for assessing impacts of AD technology. However, we further conclude that the TIA framework is a potential addition, especially since the framework covers political goals for the transport system.

This paper is organised as follows. Section 2 describes previous frameworks used to evaluate the impacts of AD technology. Section 3 describes the TIA framework and how it has previously been used, Section 4 describes the case study, the method of evaluation and the assumptions made. The results of the evaluation of the scenarios are shown in Section 5, followed by Section 6 where we discuss the use of the TIA framework and how it relates to previously used frameworks. Finally, we draw conclusions in Section 7.

**Frameworks for comprehensive impact assessment of automated driving technology**

The frameworks used in this study were initially collected through a search on Web of Science using their ‘Keywords Plus’ tag (Zhang et al. 2016) and the keywords ‘framework’ AND (‘self-driving vehicle*’ OR ‘autonomous vehicle*’ OR ‘driverless vehicle*’ OR ‘automated vehicle*’ OR ‘self-driving car*’ OR ‘autonomous car*’ OR ‘driverless car*’ OR ‘automated car*’ OR ‘autonomous driving’ OR ‘automated driving’), which yielded 588 results out of which two concerned societal impacts. Additional frameworks were found through snowballing as well as previous knowledge by the authors and literature seminars with colleagues. We included all previous work that explored impacts in more than one area and that have sought to draw conclusions on broad societal impacts (e.g. public health, energy use and economy). Moreover, the included papers try to explain impacts by putting them in their context, by showing direct or indirect relationships between variables and working with different orders of magnitude, such as street, neighbourhood and city-level implications. We use the word framework, as Gudmundsson et al. writes, as a way to organise information (Gudmundsson et al. 2016, 172, italics used in source), and not just present information.
However, it should be noted that some papers do not explicitly reference their content as frameworks and that some cover only a certain type of societal impact. Similarly, some of the works included have explicitly tried to design new frameworks, whereas others have adapted existing frameworks. A summary of the frameworks reviewed can be found in Table 1.

We have categorised the identified frameworks into four types – Conceptual; System dynamics; Mathematical relationship; and State-of-the-art. These types should not be seen as exhaustive and the differences between the types are not always clear-cut. System dynamics diagrams could for example be viewed as conceptual frameworks, and all frameworks rely in varying degrees on state-of-the-art references.

**Conceptual frameworks** are overviews of a field that indicate general relationships between variables at a granular level, with the main intent to provide understanding rather than explain outcomes (Jabareen 2009). The Benefits Estimation Framework for Automated Vehicle Operations (Smith et al. 2015) exemplifies this, by dividing impacts into eight categories with 63 indicators in total. Similarly, Milakis, van Arem, and van Wee (2015) constructed their Ripple Effect Model in 2015, which was then subsequently used in their 2017 paper (Milakis, Van Arem, and van Wee 2017). This model categorises implications into different time scales but does not indicate how different factors interact with each other. Building on the work by Smith et al. (2015) and the FESTA (Field opErtional teSt supporT Action) framework (FESTA 2018), Innamaa et al. (2018) proposed the Trilateral Impact Assessment Framework (TIAF) for evaluating automation, mainly in the form of pilots. Similarly as the TIAF, the L3Pilot Evaluation Plan (Innamaa et al. 2020) was influenced by the FESTA framework, with the intent on evaluating the SAE level 3 (SAE International 2021) AD.

**System dynamics** is a technique with a focus on analysing the impacts of feedback loops, identifying causalities, exploring time delays within a system and providing a holistic worldview. The intent is to understand systems that are non-linear, dynamic and historically dependant (Forrester 2007). This approach has been used by Gruel and Stanford (2016) to explore the impacts of AD technology, investigating impacts on e.g. congestion and energy usage. Similarly, the TIAF incorporates parts of the system dynamics technique, exploring the feedback loops of travel behaviour, safety and land use.

**Mathematical relationships** are integrated in all quantitative frameworks to some extent. However, a few studies use them as their main technique. Fagnant and Kockelman (2015) approximated the economic effects of various impacts of AD technology using assumptions of e.g. accident reduction and saved parking costs. Similarly, Alonso Raposo et al. (2018) estimated impacts for the workforce in the EU using simple estimations of effects for different industries related to transport. Exploring the emissions and energy use, Wadud, MacKenzie, and Leiby (2016) used the ASIF (Activity Level, Modal Share, Energy Intensity, Fuel Carbon Content) framework for AD technology using previous literature on e.g. the potential fuel effects of platooning. The ASIF framework focuses on the impacts of travel (mainly vehicle miles travelled), energy and carbon emissions, but also touches upon other areas, including increased accessibility and induced travel demand. In contrast to other approaches to impact estimation, Andersson and Ivehammar (2019) used a cost–benefit calculation to estimate thresholds for when AD technology may become feasible for different use cases. Additionally, the L3Pilot Evaluation Plan used mathematical relationships to explain interaction
<table>
<thead>
<tr>
<th>Name/Source</th>
<th>Type of framework</th>
<th>Scope</th>
<th>Modes covered</th>
<th>Motivation</th>
<th>Main dimensions</th>
<th>Number of indicators</th>
<th>Quantitative</th>
<th>Interaction between variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fagnant and Kockelman (2015)</td>
<td>Mathematical relationships</td>
<td>Transport system</td>
<td>Passenger: Mainly car</td>
<td>Explore the feasible aspects of AD vehicles, their potential effect on the transport system and policy impacts</td>
<td>Safety, Congestion, Travel behaviour, Freight</td>
<td>14</td>
<td>Partly</td>
<td>No</td>
</tr>
<tr>
<td>Ripple effect model Milakis, van Arem, and van Wee (2015)</td>
<td>Conceptual</td>
<td>Societal</td>
<td>Passenger: Car, public transport, walking and cycling</td>
<td>Conceptualise sequential effects of automated driving to mobility and society</td>
<td>Short-term effects – including e.g. Cost of travel, Road capacity and Mode choice Medium-term effects – including e.g. vehicle ownership rates, location choice and infrastructure Long-term effects – including wider impacts such as energy usage or health issues or economic impacts</td>
<td>21 areas affected, with implicit sub-indicators</td>
<td>No</td>
<td>Broadly</td>
</tr>
<tr>
<td>Gruel and Stanford (2016)</td>
<td>System dynamics</td>
<td>Transport system</td>
<td>Passenger: Mainly car</td>
<td>Identify automation effects at the system level, especially long-term and indirect effects</td>
<td>Several, mainly revolving around the Attractiveness of Travelling by car.</td>
<td>31</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>ASIF Framework Wadud,</td>
<td>Mathematical relationships</td>
<td>Kilometres travelled, Energy</td>
<td>Freight and passenger:</td>
<td>Quantitatively estimate the potential magnitudes of effects</td>
<td>Mainly Kilometres travelled, Energy consumption and CO2 emissions</td>
<td>4</td>
<td>Yes</td>
<td>Explicit</td>
</tr>
</tbody>
</table>

