Suitable routes for implementing autonomous passenger transports

Development of a framework of infrastructure requirements to analyse routes for use in autonomous bus systems

Master's thesis in Supply Chain Management

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Abstract

New technology, and especially technology related to autonomous vehicles (AV), will create new demands on infrastructure and the infrastructure owners. The purpose of the report is to create a framework of general characteristics that a route should possess in order to make it feasible to implement AVs on routes, and to analyse a few routes on roads that is owned by the Swedish Transportation Administration, using the framework for evaluation of the suitability of AV operations. In addition to the infrastructure requirements, future predictions when the technology is expected to be implemented, and which application that is suitable to use for autonomous buses is also included. The report mainly focuses on passenger transportation, but the framework is a general guideline that could in practice be used for other applications as well.

To formulate the requirements a literature study was conducted in conjunction with interviews with representatives of different companies and organisations that are involved in the development and operations of AVs in relation to passenger transportation. The framework was then formulated using the data collected in the literature review and using the answers from the interviews the different categories was classified either low, medium, and high depending on how many of the interviewees covered the subject. The routes to be analysed was selected from four different road categories; highway, four-lane road, separated 2-lane road, and 2-lane road. One route of each category was selected depending on the combined traffic volume of cars and public transit passengers, where it was found that there were the most potential users of the service, if implemented. For the future predictions, mainly data from the interviews was used to create a time-line but it was also supplemented by data from the literature study. As for the potential applications of AVs in public transport, both literature and interviews is used.

The study found that the eight areas of road layout, signs, intersections, lane markings, maintenance, digital maps, V2I/I2V, and connectivity should be included in the framework, the first five classified as physical infrastructure and the remaining three under digital infrastructure. The most important factors, that was mentioned the most in the interviews, is the road layout and connectivity, due to their direct and heavy impact on the feasibility in AV operations. The category that is deemed the least important is the lane markings, mostly due to existing technologies that is able to function without them even though AV operations become easier if they are present due to less difficult to read situations. The rest of the categories is classified as having roughly the same importance, somewhere in-between the previously mentioned characteristics. Each of the categories was each further divided into subcategories that each had either positive or negative effects on the evaluation of the routes, depending on the factors are present or not. The analysed routes had different prerequisites in almost all categories making the recommendation of a specific route, or route type, hard to do because of all the factors involved that is going to vary from case to case. The result is therefore to not generally recommend any specific type of road without analysing all context for the specific application in detail first. The general predictions made for when AVs will become available was a span between 2025 to 2045, with most interviewees and literature agreeing on that between 2030 and 2035 was the most likely for AVs with limited capabilities. The potential application of AVs in public transit is mainly concentrated to two areas, first- and last-mile transit as well as hub-to-hub transport. The implementation of AVs in public transit would likely bring the benefits of either operating current systems at lower cost, or to be able to expand the system without increasing the cost as the operating cost of AVs are lower than conventional vehicles. Overall, it can be said that different AVs are suitable for different situations and a deeper analysis of the intended application is necessary to determine the suitability.

Keywords: Autonomous vehicle, autonomous bus, automated bus, automated transit, infrastructure requirements

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Victor Berndtsson & Oskar Vamling, Gothenburg, May 2020

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Acronyms

ABS Anti-lock Braking System.
ACC Adaptive Cruise Control.
AD Autonomous Driving.
ADAS Advanced Driver Assistance System.
ADS Automated Driving System.
AI Artificial Intelligence.
AV Autonomous Vehicle.

BASt Bundesanstalt für Straßenwesen.
BRT Bus Rapid Transit.

CAS Collision Avoidance System.
CAV Connected Autonomous Vehicle.

DARPA Defence Advanced Research Projects Agency.
DSRC Dedicated Short-Range Communications.

EV Electric Vehicle.

FPV Functionally prioritised road network.

GHG Green-House Gases.
GIS Geographical Information Systems.
GNSS Global Navigation Satellite System.
GPS Global Positioning System.
GRT Group Rapid Transit.

HD High Definition.
HOV High-Occupancy Vehicle.

I2V Infrastructure to Vehicle communication.
INS Inertial Navigation System.
IRI International Roughness Index.
ITS Intelligent Transport System.

LDWS Lane Departure Warning System.
LiDAR Light Detection And Ranging.
LRT Light Rail Transit.
LRV Light Rail Vehicle.

NHTSA National Highway Transportation Safety Administration.
NVDB Nationell vägdatabas, *lit. National Road database*.

ODD Operational Design Domain.
OEDR Object and Event Detection and Response.
OEM Original Equipment Manufacturer.

PRT Personal Rapid Transit.

RISE Research Institutes of Sweden.
RNP Required Navigation Performance.

SAE International Society of Automotive Engineers.
SAV Shared Autonomous Vehicle.
SDV Self-Driving Vehicle.
SLAM Simultaneous Localisation and Mapping.
sonar Sound detection and Ranging.

UN United Nations.

V2I Vehicle to Infrastructure communication.
V2V Vehicle to Vehicle communication.
V2X Vehicle to Everything communication.
VDA Verband der Automobilindustrie.
VRU Vulnerable Road Users.

Glossary

2+1 road	A road that alternates between one and two lanes in each direction, usually combined with a barrier separating the directions of travel. Considered much safer than a standard, non separated, country road.
BRT	Bus Rapid Transit (BRT) is a form of bus system that is characterised by dedicated lanes, signal priority at intersections, and a high frequency service.
Dedicated lane	A lane dedicated to, in this case, autonomous vehicles, both public and private.
Grade-separated intersection	An intersection where the roads meet at different grades, meaning that no direct interference between traffic occurs.
GRT	Group rapid transit is a mode of transit that operates similarly to PRT, but on a slightly larger scale. Commonly used at airports for transfers between terminals and can also be called people movers.
Hub-and-spoke network	A method within traffic planning that involves making most routes connect at one or a few central points in the network. This means that most journeys involve a transfer at that central point, to connect two different areas. Airlines commonly use this model.
Induced traffic	A phenomenon within traffic planning & management that describes the increase in traffic after an expansion in capacity is made, due to more capacity being available. Related to induced demand.
INS	An intertial navigation system is a navigational system that relies on internal sensors to calculate the position through movement of the sensors. Becomes unreliable over time due to navigational drift that occurs due to no external references.
Level crossing	An at-grade railroad crossing where the railroad intersects a road.
ODD	*"Operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics"*(SAE International, 2018).
Protected lane	A lane with protected use, such as a bus lane.

PRT Personal rapid transit is a mode of transit that is characterised by small pods that move along a dedicated track only stopping at stations that the rider chooses, similar to how an elevator operates.

Smart sign Signs that can vary the displayed information depending on the traffic situation.

Swedish Transportation Administration A Swedish governmental agency responsible for long-term planning in public transportation infrastructure, as well as maintaining public roads and railways within Sweden. *Trafikverket* in Swedish.

Traffic calming measures For instance speed bumps, rumble strips, or chicanes.

Trickle-down effect New technology making its way to less expensive products from only being implemented in more expensive products.

Unprotected intersection An intersection that does not use any signs or traffic control devices and instead relies on the ”priority from the right”-rule.

Utilisation rate How much of the available time the vehicle is used.

Västtrafik The regional public transportation authority for the Västra Götaland region in Sweden.