(Continued)
<table>
<thead>
<tr>
<th>Name/Source</th>
<th>Type of framework</th>
<th>Scope</th>
<th>Modes covered</th>
<th>Motivation</th>
<th>Main dimensions</th>
<th>Number of indicators</th>
<th>Quantitative</th>
<th>Interaction between variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>MacKenzie, and Leiby (2016)</td>
<td>Mathematical relationships</td>
<td>consumption and CO₂ emissions</td>
<td>Mainly cars and trucks</td>
<td>Understand effects on economy, workforce and society and identify policy implications for future skill needs of workers</td>
<td>Mainly divided into effects for different industries</td>
<td>39</td>
<td>Yes</td>
<td>Explicit</td>
</tr>
<tr>
<td>Alonso et al. (2018)</td>
<td>Conceptual System dynamics</td>
<td>Freight and passenger: Cars, public transport, walk, cycling and trucks.</td>
<td>Provide a transparent framework in order to clearly state results and assumptions</td>
<td>Safety, Vehicle Operations, Personal Mobility, Energy/ Emissions, Network Efficiency, Travel Behaviour, Public Health, Infrastructure &amp; Land Use and Socio-Economic Impacts</td>
<td>169</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Taiebat et al. (2018)</td>
<td>State-of-the-art Conceptual</td>
<td>Societal/ Environmental</td>
<td>Passenger: Mainly cars and buses to a smaller extent. Lightly discusses trucks.</td>
<td>Divides impact into individuals (e.g. increased accessibility) and societal gains (e.g. noise increase)</td>
<td>11</td>
<td>Yes</td>
<td>Explicit</td>
<td></td>
</tr>
<tr>
<td>Andersson and Ivelhammar (2019)</td>
<td>Mathematical relationships</td>
<td>Transport system</td>
<td>Trucks and cars</td>
<td>Determine likely impacts of a wider uptake of AD technology and how to achieve desired smart urban mobility outcomes.</td>
<td>Divides impacts into (1) Societal impacts (e.g. Employment, Land use and Energy consumption) and (2) Impact to the transport system. Also covers interventions, uptake factors and driving forces.</td>
<td>43</td>
<td>No</td>
<td>Broadly</td>
</tr>
<tr>
<td>Name/Source</td>
<td>Type of framework</td>
<td>Scope</td>
<td>Modes covered</td>
<td>Motivation</td>
<td>Main dimensions</td>
<td>Number of indicators</td>
<td>Quantitative</td>
<td>Interaction between variables</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------------------------------------</td>
<td>--------------------------------------------</td>
<td>---------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>----------------------</td>
<td>--------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>L3Pilot Evaluation Plan (Innamaa et al. 2020)</td>
<td>Conceptual Mathematical relationships</td>
<td>Technical, user experience and societal</td>
<td>Passenger: Car</td>
<td>Ensure that pilots in the L3Pilot project are successful.</td>
<td>Divides impacts into (1) technical and traffic, (2) user and acceptance, (3) impacts including travel behaviour personal mobility, safety, traffic efficiency and the environment and finally (5) cost–benefit calculations of monetised values for impacts</td>
<td>Research questions in three tiers, with 11, 35 and 71 research questions per tier. Each research question can have multiple sub-indicators</td>
<td>Yes</td>
<td>Explicit</td>
</tr>
<tr>
<td>Narayanan, Chaniotakis, and Antoniou (2020)</td>
<td>State-of-the-art</td>
<td>Societal</td>
<td>Passenger: Car, public transport, walking and cycling</td>
<td>Create a comprehensive review of impacts with regards to penetration rates, business models, demand estimates and required policies. Assess sustainability aspects</td>
<td>Societal, Environmental, Economic, Governance, System performance</td>
<td>24</td>
<td>Mix</td>
<td>No</td>
</tr>
<tr>
<td>Horschutz Nemoto et al. (2021)</td>
<td>State-of-the-art, complemented with interview of experts</td>
<td>Societal</td>
<td>Passenger: Car, public transport, walking and cycling</td>
<td>Investigate societal impact in relation to political goals</td>
<td>Quantitative and qualitative variables evaluated, distributional effects and evaluation of goal fulfilment</td>
<td>33, but some have sub-categories</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>TIA Framework (Trafikverket 2020a)</td>
<td>Mathematical relationships Conceptual (Simulation model)</td>
<td>Societal</td>
<td>Freight and passenger: Cars, public transport, walking, cycling, trucks, train, sea and air.</td>
<td>Investigate societal impact in relation to political goals</td>
<td>25 variables, 25 political goals, 8 distributional variables</td>
<td>Partly</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
between different variables, and like Andersson and Ivehammar (2019) included a cost–benefit calculation to explore overall societal impacts.

State-of-the-art frameworks are compositions of other research, drawing conclusions from past works. They generally include some sort of taxonomy and typically do not include relationships between variables. Previous work include: Taiebat et al. (2018) focusing on environmental aspects; Faisal et al. (2019) investigating policy implications; Narayanan, Chaniotakis, and Antoniou (2020) carrying out a review of business models and demand estimates; and Horschutz Nemoto et al. (2021) who concentrated on sustainability impacts.

A large body of papers has used various simulation models (e.g. MatSIM) to investigate impacts on the transport system, exploring impacts on congestion, vehicle kilometres travelled or emissions, but mainly through individual indicators rather than overall societal effect (Soteropoulos, Berger, and Ciari 2019). The L3Pilot Evaluation Plan (Innamaa et al. 2020) used the model Vissim to calculate transport efficiency (e.g. how congestion could be minimised by different travel behaviour). However, this approach does not link the simulation model results to e.g. emissions or time savings for travellers, which are instead calculated through assumptions and direct relationships. In contrast, the TIA framework integrates modelling results into societal impacts through the four-step model Sampers model (see Section 3 and 4).

Most surveyed frameworks aim at covering societal- or transport-wide impacts. The motivation is generally to investigate effects of automation, although some frameworks aim to understand uptake (e.g. Andersson and Ivehammar 2019 and Faisal et al. 2019), the intent to increase comparability of automation studies (TIAF) or have more explicit policy-driven motivations (such as Alonso Raposo et al. 2018 or Andersson and Ivehammar 2019). The focus is mainly on car transport and only the framework by Alonso Raposo et al. (2018) aims at covering all major forms of transport – cars, buses, trains, walk, cycling, ships and trucks.