1

Introduction

This chapter contains a background of Autonomous Vehicles (AVs), autonomous buses, public transport and infrastructure requirements related to AVs. The chapter does also contain a problem definition, the aim and limitations of the report, and finally the research questions.

1.1 Background

With a climate crisis on the horizon, Sweden is committed to reducing emissions of greenhouse gases in accordance with the United Nations (UN) resolution of reduction of emissions (Hunhammar, Krafft, Wildt-Persson, & Wenner, 2019). One important sector for achieving the UN goal is the transportation sector. The Swedish Transportation Administration has adopted ”Målbild 2030”, or Target 2030, which is based on the UN Agenda 2030 (Hunhammar et al., 2019), and one of the goals of Target 2030 is for the transportation sector to lower their emissions by 70% by 2030 compared to 2010 (Hunhammar et al., 2019). To achieve this target, Hunhammar et al. (2019) argues that the number of private vehicles on the road need to decrease. Simultaneously, Hunhammar et al. also state that there needs to be an increase in the use of shared vehicles and public transit to satisfy the demand for transportation. As of today, the biggest challenge for an increase of the public transport network is the lack of drivers (Transportföretagen, 2018) and the physical limitation of how many vehicles that can operate on the infrastructure while maintaining efficiency (Backström, 2018).

One solution to mitigate some of the issues raised and to increase the capacity of the passenger transportation system is to digitalise it, and the Swedish Transport Administration has already started this process (Palm et al., 2019). Palm et al. (2019) states that the digitalisation of the transportation system is a challenge for the Swedish Transportation Administration, as it presents new problems, opportunities and ways of thinking about infrastructure. The goal of the Swedish Transport Administration is to make Sweden one of the leading countries regarding the exploitation of advantages enabled by the digitisation (Hunhammar et al., 2019; Palm et al., 2019). Two effects of digitisation of the transport system are the change in travel patterns and the use of autonomous vehicles for public transportation (Grush & Niles, 2018; Guerra, 2016).

Self-driving cars have since long been a thing of the future, with the first concept being shown to the public in the late 1930s by General Motors (Faisal, Yigitcanlar, Kamruzzaman, & Currie, 2019; Shladover, 2018). Autonomous Vehicles, or *AVs*, have also been frequently featured in popular media, such as in the scientific magazine *Mechanix Illustrated* (Maurer, Gerdes, Lenz, & Winner, 2016), movies such as *Minority Report* and Disney's *The love bug* (Salo, 2019), and TV-series like *Knight Rider* (Herrmann, Brenner, & Stadler, 2018; Lee, 2014). The peak of the early developments of AV technology was reached in 1994, with the demonstration of automated bus- and truck platoons that lasted until 2003 (Shladover, 2018). During DARPAs grand challenge in 2004 autonomous vehicles started to become a thing of the present (Fagnant & Kockelman, 2015). The route the vehicles were to drive was 150 miles, but the winner of the challenge only managed to drive 7 miles, however, in 2005 seven teams managed to complete the route, which also indicates the rapid development of AVs (Fagnant & Kockelman, 2015). AVs was originally meant to have a military application but is today developed by car manufacturers and tech companies (Herrmann et al., 2018).

There are different levels of autonomous driving, and as can be seen in figure 1.1, autonomous driving level 5 is nearing the peak of ”inflated expectations”, where the hype for the technology is the greatest, possibly reaching unrealistic levels, due to early successes and media attention (Gartner, 2019). Autonomous driving at level 4 has already passed the peak and is in the ”trough of disillusionment” phase of the hype cycle where the expectations of the technology are lowered since experiments and implementations fail to live up to the promised standard (Gartner, 2019). However, Shladover (2018) states that the capabilities of autonomous vehicles often are overstated and held to an unrealistic standard. A scepticism that the promises and capabilities are exaggerated exists, (Grush & Niles, 2018) and authors such as Currie (2018) criticise the hypothesis that AVs will be the technology that solves all transportation problems, and in the process of doing so will eliminate, or severely reduce the need for public transit by replacing it by autonomous cars. Even though the future development of autonomous vehicles remains unclear, Herrmann et al. (2018) state that this is not only a change to new technology but will change the mobility on a large scale.

As mentioned previously, autonomous buses will be beneficial from an environmental perspective and with regards to any capacity problems regarding driver availability, but it will also be beneficial in terms of congestion reductions (Fagnant & Kockelman, 2015) road capacity improvements (Friedrich, 2015) and safety improvements (Acheampong & Cugurullo, 2019; Tettamanti, Varga, & Szalay, 2016). Regarding the safety aspects, human error is the cause of 95% of accidents, and AVs can according to some estimates reduce traffic accidents by up to 90% by removing the human element (Sarmah, 2015). The European Commission has a traffic safety agenda called "vision zero" which includes the aim of reducing the number of traffic fatalities by 50% until 2020 and by 100% 2050 (European Commission, 2019). In order to reach the goal of zero fatalities, autonomous vehicles play an important role (European Commission, 2019). Other advantages of using autonomous vehicles are the lower cost of transportation and better utilisation of vehicles (Chan, 2017).

Figure 1.1: Gartner Hype Cycle for Emerging Technologies 2019, with autonomous driving circled in red (Gartner, 2019)

The Swedish Transport Administration wants to increase their knowledge about autonomous vehicles, and one of the areas they have focused on is automated buses (Palm et al., 2019). This area of research is relevant since Guerra (2016) and Walker (2016) states that freight and transit are likely to become early adopters of AVs as the vehicles involved often travel along predetermined routes making a potential automation easier, as well as lowering the operating costs for the vehicles. There are also many issues surrounding autonomous vehicles, and especially their use in transit, that needs to be solved (Millonig & Fröhlich, 2018). These include technical uncertainties that need to be addressed, such as if the currently available technology is mature and reliable enough (NTSB, 2019b; Pessaro, 2016). To test these systems, there have been trials with AV technology performed on transit vehicles(Nyström, 2015). The results vary from being technologically considered unsuitable (Nyström, 2015), to implementations that can be considered a success (Gregg & Pessaro, 2016). There are also questions regarding where it is most suitable to implement autonomous vehicles first (Palm et al., 2019). This question gets even more complicated when considerations for public transit must be taken into account, such as cost-effectiveness, demand, and routing (Fagnant & Kockelman, 2015; Owczarzak & Zak, 2015; Walker, 2012).

There have been many articles written about autonomous vehicles and their impacts on society, such as Bissell, Birtchnell, Elliott, and Hsu (2018) and Davidson and

Spinoulas (2015). However, the area surrounding automated and autonomous buses and public transit remain relatively unexplored (Gandia et al., 2019). The articles that have been written on the subject mainly focuses on small shuttles, such as Fernández, Domínguez, Fernández-Llorca, Alonso, and Sotelo (2013) and Nordhoff, de Winter, Payre, van Arem, and Happee (2019), or shared autonomous vehicles and what implications they will bring for public transit, such as Narayanan, Chaniotakis, and Antoniou (2020) and Jones and Leibowicz (2019).