The number of dimensions and/or indicators used within each framework also differ substantially, due to the varying motivations and methods used. However, most use a categorisation between different system levels, e.g. impacts on vehicle behaviour, road network and society.

The conceptual and system dynamics frameworks are mainly qualitative with varying degrees of explanations of interaction between variables. Some of the state-of-the-art frameworks draw quantitative conclusions, but are mainly reporting on previous findings and are generally not describing the interaction between variables (Taiebat et al. 2018 is an exception). Meanwhile, the mathematical frameworks are by their nature more explicit about quantitative data and relationships between variables but tend to only cover a few areas of inquiry.

A major benefit of using quantitative approaches is that advantages and disadvantages are comparable (e.g. the number of saved lives compared to the technological costs), which makes it possible to compare different measures (e.g. the benefit of increased accessibility to CO₂ emissions). This approach is used by both the L3Pilot Evaluation Plan (Innamaa et al. 2020) and (Andersson and Ivehammar 2019) with the use of cost–benefit calculations which are an established technique for monetising impacts.

The frameworks cover a broad range of variables (Table 2), from vehicle damages to land use and travel time. Only two variables – Energy Consumption and Travel Time – are covered by all frameworks, and Greenhouse Gases are covered by all but one (Gruel
and Stanford (2016) only mention ‘pollution’). The TIAF and the framework by Horschutz Nemoto et al. (2021) are the most extensive frameworks, covering 19 of the 24 identified variables. However, neither of these frameworks are both quantitative nor covering interactions between variables, making it difficult to understand feedback loops and interactions with other variables.

Some areas with potential impact from AD technology are overlooked by most of the reviewed frameworks (see Table 2). These areas include users’ perceptions of the vehicles and cybersecurity issues. In addition, factors such as biodiversity implications (from e.g. increased road pollution) or impacts on cultural artefacts are not mentioned. Furthermore, only the framework by Horschutz Nemoto et al. (2021) explicitly investigates how impacts may vary between different societal groups (e.g. if children are affected differently than adults). Impacts varying between e.g. men and women could likely be easily incorporated in most frameworks but are not explicitly mentioned.

Similarity among the used frameworks is that they have mainly been constructed by ‘experts’, either researchers themselves (drawing upon previous research) or through interviews with public planners, manufacturers or other researchers. A contrasting approach would be to start with politically decided needs, instead focusing on which areas are deemed important by elected officials and investigate how these areas are

Table 2. Overview of which impacts are covered by each framework. Black, grey and white means that each framework either captures the aspect, partially captures it or does not respectively.
affected by AD technology (Horschutz Nemoto et al. 2021 use this approach to some extent). This contrasting approach will be investigated within the following sections where we investigate a case of AD technology and evaluate impacts using the TIA framework.

**Cost–benefit analysis in Sweden – the TIA framework**

The Swedish Transport Administration (STA) uses Total Impact Assessment (TIA) to assess effects of changes to the transport system. The framework incorporates four different parts, further described in Trafikverket (2020a):

- **Cost–benefit calculation** of impacts of e.g. change in travel time and accident costs.
- Variables deemed to be **Non-monetisable effects** such as biodiversity.
- A **Goal fulfilment analysis**, regarding political goals for the transport sector.
- A **Distributional effects analysis**, e.g. differences between men and women.

The TIA framework is extensive, and each category is further divided into several subcategories, where each subcategory may contain varying degrees of information (e.g. a road construction project may have different impacts in the construction and operations phases) and is therefore summarised in several steps.

The **Cost–benefit calculation** is performed mainly using the transport model frameworks Sampers for person transport (Beser and Algers 2002) and Samgods for goods transport (De Jong and Baak 2020) (we only use Sampers in this paper). Sampers is a four-step transport model that calculates transport movement for each mode and uses established values for calculation of associated costs (e.g. monetised cost of injury reductions or time savings). Please see Appendix 3 for a more thorough overview of Sampers.

Assessment of **Non-monetisable effects** is generally done by experts within each subfield. The **Cost–benefit calculation** and the **Non-monetisable effects** are then summarised into conclusions of the effects of the proposed change. This summary then informs the assessment of the **Distributional effects analysis** and then the **Goal fulfilment analysis**.

Previously, the STA has mainly used the TIA framework to evaluate different infrastructure investments (Bondemark et al. 2020), but the framework has also been used to evaluate e.g. congestion charges (e.g. Eliasson 2009). To the best of our knowledge, the TIA framework has not been used previously to investigate new services or technologies.

See Trafikverket (2020) or Trafikverket (2020c) for further details of the TIA framework and the parameters included in default calculations.

**Method of applying the TIA framework**

This section provides a description of the method of applying the scenarios to the TIA framework, including assumptions made. Within this paper, we exemplify the use of the framework through the description of a full-sized AD bus line in Stockholm, Sweden, further described in Sjöström et al. (2021).

The first step of the TIA framework (see Figure 1 for an overview) consists of developing the scenarios to be analysed (Section 4.1), followed by an interpretation of the
scenarios into more concrete assumptions (Section 4.2). These assumptions are then evaluated through two separate steps – either applying the assumptions into the Sampers model, or through manual calculations. Assumptions that are deemed non-monetisable (e.g. barrier effects) are qualitatively assessed using the results of interviews and workshops with experts. As part of the TIA process, experts within the different affected fields review the assessed results, which may lead to revisions of the results.

The scenarios presented in the next Section were constructed by first interviewing seven people who were part of organisations in the Södertörn Crosslink project, or who we were recommended to contact. All interviews lasted about 40–60 min and were semi-structured with the same general questions/areas having been sent out previously to all interviewees. Our questions mainly revolved around the impacts of AD technology on drivers, travellers, manufacturers and public authorities.

All interviewees worked with AD technology on a strategic level within the respective organisations:

- Two men from Scania, a vehicle manufacturer, aged approximately 40–50 and 60–70 years old.
- One man from Keolis, a public transport operator, aged approximately 50–60 years old.
- Two men from Volvo Cars, a vehicle manufacturer, aged approximately 30–40 and 40–50.
- One woman from Region Stockholm, aged approximately 50–60 years old.
- One man from the STA, aged approximately 40–50 years old.

Using the results of the interviews, three scenarios were constructed through iterative meetings together with the Södertörn Crosslink project group, consisting of the first three authors of this paper, three consultants from Sweco and one person from the STA (see Sjöström et al. 2021).
The assessment of the three scenarios was done initially by the first author and then audited:

1. By the Södertörn Crosslink project group through iterative meetings.
2. In a workshop with four experts at the STA who specialised in transport analysis (i.e. the Sampers model), infrastructure requirements, accessibility for children and the disabled, environment and biodiversity. However, all aspects of the TIA were discussed.
3. And finally, the results were presented to 17 experts from vehicle manufacturers, public planners, operators and consultants within a workshop.

This process led to some minor changes in the results, mainly of the impacts on local wildlife and local barriers in the scenario Automation with Adaption and of infrastructure requirements for each scenario.

These requirements were then interpreted to fit the work of Kulmala, Jääskeläinen, and Pakarinen (2019) who established estimates of costs for different physical and digital infrastructure related to AD capabilities.

**Three scenarios for AD full-sized buses**

Within this paper, we evaluate three scenarios developed within the Södertörn Crosslink project. The project aimed to evaluate the feasibility of introducing AD technology on buses for a proposed bus line on a planned highway south of Stockholm, Sweden, and especially investigate infrastructure requirements. Public transport using AD has previously been investigated mainly as smaller shuttles serving as a first or last mile service (Azad et al. 2019; Levine et al. 2018), but this project focused on full-sized buses.

The three scenarios for AD buses explored different technical maturity levels around two dimensions – digital and physical infrastructure requirement (Figure 2). Two scenarios were therefore developed with either extensive requirements on digital or physical infrastructure and the third scenario with low requirements for both digital and physical infrastructure. These scenarios were then compared to the proposed ‘ordinary’ bus line, which acted as the base scenario.

The scenario Bus Driver Plus envisioned a bus service capable of AD on SAE level 4 (SAE International 2021), i.e. mostly autonomously but in this case within only certain contexts, e.g. highway driving, and in other contexts handled manually, e.g. busy intersections. An important aspect of this is the assumption that the bus needed to have a driver on board, who does not actively monitor the operations at all times and can perform other tasks (such as controlling tickets).

The scenario Automation with Adaption considered a bus that did not require a driver onboard. This was assumed to be possible through the adaption of the physical infrastructure, mainly constructing a separate highway lane. However, the bus was assumed to have an operator who can remotely control the vehicle if needed. This operator was assumed to control five vehicles simultaneously, replacing five drivers (for comparison, currently most bus fleets have an operator responsible for around 40–60 vehicles, handling e.g. replacement of faulty vehicles).

The last scenario, Automation Utopia, envisioned a vehicle at SAE level 5 (SAE International 2021), i.e. a vehicle that could operate in mixed traffic. This was assumed...
possible by requiring extensive digital infrastructure (e.g. real-time maps of the roadway). Still, an operator working remotely is assumed to remotely control 20 vehicles simultaneously.

**Interpretation of scenarios to concrete assumptions**

Table 3 outlines our interpretations and general assumptions of the three scenarios, as well as concrete quantitative assumptions. Table A.1 in Appendix 1 further describes quantitative assessments of the assumptions and the sources of each assumption. This section further discusses these assessments.

Several interviewees expected AD technology to substantially decrease vehicle accident and injury rates. This is mirrored by previous research into expectations of AD cars where several researchers find large potential to decrease accident rates by up to 90% (Fagnant and Kockelman 2015). Within this paper, we assume a reduction of bus-related accident and injury rates by 50% for the *Bus Driver Plus* scenario, where the bus is still at times driven by a human driver, and by 90% for *Automation with Adaptation* and *Automation Utopia* where the bus is mainly AD. For simplicity, we assume a symmetric reduction in accidents and injuries, i.e. that all types of accidents and injuries are reduced at the same rate.

One of the more debated topics regards the value of travel time for passengers of AD vehicles, see, e.g. Mokhtarian (2018), Nordström and Engholm (2021) and Singleton (2019) for different perspectives. This topic has mostly been explored in regard to car drivers’ potential to perform other tasks in AD vehicles (Singleton 2019) and the effects on public transport have not been investigated previously to the best of our knowledge. Several interview participants brought up potential gains related to AD technology, including smooth driving with less braking and acceleration compared to manually driven vehicles which they assumed could be similar to travelling by train. Smoother driving in manually driven buses is linked to increased satisfaction with public transport (Börjesson and Rubensson 2019) and a factor likely to be incorporated into AD vehicle design (Roeckle et al. 2018), through better path planning and suspension design for increased comfort and reduced...
motion sickness (Htike et al. 2022; Zheng et al. 2022; Papaioannou et al. 2021). In general, trains are perceived to be the most comfortable mode of transport (Wardman 1998) and can thus be seen as the upper limit of transport comfortability. To take this into account, the perceived travel time cost was set to the value for train travel, estimated to be about 30% lower than for bus travel (Börjesson and Eliasson 2014).

The interviewees also stressed that increased digital communication with e.g. traffic signals could decrease the number of unnecessary stops and braking. As was highlighted by a traffic planner, a smoother driving behaviour also reduces stop times, as passengers get ready to get off while the bus is still moving. Calculations for the current bus line determined that the bus service speed could be increased by approximately 20% with shorter station stop times and reduction in the number of stops at intersections. This 20% decrease was based on the maximum allowed speed on the different road segments plus an average stop time of 30 s (including deceleration and acceleration). This effect was thus included in the scenario Automation Utopia scenario, where digital infrastructure is expected to be extensively expanded, facilitating higher speeds and shorter stop times.

The investment costs of adding an extra lane in both directions were assessed by an expert at the STA to be 3–4 M€/km for open roads and 20–40 M€/km for tunnels. The expert expressed that these numbers were quite uncertain and could vary substantially due to local conditions. In this paper, the middle values of these cost ranges are used.

The quantitative calculations of these assumptions and assumptions of required infrastructure costs are found in Appendix 1.

### Results – evaluation of the three scenarios

This section describes the results of applying the TIA framework to the scenarios described in the previous section. The results consist of four parts – cost–benefit calculation (Figure 3); non-monetisable effects (Table 4); a distributional effects analysis (Table B.1, Appendix 2); and a goal fulfilment analysis (Table B.2, Appendix 2).
Two of the three scenarios have greater overall benefits than costs, with the second scenario Automation with Adaption seeing substantial costs and impacts connected to the construction of physical infrastructure along the bus route. Bus Driver Plus and Automation Utopia, meanwhile, have mostly positive impacts, with most citizen groups benefitting from the scenarios.

The by far largest calculated benefit originates from the assumption that passengers attribute a smaller cost of time for the assumed bus service compared to a regular bus line. This finding is on par with similar identified benefits regarding changing the value of time for car driving (Kolarova, Cyganski, and Lenz 2019). However, it should be noted that the assumption that the service is perceived as considerably better than a ‘normal’ bus line is quite optimistic and likely exaggerated (see Singleton (2019) and Wadud and Huda (2019) for two critical views). The added effect of speeding up the bus line is also a major contributor to the positive calculated results, and as such a sensitivity analysis of the Automation Utopia scenario was made without the assumptions of changes to the value of time and to speed increases, shown within Figure 3.