AVs are presented by many actors as revolutionary as they are presented not to require any additional or specialised infrastructure to operate (Arbib & Seba, 2017; Lutin, 2018; Owczarzak & Zak, 2015). However, as previously mentioned there have also been concerns raised that the infrastructure relating to AVs is an area that has received considerably less attention than others (Fagnant & Kockelman, 2015; Huggins et al., 2017). Although no additional infrastructure will have to be installed according to some manufacturers, the issue of mixing different types of traffic remains a major challenge to overcome (Kockelman et al., 2016). There are several aspects of the infrastructure that might have an impact on AV adoption, such as how they will handle intersections (Levinson et al., 2011), how they are going to navigate in long tunnels (Ehrlich & Hautière, 2016), and if certain infrastructure is helpful or detrimental for AV operations (Parsons, Shaw, Rubenstone, Cho, & Jost, 2018). There is also the aspect if an AV actually *requires* any infrastructure, or if certain infrastructure just *facilitates* the implementation and operations of AVs. As such, infrastructure requirements, future predictions regarding AVs, and application of autonomous buses in society are three areas of interest that will be analysed in this report.

1.2 Problem definition

The implementation of AVs can introduce new demands on the road owner since it might be necessary to modify the existing infrastructure. There is a need for increased knowledge in the potential for implementation of the autonomous vehicles, and how and where autonomous vehicles will be implemented. By analysing passenger flows between transit hubs for specific routes, and the road characteristics on the routes, is it possible to identify the potential benefits autonomous transit vehicles can imply. The Swedish Transportation Administration wants to be one of the leaders in the development of the future infrastructure, and not to be a hindrance to the implementation of new technologies, especially since they are the road owner of many of the busiest roads.

To be able to anticipate the future needs for infrastructure that is required by autonomous vehicles, an analysis of the current state of the technology and what requirements different actors predict will be necessary. This is especially important since infrastructure has to be adapted or prepared in advance, in order to have a smooth implementation of new technologies. However, there is no widely adopted industry standard for AVs that makes it clear what the technology is going to require, and Fagnant and Kockelman (2015) argue that there is a lack of research in the area regarding AV infrastructure requirements. Furthermore, different actors have adopted different approaches, that further have different infrastructure requirements.

1.3 Aim and purpose

In order to cope with the challenges in the transportation sector, the purpose of the report is to create a framework that can be used to evaluate the infrastructure and to determine the suitability of autonomous public transport on specific routes. This is important for the Swedish Transportation Administration in order to adjust the current infrastructure according to the requirements to become one of the leaders in this field.

1.4 Limitations

The report will in the literature review cover autonomous driving on a general level, and research based on autonomous cars and trucks will therefore be included. However, the routes will be evaluated based on transportation by bus, and it will only cover the road network owned and maintained by the Swedish Transportation Administration. The selection of routes will be limited to the region of Västra Götaland to limit the number of routes. The routes selected for further analysis should also to some extent be part of the Swedish Transportation Administrations "*functionally prioritised road network for public transit*" (FPV). The analysis concerns the use of autonomous vehicles in public transit. The evaluation of infrastructure requirements will not cover the segments within the city centres of two reasons, namely that the road is not owned by the Swedish Traffic Administration and that the infrastructure characteristics would be highly dependent on the chosen route within the city and where the bus stop would be located.

1.5 Research questions

In order to analyse the issue a number of research questions have been formulated:

- What characteristics should a route possess to make it suitable for implementing autonomous passenger vehicles?
- How can the road infrastructure characteristics be evaluated for implementation of autonomous vehicles?
- What application is suitable for autonomous buses?
- What are the future predictions that can be made regarding autonomous driving?

2

Literature review

This chapter consists of the definitions which define the concept of AVs and introduce the different levels of AD. This is followed by the current state of AVs, where the current capabilities and limitations are explained, but also different approaches to AD and autonomous buses. The infrastructure requirements are later described, where both physical and digital infrastructure is presented. This is followed by the section for future predictions where future AV capability is estimated and roadmaps are presented. The applications of AVs in public transport is then presented. Finally, a conceptual framework of infrastructure requirements for AVs is presented.

2.1 Definition of autonomous vehicles

Nikowitz (2015) states that there is no industry-wide definition of autonomous vehicles. The two definitions for autonomous vehicles used by Nikowitz are *"a vehicle that is designed to travel between destinations without a human operator"* and *"a vehicle which is able to perceive its environment, decide autonomously which route to take to its destination, and conduct itself along the route it selects"*, while Thomas and Trost (2017) defines an autonomous vehicle as a vehicle that is able to drive safely and efficiently without a driver in normal weather, road and traffic conditions. There are also different definitions for autonomous and autonomous driving including the one used by Näringsdepartementet (2018) where automated driving is that the vehicle must be able to completely conduct itself according to a certain set of parameters, while according to Grush and Niles (2018) the Merriam-Webster dictionary definition of *autonomous* is *"something that is undertaken or carried out without outside control; self-contained, existing or capable of existing independently; responding reacting or developing independently of the whole"*. Grush and Niles (2018) states that there is a distinction between *autonomous* and *automated* vehicles, and that most new vehicles are automated but that the word "autonomous" have become wide-spread and accepted for all kinds of self-driving vehicles, regardless of how capable they are.

There are many definitions of autonomous driving levels, as can be seen in table 2.1. The different definitions are similar in their way of defining the levels but differ in terms of name and number of levels. The most commonly used definition, which is also the definition used in the report is the one used by International

Society of Automotive Engineers (SAE), which contains six levels for describing the capabilities (Coppola & Silvestri, 2019). Other definitions that are used to classify the capabilities of autonomous vehicles are the definition used by Bundesanstalt für Straßenwesen (BASt) that contains five levels (Gasser et al., 2013), the definition used by Verband der Automobilindustrie (VDA) that contains six levels (Verband der Automobilindustrie, 2015), and the definition used by the National Highway Transportation Safety Administration (NHTSA) that contains five levels (Marinik et al., 2014). If the vehicle is designed to require human intervention it is not to be considered as having automated driving, rather it should be considered a vehicle with Advanced Driver Assistance System (ADAS) (Näringsdepartementet, 2018).

Table 2.1: Autonomous driving definitions (Gasser et al., 2013; Marinik et al., 2014; SAE International, 2018; Verband der Automobilindustrie, 2015)

Level	SAE	BASt	VDA	NHTSA	Driver activities	ADS activities
0	No automation	Driver only	Driver only	No automation	Driver performs all parts of driving.	Active safety features can be enabled.
1	Driver assistance	Assisted	Assisted	Function specific automation	Performs what the ADS does not perform.	Lateral or longitudinal motion control.
2	Partial driving automation	Partial automation	Partial automation	Combined function automation	Performs what the ADS does not perform. Supervise autonomous driving system	Lateral and longitudinal motion control and partial OEDR
3	Conditional driving automation	High automation	Conditional automation	Limited self-driving automation	Monitors system and is ready to intervene.	Complete OEDR
4	High driving automation	Full automation	High automation	n/a	Only drives outside the systems Operational Design Domain (ODD).	Drives within its ODD . System fallback instead of driver fallback
5	Full driving automation	n/a	Full automation	Full self-driving automation	Becomes the passenger.	Unlimited operational design domain.

2.2 Current state of Autonomous vehicles

The current efforts to develop autonomous vehicles can be divided into two different approaches (Herrmann et al., 2018; Kaslikowski, 2019; Mohan et al., 2016; Thomas & Trost, 2017). One approach is to further develop existing technologies with current constraints in mind, such as Adaptive Cruise Control (ACC) with lane-keeping assistance, which is a type of ADAS. The other approach is to develop new technologies and implement them on a clean slate design, such as driverless shuttles.