This sensitivity analysis still shows large gains, mainly due to the assumption of decreased headway which decreases waiting time, and indirect effects, e.g. decreased pollution due to travellers changing from car to public transport. However, the increased number of travellers would increase crowding on-board the vehicles during peak hours, which would abate the effect somewhat. During non-peak hours, crowding would likely not be a problem due to the increased headway.

The costs of AD technology for the vehicles are low compared to other costs and gains (Figure 3), while the costs of infrastructure related to AD capabilities are larger in the two scenarios Automation with Adaption and Automation Utopia. However, these results are uncertain, especially since the exact technological demands are unknown.

The lower costs for personnel outweigh the increased costs for technology for the calculated time period, confirming findings by Andersson and Ivehammar (2019). The extra road lane required in the Automation with Adaption scenario, however, constitutes a large cost that outweighs large parts of the benefits. Furthermore, it should be noted that it may not be the same actor receiving the monetary benefit (in this case the operator) as the one constructing the necessary infrastructure (Table B.1, Appendix 2), which may necessitate changes in infrastructure funding or business models.

The frequency of personal injuries and vehicle damages was assumed to drastically drop in all scenarios, but it is clear that these reductions have little impact on the overall results, since injuries and vehicle damages account for a small part of societal costs of operations.

In addition to the benefits of decreasing car traffic, results also show that the increased attractiveness of the bus service attracts a lot of pedestrians and cyclists, leading to decreases in physical activity in all scenarios, confirming the results of Cohen and Cavoli (2019) and Hörl, Ciari, and Axhausen (2016). The scenario Automation with Adaption could also lead to local barrier effects for e.g. children who may find it harder to cross roads. One auditor at the STA expressed concern that citizens may be wary of crossing the path of a driverless vehicle if they are not sure that they have been ‘seen’ by the vehicle.

The uncertainty of the perception of the driverless bus may be further expressed by passengers riding the bus. Currently, many citizens express doubts regarding the
reliability of AD technology (Gkartzonikas and Gkritza 2019). It may be reasonable to expect that this mistrust will decrease over time when people become more accustomed to the new technology (Gkartzonikas and Gkritza 2019), but an auditor from the STA highlighted that service without a human operator may constitute a problem for

**Figure 3.** Cost–benefit calculation of the three scenarios compared with planned ‘ordinary’ bus service, and a sensitivity analysis of the Automation Utopia scenario without changes to value of time or vehicle speed. A positive value demarks a positive societal impact, e.g. a reduction in accidents has a positive value, while e.g. costs of infrastructure is viewed as a negative societal impact.

The table below shows the cost–benefit calculation for different factors:

<table>
<thead>
<tr>
<th>Factor</th>
<th>Bus Driver PLUS</th>
<th>Automation with adaption</th>
<th>Automation Utopia - Sensitivity analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel times</td>
<td></td>
<td></td>
<td>252</td>
</tr>
<tr>
<td>Ticket revenues</td>
<td></td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>Travel costs for consumers</td>
<td></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Pollution and greenhouse gases</td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Accident costs, other modes</td>
<td></td>
<td></td>
<td>53</td>
</tr>
<tr>
<td>Accident costs, bus</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Autonomous infrastructure technology costs</td>
<td></td>
<td></td>
<td>-11</td>
</tr>
<tr>
<td>Autonomous bus technology costs</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Vehicles damages</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Public transport operating costs</td>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>New highway lane</td>
<td>-181</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Summary</td>
<td></td>
<td></td>
<td>374</td>
</tr>
</tbody>
</table>
people with disabilities (who may require the driver to adapt to ad hoc requirements) or children (who may not express distress explicitly).

Similarly, women perceive train services to be less safe than buses (Kim 2021), probably due to the lack of a responsible person present (Friman and Edvardsson 2003). This,

<table>
<thead>
<tr>
<th>Non-monetised effects</th>
<th>Bus Driver Plus</th>
<th>Automation with Adaption</th>
<th>Automation Utopia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operations</td>
<td>May lead to some increased costs for operations</td>
<td>Likely increased costs of operations</td>
<td>Likely increased costs of operations</td>
</tr>
<tr>
<td>Greenhouse gases</td>
<td>May decrease somewhat due to smoother driving</td>
<td>May decrease somewhat due to smoother driving. Substantial increase of emissions during construction and maintenance of both AD infrastructure and an extra lane.</td>
<td>May decrease somewhat due to smoother driving. Increased emissions during construction and maintenance of AD infrastructure.</td>
</tr>
<tr>
<td>Local pollution</td>
<td>May decrease somewhat due to smoother driving</td>
<td>May decrease somewhat due to smoother driving. Increase of emissions during construction and maintenance of both AD infrastructure and an extra lane.</td>
<td>May decrease somewhat due to smoother driving. Increased emissions during construction and maintenance of AD infrastructure.</td>
</tr>
<tr>
<td>Noise</td>
<td>May decrease somewhat due to smoother driving</td>
<td>May decrease somewhat due to smoother driving. Increase due to increased public transport service levels during off-peak hours and due to an extra lane, which decreases the distance to e.g., nearby houses. Also, substantial noise during construction phase.</td>
<td>May decrease somewhat due to smoother driving Increase due to increased public transport service levels during off-peak hours.</td>
</tr>
<tr>
<td>Landscape</td>
<td>No effect</td>
<td>Increases the land use due to construction of an extra lane. Parts of the area is a wild-life refuge.</td>
<td>No effect</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>No effect</td>
<td>The extra lane may increase the barrier effect of the highway, leading to habitat fragmentation. Parts of the area is a wild-life refuge.</td>
<td>No effect</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>Included in the cost-benefit calculation.</td>
<td>Maintenance costs of an extra lane not included in the calculation.</td>
<td>Included in the cost-benefit calculation.</td>
</tr>
</tbody>
</table>
together with variations in the perception between e.g. adults and children, may lead to some citizens rating the service as better than a present bus line, whilst others may rate it as worse.

**Discussion**

Within this paper, we have reviewed existing frameworks for societal impacts of AD technology and then evaluated three scenarios of an AD bus service using the TIA framework, which has previously mainly been used for infrastructure investment appraisal. The results given by the TIA framework highlight that a wide array of implications could be expected from introducing AD buses. Within this section, we discuss drawbacks and advantages of using the TIA framework and discuss how it may enhance our understanding of societal impacts of AD technology.

The current TIA framework has weaknesses and our application to new technology also has notable limitations. The TIA framework’s division into calculable and non-monetisable effects leads to three major issues: first, that quantifiable effects may be viewed as more important; second, that quantification may not always be done consistently (Witzell 2021); and third, the results might come from problems with the model framework not attributable to the assumed change, which may be a big concern with large simulation models (Curtis et al. 2021). Within this study, we have needed to make quantitative assumptions on changes in e.g. value of time, cost estimates and accident reduction in order to fit the scenarios into the TIA framework. Many of the assumptions are uncertain, and the results are largely influenced by our estimates, especially the assumed change in value of time.

Furthermore, our initial results were assessed by experts within the STA and by experts from consultancy firms, vehicle manufacturers and public actors. This process led to changes in the results, but it may be argued that the final results are in large part the experts’ (including our) views of effects, rather than actual effects. We have similarly also limited our study to changes made to the buses, with other modes of transport assumed to be unaffected.

However, with these caveats in mind, the TIA framework has numerous advantages. First, it is a broad framework based on politically decided goals that intends to capture all societal aspects of changes to the transport system.

Second, in comparison to previous frameworks used, it covers a broad range of impacts, similarly to e.g. the TIAF or the frameworks by Horschutz Nemoto et al. (2021) and Smith et al. (2015), but with the benefit of assessing interactions between variables and (partly) measuring quantitative outcomes. Additionally, no previous frameworks have incorporated impacts on biodiversity and impacts on cultural artefacts (which may be limited). Meanwhile, the TIA framework does not incorporate employment impacts or effects on land use, which are important factors to consider.

Third, the main advantage of quantitative frameworks such as the TIA, Andersson and Ivehammar (2019) or the L3Pilot Evaluation Plan (Innamaa et al. 2020) is that they convey a sense of scale, as opposed to e.g. conceptual frameworks where it may be difficult to assess whether all impacts are equally important. The initial interviews with experts emphasised accident reduction, but the quantitative assessment
showed clearly that the societal gains of reductions of vehicle damages and personal injury were comparatively small for public transport, even considering drastic reductions.

Fourth, the Distributional effects analysis part of the framework (Appendix 2) conveys differences in outcomes for different societal groups and institutions. A clear example of this is that the Automation with Adaption scenario was assessed to provide overall accessibility increases, but that children may be negatively impacted by the increased width of the highway. This effect would also be apparent for other road users, such as cyclists or those with e.g. visual impairment, as well as interactions with adults with no impairments. In conclusion, an introduction of an AD bus would likely both have positive and negative effects on accessibility. Similarly, the societal costs of infrastructure construction would be financed by road operator, while the reduced cost of operation would benefit the public transport operator, necessitating a shift in the financial model.

In summary, the TIA framework and the frameworks previously reviewed cover a wide range of topics, from vehicle damages to pollution and wider economic impacts. However, some topics are notably missing from the majority of the frameworks, namely impacts on cultural artefacts and landscapes, biodiversity, users’ perception, cybersecurity and impacts divided into different actors and socioeconomic groups. Furthermore, more general areas such as general well-being, economic impacts or social sustainability are in general not addressed by no frameworks reviewed. Out of these areas, we feel that impacts on cybersecurity and biodiversity are especially important to cover. Biodiversity is a threat on a similar level and climate change and is heavily influenced by transport (Díaz et al. 2019). Cybersecurity is seen as a major concern for AD technology, with the risk of cyber operations and the ability to remotely control large number of vehicles (Tafidis et al. 2022). These areas need to be further investigated in future research.

**Conclusions**

In this paper, we have provided an overview of frameworks used for evaluating AD technology. The reviewed frameworks cover a wide variety of impacts and none cover all areas that may be impacted. The frameworks also differ in their scope, motivation and type of results – some are quantitative and others more qualitative.

We have introduced the TIA framework, previously for evaluating infrastructure investments and adapted it to a case study of AD buses in southern Stockholm. The use of this framework uncovered impacts not previously discussed, such as biodiversity aspects, and also made it possible to compare the scale of impacts for e.g. accident reduction and infrastructure costs. Furthermore, the TIA framework also highlighted that the benefits and costs are not necessarily generated by the same actor, and this may necessitate a change in business model for the transport system.

We have shown that no existing framework succeeds in covering all impacts. The variation in how frameworks are used and their scope also limits the possibility to compare outcomes of different frameworks, hindering our understanding of the complete societal impacts. However, decisions regarding the future of the transport system need to be made today, since investments in e.g. infrastructure generally have a long lifetime. The
introduction of the TIA framework may increase our understanding of AD technology, but the framework needs to be further improved by incorporating aspects such as cybersecurity, employment and land use impacts.

Acknowledgements

The authors would like to thank colleagues for valuable feedback throughout the writing of this paper and two helpful reviewers who highlighted important shortcomings and potential improvements in the manuscript.

Disclosure statement

Erik Almlöf is in addition to his role as a researcher also an employee of Region Stockholm. The other authors do not state any competing interests.

Funding

This work was supported by Trafikverket [grant number TRV 2019/118695].

ORCID

Erik Almlöf https://orcid.org/0000-0002-6986-972X
Xiaoyun Zhao https://orcid.org/0000-0002-3342-0859
Anna Pernestål https://orcid.org/0000-0003-2011-6273
Erik Jenelius https://orcid.org/0000-0002-4106-3126
Mikael Nybacka https://orcid.org/0000-0002-2265-9004

References


Appendices

Appendix 1

Calculation of costs and benefits for scenarios

This appendix describes the calculation of quantitative effects of each scenario. The depreciation time for AD technology may be short given a fast technological development. The depreciation time of buses is about 10 years in Sweden (Sveriges bussföretag 2019) while the depreciation time of infrastructure is in general 40–60 years (Mackie, Worsley, and Eliasson 2014). In this paper, we assumed the lowest depreciation time available in Sampers, 20 years. The discount rate was set to the default value used in Sweden, 3.5% (Trafikverket 2020b).

The impacts from decreased headway, increased vehicle speed and decreased value of time were modelled using the Sampers model (Beser and Algers 2002; Trafikverket 2020c) through changing the bus lines within the model for the year of 2040. The model then calculated mode choice, changes in route choices for public transport and finally effects on travel time savings, ticket revenues, travel costs for travellers, accident reductions, decreased pollution and decreased greenhouse gases (through a reduction in car travel).