According to (Coppola & Silvestri, 2019), companies such as Tesla, Volvo and Audi offered level 3 autonomy already in 2017. On the contrary, Teoh (2020) argues that the most advanced commercially available system is at level 2.

2.2.1 Approaches to autonomous driving

Maurer et al. (2016) characterise the different approaches to autonomous vehicle in to three categories, including evolutionary, revolutionary and transformative, while authors like Thomas and Trost (2017), Coppola and Silvestri (2019),Chan (2017), Grush and Niles (2018) and Kaslikowski (2019) only use the evolutionary and transformational approach in their papers. This could be due to the fact that the revolutionary approach is a combination of the two other approaches (Maurer et al., 2016). This paper will only cover the two approaches identified as the most commonly adopted ones. The main difference between them can be seen in table 2.2.

Table 2.2: Comparison of approaches

	Evolutionary	Transformative
Automation	Partial/conditional	High/full
Geographical area	Unlimited	Limited

Evolutionary approach

As described by Maurer et al. (2016) and Thomas and Trost (2017), the evolutionary approach is mainly adopted by the automotive manufacturers like Daimler, Ford, Audi and Tesla. The functions of the driver assistance system are continuously improved over time (Chan, 2017), and the introduction of this kind of assistance started at the beginning of 1980's (Maurer et al., 2016). These systems can include features like ABS, ACC and Lane Departure Warning System (LDWS), which have increased safety and comfort for the driver (Maurer et al., 2016). The idea with this approach is to gradually convert the driver from driving to monitoring (Coppola & Silvestri, 2019) and this approach is sometimes called "something everywhere" since this approach allows for some assistance wherever you drive (Chan, 2017).

In 2016 Maurer et al. (2016) mention that the next step for the evolutionary approach is to combine the adaptive cruise control with the lane-keeping (Maurer et al., 2016). In this scenario, the driver will monitor the situation and intervene if they consider the situation to be risky (Maurer et al., 2016). According to Maurer et al. (2016) the next steps for this approach is the introduction of increasing the automation of parking. Currently, companies like Tesla is updating their software for their cars remotely, providing the driver with new features (Herrmann et al., 2018). One drawback mentioned with this approach is that the new features that are added may provide some risks at the beginning, after the release of the features, which Herrmann et al. (2018) calls "danger zone". This phenomenon is illustrated in figure 2.1.

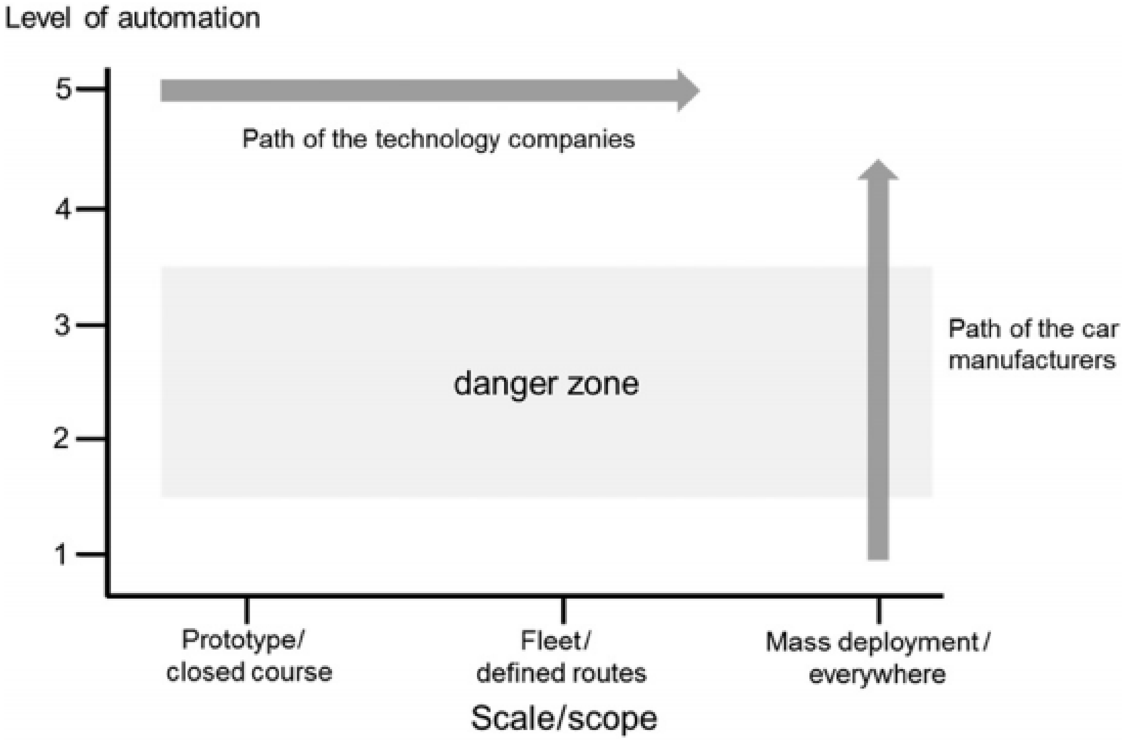


Figure 2.1: Illustration of the danger zone (Herrmann, Brenner, & Stadler, 2018)

Bainbridge (1983) argues that when using automation, the operator will become less skilled due to lack of experience. However, in cases where the operator needs to take over control from the automation, high skill and attention is likely required from the operator to be able to succeed with the task (Bainbridge, 1983). Bainbridge calls this an ”Irony of Automation”, that the automation over time decreases the number of situations where the operator can gain experience, while at the same time require highly skilled operators in those cases where the automation can not perform properly. This paradox is confirmed to be existing for AVs by Strauch (2018).

Transformational approach

The other approach is the transformational approach, which is the implementation of fully autonomous vehicles, that are currently slow-moving and operate in a specified and narrow geographical area (Maurer et al., 2016). The majority of companies using this approach is high-tech start-ups (Maurer et al., 2016), but also tech giants like Google, Apple and Uber utilise this more radical approach and instead develops fully autonomous vehicles for a limited geographical area (Thomas & Trost, 2017), where the driver can be completely removed (Coppola & Silvestri, 2019). This approach is sometimes called "everything somewhere" which refers to that all of the driving is autonomous, but only in some areas (Chan, 2017). If using this approach, Fröhlich et al. (2019) argues that it is important to show the passengers what the vehicle is seeing, doing and planning to do for the passengers to be able to trust the vehicle. Fröhlich et al. attributes this need to the fact that since the passengers can not see the actions the vehicle is undertaking in the same way as if the vehicle would have a traditional control set-up.

One of the most notable companies using the transformative approach is Google and their subsidiary Waymo (Chan, 2017; Coppola & Silvestri, 2019; Villagra et al., 2018) who develop their AV-technology for urban areas (Herrmann et al., 2018). It is mentioned that the success of Waymo is not due to the vehicles ability to adjust to different situations but rather the intensive mapping of the specific routes beforehand (Villagra et al., 2018).

2.2.2 Functional capabilities and limitations

Capabilities

Most commercially available AVs are currently operating at SAE level 2 and 3 (Kaslikowski, 2019), and the capability of the AV is largely influenced by the use of big data and AI (European Commission, 2019). Most vehicles described as "self-driving" today are categorised as level 3, with some being classified as level 4 (Grush & Niles, 2018). Contrary to this Teoh (2020) states that all commercially available vehicles in the US only fulfils the requirements for level 2. The capability of these vehicles is often described, according to Teoh, as advanced driver-assistance systems that can keep the vehicles in a lane, keep a set speed and in some situations overtake other vehicles if the situation allows. Under optimal conditions, a level 3 vehicle is able to navigate by itself on highways, or roads of a similar standard, and reach a predetermined destination such as an off-ramp without human intervention (Zlocki, Fahrenkrog, & Meng, 2016). Examples of this include vehicle manufacturer Tesla Inc. that claims that one of their vehicles travelled from San Francisco to Seattle without human intervention (Nikowitz, 2015) and California-based start-up *plus.ai* that claims that one of their autonomous semi-trucks made a trip from California to Pennsylvania without any unexpected disengagements of the self-driving system (Sumagaysay, 2019). From 2019, Coppola and Silvestri (2019) state that a majority of all personal vehicles will have conditional automation (SAE level 3), but it will take more time for level 4 and 5 to be available.

Alambeigi, McDonald, and Tankasala (2020) conducted a study on accidents involving AVs and found that the majority was either caused by the operator using manual control of the vehicle, or other vehicles hitting the AV, usually at intersections. A similar study by Dixit, Chand, and Nair (2016) points at the same results and found that one of twelve reported accidents could be attributed to being caused by the AV. The rest were, according to Dixit et al., results of manual control by the operator or rear-end accidents caused by other vehicles. Kopelias, Demiridi, Vogiatzis, Skabardonis, and Zafiropoulou (2020) found that there is a significant environmental benefit with AVs, with reductions in GHG emissions and fuel consumption, which they relate to a more consistent and planned driving style of the vehicles that can be optimised. Furthermore, Salonen and Haavisto (2019) found that some passengers that had used an autonomous shuttle, which can be compared to a small autonomous bus, stated that the AVs actions were more predictable than a human and therefore the vehicle was thought to be safe to travel in. Similarly, Millard-Ball (2018) states that AVs are more predictable than human drivers at crosswalks.

Heineke, Kampshoff, Mkrtchyan, and Shao (2017) state that the ”sensor package” most commonly used in AVs consists of radar, sonar, and cameras that are capable of detecting signs, lane markings, and other vehicles at a lower definition while not requiring a large amount of data processing, which is also supported by Huggins et al. (2017). LiDAR is another technology that can be used in addition to the other sensors that is useful in high-traffic conditions since it offers a more detailed view of the surroundings, with the capability to detect road edges without relying on lane markings (Heineke et al., 2017; Huggins et al., 2017), with an example given in figure 2.2.

Figure 2.2: Example of what a LiDAR detects (Volvo Group, 2018)

Limitations

The autonomous functions of currently available vehicles are usually constrained to a certain set of parameters to function, such as only being available on highways or certain previously mapped locations (Mudge, 2016; Nikowitz, 2015). According to Mudge (2016) the autonomous driving functions are specifically susceptible to certain types of equipment malfunctions and failures which must be avoided and overcome in order to enable level 4 & 5 AVs. According to Ehrlich and Hautière (2016) the most common failures include various GPS failures, high latency, and camera failures. Ehrlich and Hautière attributes the failures to several different causes, but state that GPS failures are commonly caused by the satellite signals being blocked, for instance by tunnels or tall buildings, or that the positioning gets a bad fix on the location placing the vehicle on a different road than it is on. This type of situation, that Ehrlich and Hautière calls ”Map matching failure” can limit the usefulness of the systems and can occur at complex intersections or if there is a parallel road adjacent to the road the vehicle is driving on.

The sensors that AVs use for obstacle detection and positioning currently also have some limitations, including improper detection of lane markings, traffic lights and bad road conditions (Dixit et al., 2016). The cameras can get dirty or blocked by leaves, snow, or dust which makes it difficult to operate reliably in those conditions (Ehrlich & Hautière, 2016; Salonen & Haavisto, 2019), but low standing sun and sun glare are also reported to cause issues with the cameras (Dixit et al., 2016; Ehrlich & Hautière, 2016). Weather such as snow can also present issues for AVs to properly identify objects that are covered, such as parked cars, and snow can cause issues with sensors as well if they are covered (Knight, 2020). Coppola and Silvestri (2019) argues that when high automation is standardised, V2V, V2I, I2V, and V2X communication needs to be available to support the sensors in the vehicle. The vehicle systems can act unpredictably in snowy weather and will have lots of issues with both false positives and negatives, i.e. detecting non-existent obstacles and failing to detect existing obstacles. Furthermore, interviews conducted by Knight (2020) shows that industry actors have not focused on the issues, with a spokesperson for Argo AI stating that new hardware and software will be required for AVs to deal with inclement weather.

According to Neumeister and Pape (2019) adverse weather can affect the sensors significantly under certain circumstances, a summary of which can be seen in table 2.3. It was also found that camera-based systems were more consistently affected by weather compared to systems that used radar and LiDAR in addition to cameras.

Table 2.3: Summary of how weather affects AVs (Neumeister & Pape, 2019)

Weather condition	Effect
Water on road	No effect on systems
Snow on road	AV could not find lane
Falling rain	Short interruptions of ACC
Heavy rain	False positives & negatives
Ice on sensors	Complete black-out of sensors
Light snowfall	No effect on systems

The sensors sometimes pick up information on a non-existent object, alternatively that the AV misinterpret data and detect non-existent objects, an error called a *false positive* (Helmer, Kompaß, Wang, Kühbeck, & Kates, 2016; Huggins et al., 2017). According to Huggins et al. (2017) this can cause vehicles spontaneously braking on an open road, which in itself can put the vehicle and its occupants in danger. A similar error is the false negative wherein the sensors do not detect an object or the vehicle acts like the object is not there (Helmer et al., 2016; Huggins et al., 2017). It is such a scenario that was a contributing factor in a crash between a car operating with ADAS and a stationary fire truck in California (NTSB, 2019c). In tests using a Collision Avoidance System (CAS) on trams in Gothenburg it was found that the system gave many false positives when the vehicle was approaching stops (Nyström, 2015). For buses using a retro-fitted CAS in Cleveland, Ohio the accuracy of the system was 81% with 10% incorrect alerts and 9% false alarms (Valentine et al., 2019). Failure of the systems to detect obstacles or failure to properly identify objects have been contributing factors in accidents involving AVs or vehicles with ADAS (NTSB, 2019a, 2019c). When analysing disengagements of the autonomous driving functions of AVs Dixit et al. (2016) found that system failures, i.e. hardware or software failure, was the cause of 56.1% of disengagements. Dixit et al. also found that road infrastructure, such as not being able to detect traffic signals, potholes, poor lane markings, and bumps, was behind 10% of disengagements. The AVs have also shown to be limited when it comes to situations when there is a need to communicate to another vehicle, especially conventional vehicles, for instance at four-way stop intersections or at narrow passages in the road where it isn't clear who has the right of way (Huggins et al., 2017).