In order to apply the assumptions of the scenarios, changes were made to the Sampers model for the speed and headway of the proposed bus line in the 2040 model, with all other parameters remaining unchanged from the base model. An initial review of the base scenario (named Person2040_200615_v5_trangsel_sth_gbg by the STA) revealed that the travel time between some stations seemed unrealistic (unrealistically high speeds through densely populated areas) and this was therefore changed in all scenarios, including the base scenario. The changes to headway and travel time stipulated in Table A.1 were then applied to each respective scenario, and no further changes was made to the model.
Table A.1. Quantitative assumptions for each scenario.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Bus Driver Plus</th>
<th>Automation with Adaption</th>
<th>Automation Utopia</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle accident rate</td>
<td>−50%/km</td>
<td>−90%/km</td>
<td>−90%/km</td>
<td>Estimate based on interview subjects’ expectation of substantial reduction in accident rates.</td>
</tr>
<tr>
<td>Personal injury rate</td>
<td>−50%/km</td>
<td>−90%/km</td>
<td>−90%/km</td>
<td>Estimate based on interview subjects’ expectation of substantial reduction in injury rates.</td>
</tr>
<tr>
<td>Increased cost of vehicles</td>
<td>+12.7 k€/vehicle</td>
<td>+15.4 k€/vehicle</td>
<td>+15.4 k€/vehicle</td>
<td>Long-term estimate on investment cost by Wadud (2017).</td>
</tr>
<tr>
<td>Passenger perceived value of time</td>
<td>Used value for train travel (30% less)</td>
<td>Used value for train travel (30% less)</td>
<td>Used value for train travel (30% less)</td>
<td>Smoother driving assumed to be highly valued by passengers according to interview subjects. Cost/min. from Börjesson and Eliasson (2014).</td>
</tr>
<tr>
<td>Cost of digital and physical infrastructure</td>
<td>See Table A.2 in Appendix 1.</td>
<td></td>
<td></td>
<td>Assumption based on interview subjects’ expectation of increased headway due to the reduced marginal cost of operations outside of peak hours.</td>
</tr>
<tr>
<td>Headway</td>
<td>Unchanged</td>
<td>Peak headway used for all service hours (6 min)</td>
<td>Peak headway used for all service hours (6 min)</td>
<td>Estimate based on interview subjects’ assessment that a remote operator can control multiple vehicles. One driver per vehicle is assumed for Bus Driver Plus, whereas 1 operator is expected to be able to run 5 vehicles in Automation with Adaption and 1 operator runs 20 vehicles in Automation Utopia. We assume no further costs of operations.</td>
</tr>
<tr>
<td>Cost of operations</td>
<td>Unchanged</td>
<td>Cost per hour of service for personnel lowered by 80%. Cost of operations increased due to increased service levels off-peak.</td>
<td>Cost per hour of service for personnel lowered by 95%. Cost of operations increased due to increased service levels off-peak.</td>
<td></td>
</tr>
<tr>
<td>Average vehicle speed</td>
<td>Unchanged</td>
<td>Unchanged</td>
<td>Increased by 20%</td>
<td>Interview subjects expressed an expectation of higher average speed with increased autonomy and digitalisation due to (1) smoother driving behaviour and reduced stop time and (2) better communication with traffic signal, enabling shorter stop times at traffic lights. A speed increase of 20% was calculated as the potential.</td>
</tr>
</tbody>
</table>

In addition, the following effects were calculated separately: vehicle technology costs; infrastructure costs; reduction of injuries caused by bus operation; effects on vehicle damage reduction; and increased operational costs for bus traffic due to increased headway.
Vehicle technology cost was calculated as

\[ \Delta TC = VN \cdot \varphi \]  

(1)

Where \( \Delta TC \) demarks increased technology cost, \( VN \) the number of vehicles needed for operations and \( \varphi \) the assumed technology cost (see Table A.1).

Infrastructure cost was calculated as

\[ \Delta \text{InfC} = KU \cdot A + KM \cdot B \]  

(2)

Where \( \Delta \text{InfC} \) demarks the increased infrastructure cost, \( KU \) demarks the number of kilometres of urban road (5 in this case), \( A \) the matrix of assumptions of costs for urban roads for each scenario (the matrix in Table A.2), \( KM \) the number of kilometres of motorways (15 in this case) and \( B \) the matrix of assumptions of costs for motorways for each scenario (Table A.2).

Cost of injuries was calculated as

\[ \Delta I = \text{InjC} \cdot VKT \cdot \alpha \]  

(3)

Where \( \Delta I \) demarks the changed cost of injuries, \( \text{InjC} \) the cost of injuries per km (0.07 €/km (Haraldsson, Jonsson, and Ögren 2012)), \( VKT \) the number of kilometres driven and \( \alpha \) the assumed reduction in vehicle damages.

Similarly as equation 3, reduced costs of vehicle damages was calculated as

\[ \Delta VD = VDC \cdot VKT \cdot \beta \]  

(4)

Where \( \Delta VD \) demarks the changed cost of vehicle damages, \( VDC \) the cost of vehicle damages per km, (0.04 €, estimate from the Public Transport Authority of Stockholm), \( VKT \) the number of kilometres driven and \( \beta \) the assumed reduction in vehicle damages.

Cost of operations was calculated as

\[ \Delta O = KC \cdot VKT + TC \cdot VHT \cdot \gamma + VC \cdot VN \]  

(5)

where \( \Delta O \) demarks the changed cost of operations, \( KC \) the cost of operations per kilometre (1 €, estimate from the Public Transport Authority of Stockholm), \( VKT \) the number of kilometres driven, \( TC \) the cost of operations per hour (62.5 €, estimate from the Public Transport Authority of Stockholm), \( VHT \) the number of hours driven, \( \gamma \) the assumed reduction in personnel cost, \( VC \) the cost of vehicle per year (45,000 €, estimate from the Public Transport Authority of Stockholm) and \( VN \) the number of vehicles needed for operations. The decreased headway increases the number of kilometres and hours of operations, while the removal of the driver decreases the personnel cost, and the increased speed decreases the number of hours driven and the number of vehicles needed.

Table A.2. The estimated costs for digital and physical infrastructure and estimation of which infrastructure is required (Req.) per scenario. Cost estimates from Kulmala, Jääskeläinen, and Pakarininen (2019), Table 18 (averages used), except estimate of new lane cost by an expert at the STA (averages used).
<table>
<thead>
<tr>
<th>Infrastructure requirement for operations</th>
<th>Unit cost range</th>
<th>Bus Driver Plus</th>
<th>Automation with Adaption</th>
<th>Automation Utopia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positioning enhancement with dedicated landmarks</td>
<td>Investment: 5 k€/km Operations: 0.5 k€/km/year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safe harbours (broad shoulder, lay-bys etc.)</td>
<td>Investment: 70 k€/km Operations: 5.6 k€/km/year</td>
<td>Req.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>More active snow-removal</td>
<td>Operations: 2.25 k€/km/year (Motorways) Operations: 3.5 k€/km/year (Urban areas)</td>
<td>Req.</td>
<td>Req.</td>
<td></td>
</tr>
<tr>
<td>Low-latency wireless broadband infrastructure</td>
<td>Investment: 60 k€/km Operations: 4.8 k€/km/year</td>
<td></td>
<td>Req.</td>
<td></td>
</tr>
<tr>
<td>High quality real-time situational picture</td>
<td>Operations: 0.6 k€/km/year (Motorways) Operations: 0.15 k€/km/year (Urban areas)</td>
<td>Req.</td>
<td>Req.</td>
<td></td>
</tr>
<tr>
<td>Signs and/or barriers for access control</td>
<td>Investment: 52.5 k€/km Operations: 4.2 k€/km/year</td>
<td></td>
<td>Req.</td>
<td></td>
</tr>
<tr>
<td>VMS/C-ITS warnings: road works, automated road works or maintenance vehicles</td>
<td>Operations: 0.7 k€/km/year</td>
<td>Req.</td>
<td>Req.</td>
<td></td>
</tr>
<tr>
<td>Extra lane</td>
<td>Investment: 3.5 M€/km (Open road) Investment: 30 M€/km (Tunnel)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Appendix 2**