The currently available AVs also have limitations when it comes to the complexity of the traffic situations, with some manufacturers opting to remotely control the vehicle in those situations (Monios & Bergqvist, 2019). Complex situations include examples as city streets with many intersections, large highway junctions, and roadworks (Antonio Loro Consulting, 2016; Huggins et al., 2017; Monios & Bergqvist, 2019). Roadworks appear to be especially challenging for AVs according to Huggins et al. (2017) as the vehicle must be able to detect and follow temporary road markings, which is sometimes painted on top of the ordinary markings, and temporary speed limits which are marked by temporary signs. Some manufacturers, such as Navya, have opted to use a method where the vehicle only will travel along a predetermined path and stop when there is an obstacle in the way, to then require manual control by an operator to steer around the obstacle (NTSB, 2019b), however, the AV still has to manage the challenge of variability in interactions with vehicles, cyclists and pedestrians (Fridman et al., 2019). According to Machek et al. (2018) unprotected level crossings also present a significant challenge to AVs, as they are often nonstandard and require looking in odd directions or listening for a horn to detect an oncoming train. Furthermore, Machek et al. also state that protected level crossings present a challenge as the AV is at risk of getting stuck between the barriers, without it realising the danger of it. Millard-Ball (2018) states that one way of overcoming the complexity of the interaction between AVs and pedestrians is to physically separate them with barriers, but at the same time he states that this will increase the perception of roads as impassable obstacles and complicate city planning.

2.2.3 Autonomous buses

According to Liu (2017) the definition of an autonomous bus is an "automated vehicle designed to carry more than 15 passengers and operated on a non-exclusive roadway" (p.14). Buehler (2018) states that the advantages of using automated buses compared to automated cars is that buses in many locations already have access to a separate lane from the rest of the traffic, and that they have a lower average speed, which makes them suitable for early implementation of the technology. Automated buses can further draw benefits from AV-exclusive lanes if such a thing is implemented (Buehler, 2018).

While most of the efforts regarding automated buses have been focused on small shuttles, such as Levine, Zellner, Arquero de Alarcón, Shiftan, and Massey (2018) and Rau et al. (2019), some studies and trials have been performed on full-scale buses, such as Montes, Salinas, Fernández, and Armada (2017) and Lutin and Kornhauser (2013). Nowakowski, Shladover, and Tan (2015) argues that special consideration has to be taken when applying autonomous car technology to heavy vehicles, such as buses, since the use-cases differ. Furthermore, Nowakowski et al. also states the fact that the vehicles will be used commercially and be a part of a larger fleet might lead to different solution compared to an autonomous car.

Both Irizar and Scania are planning to begin public trials with full-size automated buses during 2020 in Spain and Sweden, respectively, (Irizar Group, 2020; Scania, 2019) while Mercedes-Benz has conducted trials in the Netherlands using a level 2 autonomous bus on a 20km long Bus Rapid Transit (BRT) route (Cregger, Machek, & Cahill, 2019). The bus was capable of reaching a top speed of 70 km/h and could recognise traffic lights and pedestrians to react accordingly (Cregger et al., 2019). Cregger et al. (2019) further state that there are currently no commercially available full-size automated transit buses on the market, and that the adaption will take long as transit is not a prioritised area for manufacturers and that cost is high. Pessaro (2016) argues that the development of autonomous driving systems is not as widespread for large transit vehicles as it is for private vehicles. For instance, Pessaro notes that in a survey with five contacted bus manufacturers, only one had any plans on implementing ADAS technology in their buses and that the development within the field is largely initiated by universities and not the transit vehicle manufacturers themselves. Similar statements are made by Cregger et al. (2019) and Lutin (2018), which state that some bus manufacturers do not have the resources to develop AV technology. Furthermore, the majority of transit-oriented vehicles currently developed are either minivans with autonomous driving added on or smaller automated shuttles (Cregger et al., 2019). An autonomous bus prototype developed by Volvo Buses is shown in figure 2.3.

The current experiments regarding automated busses in public transport have mainly included some type of guidance system, which often are physically buried in the ground (Liu, Fagnant, & Zhang, 2016), but in cases not using a guidance system, they operate in a slow speed (Lutin, 2018). There are, however, some exceptions to this including a bus that drove 32 kilometres autonomously in China, with a top speed of 68 km/h and without any intervention (Yutong, 2015). However, it is worth mentioning that some authors question the validity of this report due to scarce information regarding the project (Habibovic & Amanuel, 2019). According to van der Schaft (2018) the automated shuttle built by EasyMile has the capability

Figure 2.3: An autonomous bus prototype from Volvo (Volvo Group, 2018)

to travel 400 km with a speed up to 50 km/h. The shuttle uses cameras position itself and to detect obstacles up to 50 meters away, and travels along a predetermined path that it has to learn beforehand (van der Schaft, 2018). During tests with a bus retrofitted with an automated lateral guidance system in Eugene, Oregon, it was found that the particular implementation improved the experience when departing from and arriving at stops compared to a conventional bus, but that it made ”jerky” sideways motions when adjusting its lateral position (Gregg & Pessaro, 2016). However, during tests on a 32m long bus in China, it was found that autonomous driving caused less variations in steering inputs at speeds up to 72 km/h, and made the ride more stable compared to a human driver (Yuan et al., 2019).

Zhang (2019) state that automated buses have to be more careful than autonomous cars since there is a possibility that the bus will have standing passengers which means that the vehicle can not brake as suddenly, which reduces operating speed. To get around this, one approach has been to completely separate the AVs from all types of interference by having them using an elevated concrete track (Bampton, Campbell, & Heyns, 2016). This type of solution is commonly referred to as Personal Rapid Transit (PRT), Group Rapid Transit (GRT) or sometimes a people mover (Bampton et al., 2016; Liu, 2017). Cregger et al. (2019) makes the argument that most applications of ADAS or AV technology are currently found in trucks either operating within confined areas such as ports or mines, or on highways. Furthermore, Cregger et al. states that buses tend to be the last vehicle type in a manufacturers line-up that gets new technology implemented which is called the trickle-down effect, as the volumes are lower compared to trucks and cars.

In the study conducted by Azad, Hoseinzadeh, Brakewood, Cherry, and Han (2019), the authors made a literature review over the research conducted on fully autonomous buses, mainly operating in lower speeds. Azad et al. conclude that research has mainly been conducted in the fields of technology development, user acceptance, safety, social and economical aspects, regulations, policies and legal issues. Näringsdepartementet (2018) states that more research is needed in the area of infrastructure requirements since the trials currently conducted does not give a fair view of the actual requirements of widespread adoption of AVs.

2.3 Future predictions

Shaheen and Cohen (2018) predicts that automation could have the greatest transformative impact on regions and public transit since the introduction of the car. Shaheen and Cohen further state that it is likely that the introduction of AVs will change the way we think of cities, commuting and cost associated with travel. In addition, Kellett, Barreto, Hengel, and Vogiatzis (2019) state that the adoption of AVs will reduce the overall vehicle fleets, as the vehicles are predicted to have better utilisation rates compared to today. Kellett et al. also states that it is likely that, at least during the initial implementation phase, there will be more congestion as a result of increased vehicle flows the AVs will bring at the detriment of public transit. This is in accordance with Ferdman (2019) who states that automated vehicles can produce induced demand, up to 50%, and therefore making traffic problems worse as more people would have access to personal transportation. Extra trips would be a consequence of the need for re-positioning of the vehicles. Transport & Environment (2019) estimates the induced demand to be 40%, and this higher demand for mobility would, according to Currie (2018), increase the need for public transportation to alleviate the congestion created by automated vehicles.