Distributional effects analysis and Goal fulfilment analysis

**Table B.1.** Distributional effects analysis of the three scenarios.

<table>
<thead>
<tr>
<th>Distributional effects analysis</th>
<th>Bus Driver Plus</th>
<th>Automation with Adaption</th>
<th>Automation Utopia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Largest positive effect: Women, who use public transport more than men. Second-to-largest positive effect: Men. Negative effect: None.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geography</td>
<td>Largest positive effect: The residents of municipalities in which the bus line operates. Second-to-largest positive effect: Residents within the region who may use the line occasionally. Negative effect: None.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effects for individual companies or industries</td>
<td>Largest positive effect: No specific company or industry would benefit, however a general increase in accessibility for the region. Negative effect: None.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode of transport</td>
<td>Largest positive effect: Bus traffic Second-to-largest positive effect: Other modes of public transport. Negative effect: None.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age groups</td>
<td>Largest positive effect: Commuters Second-to-largest positive effect: Young adults who commute to schools Largest negative effect: Especially children and other vulnerable groups, who may experience crossing the new lane more difficult and may prefer to have a driver on-board. Negative effect: None.</td>
<td>Largest positive effect: Commuters Second-to-largest positive effect: Young adults who commute to schools Negative effect: Children and other vulnerable groups who may prefer to have a driver on-board.</td>
<td></td>
</tr>
</tbody>
</table>
Table B.2. Assessment of each scenario’s goal fulfilment for the transport system of Sweden. Green (+) demarks a positive impact on the goal (e.g. increased reliability or decreased number of accidents), yellow demarks no effect or both positive and negative effect and red (−) demarks a negative impact. (Print preferable in colour).

<table>
<thead>
<tr>
<th>Goals pertaining to the functionality of the transport system</th>
<th>Bus Driver Plus</th>
<th>Automation with adaption</th>
<th>Automation Utopia</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Citizen’s transport</td>
<td>Reliability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial transport</td>
<td>Reliability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility regionally and nationally</td>
<td>Commuting</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Accessibility metropolitan areas</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Interregional travel</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Equality</td>
<td>Equal transport opportunities</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Disabilities</td>
<td>Public transport network</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Children and young adults</td>
<td>Transport to school</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Public transport, walking and cycling</td>
<td>Walking and cycling, modal share</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Public transport, modal share</td>
<td>Public transport, modal share</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Goals pertaining to considerations of the transport system</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>Amount of car and truck traffic</td>
</tr>
<tr>
<td>Energy per vehicle kilometre</td>
<td>+</td>
</tr>
<tr>
<td>Energy for construction, operations and maintenance</td>
<td></td>
</tr>
<tr>
<td>Health</td>
<td>Noise and physical activity</td>
</tr>
<tr>
<td>Accessibility for weaker groups</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td></td>
</tr>
<tr>
<td>Landscape</td>
<td>Landscape</td>
</tr>
<tr>
<td>Biodiversity aspects</td>
<td></td>
</tr>
<tr>
<td>Cultural heritage sites and other cultural legacy</td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>Number of killed and seriously injured in traffic</td>
</tr>
</tbody>
</table>

Appendix 3

The Sampers model

Sampers is a four-step transport model (McNally 2008), covering the entirety of Sweden with one national model and five regional models, whereof the regional model ‘Samm’ covers Stockholm, the Mälaren Valley and the island of Gotland. The model is based on two travel surveys from the 1990s and early 2000s and emulates the travel behaviour of all nationals over the age of 5. The Samm model consists of 10,455 zones, ranging from small zones in Stockholm inner city (<0.5 km²) to large rural areas (>100 km²). In general, zones have been designed to have
correspond to the geography (e.g. street pattern or topography), population size and zone type (e.g. residential, industrial etc.).

Sampers uses five modes of transport – car, car as passenger, public transport, bike and walking. Car as passenger denotes shared rides, e.g. a family going together, while behaviour such as kiss-and-ride or park-and-ride is not integrated into the model. The car mode covers all major roads in Sweden, and some arterial roads, depending on geography and traffic volume, with the final stretch, including parking, is only used with ‘connectors’, emulating smaller roads and parking. All roads modelled use volume-delay functions to emulate congestion, with the various parameters used to emulate the varying types of roads in the network (Florian, Constantin, and Florian 2009). The public transport network is based on the currently used network, using headway-based route assignment (Spiess and Florian 1989). For walking and cycling, the road network is used and is only dependent on road length, with no assumed congestion.

Being a four-step model, the simulation is usually run for four iterations to reach equilibrium in demand and supply, using so called log-sums (de Jong, Daly, and Pieters 2007), mainly hindered by congestion in the road network. This means that an increased supply, in our case of the public transport offering, increases both overall demand for transport as well as changes travellers’ choice of mode.

The model divides trips into seven different trip purposes: work; school; social trips (e.g. visiting a friend); recreation; other trips; and business trips, which are calculated differently depending on their starting location. The trips generated are aggregated for the route assignment step, to properly model congestion effects.

Route choice is run for four time periods, corresponding to approximately: 06:30–07:30 (morning peak); 09:00–15:00 (mid-day); 16:30–17:30 (afternoon peak); and 19:00–22:00 (evening).

The model has been in development since the late 1990s and is updated every second or fourth year. During this process, the model is updated with new features and thoroughly validated against real world data (Samuelsson and Wang 2020) and the model seems to emulate current traffic behaviour appropriately (Jonsson et al. 2011).

Within this project, we have used the Samm model for 2040, which is the STA’s official forecast, including the proposed transport network as well as demographic forecasts from Statistics Sweden and economic forecasts from the National Institute of Economic Research (Trafikverket 2020c; Trafikanalys 2020). We have only made changes to the public transport network on link times and headway for the line traversing Södertörn Crosslink.

For more information about Sampers, please see (Beser and Algers 2002), (Trafikverket 2020c) or (Samuelsson and Wang 2020).