Maurer et al. (2016) argues that it is difficult to make future predictions for levels of autonomous driving since the forecasts of system capabilities are not reliable, while Cottam (2018) argue that it is difficult to predict and make the metaphor of asking planners to predict and plan for airports right after the Wright brothers' first flight. However, many researchers and companies still make predictions despite this (Litman, 2019), and the time for when fully autonomous vehicles will be available differs (Coppola & Silvestri, 2019).

2.3.1 Estimations

The most optimistic experts estimate that fully autonomous vehicles will available in 2021 while other experts estimate that they will be available in 2025 (Coppola & Silvestri, 2019). Car manufacturers and media, estimate that fully autonomous vehicles can be expected around 2030 (Coppola & Silvestri, 2019; Kaplan, Gordon, Zarwi, Walker, & Zilberman, 2019), and this is also supported by Villagra et al. (2018), ERTRAC (2019) and Milakis, Snelder, Van Arem, Van Wee, and De Almeida Correia (2017). However, Coppola and Silvestri (2019) mention that the predictions made by automotive manufacturers could be questioned due to the fact that they may have other incentives for estimating shorter timelines, including marketing purposes. The same argument is made by Litman (2019) who notes that the most optimistic predictions regarding the implementation of AVs are the actors who have a financial interest in the success of the industry, while academia seems to be more reserved in their predictions. For instance, Litman argues that the report by Arbib and Seba (2017) which is not necessarily factually wrong, make a few premature conclusions.

In 2018 Machek et al. (2018) did state that level 5 automation was at least a decade away from being implemented, if not more. Similar statements are found in Heineke et al. (2017), which stated in 2017 that full-fledged AVs are probably more than a decade away from being implemented. Other authors mention time-spans, including Kaplan et al. (2019) that states that level 5 autonomous vehicles are expected to be available to the general public somewhere between 2020 and 2030, while conclusions from a literature review conducted by Bimbraw (2015) stated that fully autonomous vehicles are expected to be available by 2035.

Smit et al. (2019) argue that level 1-4 are likely to be operated in 2040, but that it is still unlikely that level 5 is present. Coppola and Silvestri (2019) mention that the academia believes that this kind of autonomy level will not be available within the coming 50 years, which is supported by Mudge (2016) who states that level 4 & 5 AVs will not be available to the general public until 2075.

2.3.2 Roadmap

Chottani, Hastings, Murnane, and Neuhaus (2018) have analysed the roll-out plan for autonomous trucks and states that it is likely for the technology to be rolled out in stages. The first two stages, which are mainly related to platooning on highways, is believed to be implemented around 2025. The third stage, which is driver-less trucks on highways, but using drivers on other roads are expected between 2025-2027, with fully autonomous trucks following after 2027. Similarly to this, (ERTRAC, 2019) estimate that the use of hub-to-hub transportation for freight transport is to be established between 2020 and 2026 ERTRAC (2019).

Some authors state that it is possible for manufacturers to largely skip level 3 AD in favour of level 4 and 5, due to uncertainties for drivers responsibilities at that level (Kockelman et al., 2016). Regarding autonomous driving level 4 for buses, these are predicted to be fully implemented on dedicated roads by 2024, and in mixed traffic by 2030 (ERTRAC, 2019). Grush and Niles (2018) states that what is far more likely is that by 2030, two types of automation will grow, namely the type with the driver monitoring the SDV, and fully autonomous vehicles that operate on slow speeds in geo-fenced areas. Furthermore, this is likely to be the situation for between 20-40 years until the vehicles are unconstrained and in no need for a driver (Grush & Niles, 2018).

2.3.3 Adoption

The predictions so far have been regarding when the technology will be available, but not regarding market penetration. In Kaltenhäuser, Werdich, Dandl, and Bogenberger (2020) the market penetration is predicted. The results from Kaltenhäuser et al. show that about 25% of vehicles will be autonomous by 2040 and that the majority of these will have steering wheels, compared to the ones without it. Other researchers believe that the share of vehicles that will be autonomous will be close to 100% by between 2050 and 2060 (Kaltenhäuser et al., 2020). Litman (2019) on the other hand argues that it will not be until 2050 that 20-40 % of the vehicle fleet will be autonomous, but that 40-60% of the new sales will be autonomous vehicles by then.

Other researchers such as Grush and Niles (2018) claim that the likelihood of widespread use of level 4 or 5 automation by 2030 is "certainly zero" (p. 18) and that projections that are more optimistic are misleading. Gartner (2019) also believe that both autonomous driving on level 4 and 5 are more than 10 years away from reaching the ”plateau of productivity”, that is when mainstream adaptation is common, which can be seen in figure 1.1.

2.4 Public transport

Public transit is defined by Walker (2012) as ”*regularly scheduled vehicle trips, open to all paying passengers, with the capacity to carry multiple passengers whose trips might have different origins, destinations, and purposes*”.

Autonomous vehicles can not only be used for goods transport or taxi services, but also public transit (Zhang, 2019), and public transport may be the most suitable application since public transport operates on a fixed route, which reduces the complexity for the AV (Tettamanti et al., 2016). Currie (2018) makes the case for automated buses, as the majority of operating cost of a bus is the driver, and using automated buses, service can be increased without increasing the cost compared to today. Polzin (2016) argues that public transit is a good place for testing new technologies, due to the high exposure to the public, skilled operators, frequent maintenance, as well as the institutional environment that surrounds the industry. Another upside of using automated buses in public transit is the ability to use adaptive capacity and adaptive timetables (S. Lam, Taghia, & Katupitiya, 2016; Owczarzak & Zak, 2015). Preliminary reports state that there are some applications for AVs in public transit that would be economically beneficial for the transit operator and that the investments in the new technology would be justified by the savings it entails (Machek et al., 2018).

Polzin (2016) states that by using AV technology for public transit a more optimised vehicle size can be used, due to reduced operating costs since a driver is not needed. This could, in turn, reduce waiting times for passengers and increase the attractiveness of public transit overall. In accordance with this, Litman (2019) argue that the application of autonomous vehicles will be particularly suitable for public transport due to the high cost of a driver. Levine et al. (2018) also states that lower operating cost would be the immediate effect of implementing automated buses, but that it could increase the purchase price of the buses. However, Zhang (2019) adds that the lower operating costs will only emerge when drivers are fully replaced, which will not happen with partially automated buses, which is supported by Machek et al. (2018) who adds that more research is needed in the area to be able to perform a quantitative analysis of the costs and benefits of automated operations, such as platooning, since most of the data is speculative.

The technologies related to AVs that could benefit the industry in the short run are collision avoidance systems, autonomous steering, and platooning (Lutin, 2018). Lutin (2018) also states that platooning, in conjunction with shorter dwell times at stops, can enable a much higher capacity from a bus system compared to today. However, there are some challenges with the combination of traffic flows and autonomous buses, and the integration into current public transport systems (European Commission, 2019). Furthermore, Graving, Bacon-Abdelmoteleb, and Campbell (2019) found that buses have a higher than average incident rate involving pedestrians than other modes of transportation. This is argued by Graving et al. to be caused by a higher degree of interaction between buses and pedestrians at bus stops, and AV technology and ADAS have a big potential in reducing these accidents.

The importance of connected vehicles is highlighted by Araya and Sone (1984) who state that if a single vehicle only can make decisions for itself to reduce delay, there is a risk of the entire system becoming unstable, and therefore providing bad service to the customers. If the vehicle is connected, decisions to reduce delay could be made centrally and the system could be more stable (Araya & Sone, 1984). Leich and Bischoff (2019) analysed time saved when using a Shared Autonomous Vehicle (SAV) service compared to a traditional bus line and found that the time saved is usually less than 5 minutes, especially if the taxis are allowed to re-route during a trip to pick up another passenger. This is similar to what Walker (2012) describes as a deviating line which he states should be avoided in order to increase the attractiveness of the line.

With increased levels of autonomy and the possibility of so-called ”robotaxis”, the business model of public transport will be challenged (Grush & Niles, 2018). Merlin (2017) states that there are three likely scenarios for public transportation when it comes to the effects of automated vehicles:

1. AVs will increase public transit ridership by providing a first and last-mile service to and from stations.
2. Ride-sharing AVs will compete with public transit and draw away customers.
3. AVs and public transit will integrate with each other and draw benefit from each other’s strengths.

However, it is mentioned that most research on autonomous busses are in taxi-like situations, while the research on transport between fixed nodes is lacking (Zhang, 2019).

Watkins (2018) argues that AVs themselves will not solve issues with traffic as they, even in shared form, will take up the same space as a conventional car. If AVs are used in the same way as a transport network company operates today, such as Uber or Lyft, it is likely that the vehicle miles travelled will increase (SFCTA, 2017; Watkins, 2018). Watkins (2018) state that in order to make sure that public transit stays competitive in the future there are several things to consider. Mobility must be provided as a service, high-capacity vehicles should be given priority through High-Occupancy Vehicle (HOV) and bus lanes, focus on the service rather than technology, and making data available to both improve public perception but also spur further innovation (Watkins, 2018). Antonio Loro Consulting (2016) notes that the usefulness of automated buses increase the longer the distance travelled, and particularly in less complex situations such as highways and other grade-separated roads.

2.4.1 Application

If the bus were to have a high level of autonomy, the only difference between the current situation and the autonomous scenario would be the decreased operating costs, and the only difference between a shuttle and a bigger bus would be the capacity (Zhang, 2019). The use of autonomous buses could allow for an extension of the public transport lines to areas with lower demand (Coppola & Silvestri, 2019; Millonig & Fröhlich, 2018) or increase the frequency of the current network (Millonig & Fröhlich, 2018). Grush and Niles (2018) states that it is likely that bigger vehicles are used for longer distances and node-to-node routes while smaller vehicles are more suitable for first and last-mile transit and shorter routes. Mendes, Bennàssar, and Chow (2017) compares a fleet of AV shuttles with a light rail line and finds that to achieve the same capacity as Light Rail Transit (LRT) operating at 5-minute head-ways approximately 450 shuttles is required compared to 39 LRVs, stating that where the demand is high shuttles may not be suitable.

In order to investigate a specific use-case for automated public transit, von Mörner (2019) conducted a simulation of AVs as a complement to conventional public transit in rural areas, which are typically under-served, and concluded that it was a feasible use-case provided that the technology allowed it. Similarly, Sieber, Ruch, Hörl, Axhausen, and Frazzoli (2018) conclude that shared AVs can also provide good transit service to rural areas, and that it can be done at a lower cost compared to today, which is supported by Wen, Chen, Nassir, and Zhao (2018) who states that AV-based transit is most suitable in areas with lower population density as the savings per passenger is more noticeable. Other benefits gained by AVs is the flexible routing and dynamic scheduling, which may be especially useful in less dense areas (Fraedrich, Heinrichs, Bahamonde-Birke, & Cyganski, 2019).

Hub-to-hub

A. Lam, Leung, and Chu (2014) argue that autonomous buses are most suitable to be implemented as a transportation system using a point-to-point model approach, but Zhang (2019) states that nor the market or the technology is ready for this kind of transportation, even though this would reduce operating costs.

Machek et al. (2018) explores the possibility of using AV technology in BRT, since the application was deemed suitable because of the inherent characteristics of a BRT line. The BRT line is largely separated from other traffic, have fewer stops with better infrastructure, signal priority at intersections, and high-frequency service.

Montes et al. (2017) also recommends automated full-size buses for use in BRT, mostly due to the separation from other traffic but also in part due to the ability to provide frequent departures at a low cost.

Hedegaard Sørensen et al. (2020) argues that within cities and on routes with high demand, high-capacity public transit in the form of buses, LRT, and trains should form the foundation of the transportation system. Zhang (2019) and Antonio Loro Consulting (2016) argues that automated buses make the most sense in the corridors with the most traffic and that the main focus for the first automated buses should be on increasing the capacity during peak demand.

First and last mile

Currie (2018) and Levine et al. (2018) proposes the use of ”transit fusion”, a core network of high capacity transit modes, with smaller AVs, such as the one illustrated in fig 2.4, providing first and last-mile and other feeder services. This would be a contributing factor in the transition from using a personal vehicle to shared mobility (Currie, 2018; Levine et al., 2018). The drawback with smaller AVs is that it will be impossible to displace high-capacity transit with smaller AVs in cities as it would make congestion worse (Currie, 2018). Similarly, Mo, Cao, Zhang, Shen, and Zhao (2020) suggest the use of autonomous shuttles as feeders and last-mile services to a core system of higher-capacity vehicles. Mo et al. (2020) found that using AVs for longer low-demand routes and regular buses for high-demand routes improved the entire transportation system performance. Mo et al. also found that this improved the occupancy rate for both types of vehicle.

Figure 2.4: The Olli autonomous shuttle (Local Motors, 2019)

Wen et al. (2018) also argues that the most suitable implementation is between a suburban area and a rail-based transit station, to increase coverage and act as a first- and last-mile solution for the transportation system. On a similar note, Mahéo, Kilby, and Van Hentenryck (2019) used a simulation of a ”hub-and-shuttle” system proposed to be implemented in Canberra, Australia. Mahéo et al. found that using this type of system, where high-capacity vehicles travel frequently between hubs and smaller shuttles servicing the first and last-mile transport was both cheaper and faster than the current ”traditional” bus system.

2.5 Infrastructure requirements

The uncertainty of when AV's will be available and when the different levels of autonomous driving will be reached makes infrastructure planning difficult (Srinivasan, Smith, & Milakis, 2016). Authors such as Fagnant and Kockelman (2015) highlighted, as early as 2015, the lack of research on infrastructure requirements. Some argue that autonomous systems using the evolutionary approach will not require infrastructure adjustments since they have the required technology in the car, including sensors, cameras, digital maps and in some cases LiDAR (Coppola & Silvestri, 2019; Kockelman et al., 2016; Watzenig & Horn, 2016). On the other hand, Connected Autonomous Vehicle (CAV) have the functionality to communicate with other cars (V2V) and infrastructure (V2I) but would require more infrastructure adjustments, and it would therefore also take more time to make the needed adjustments (Coppola & Silvestri, 2019). Other authors including Olaverri-Monreal (2016) state that it is unknown if autonomous vehicles will require any infrastructure adjustments, but contrary to this, according to the (European Commission, 2019) physical and digital infrastructure is the second most important part for CAV after vehicle validation in a list of 23 different initiatives, and it is therefore of high importance. Regarding infrastructure readiness, a report conducted by KPMG (2019) states that Sweden is the fifth most ready country for AVs adoption, where infrastructure is one of the parameters evaluated. The subcategories used to evaluate infrastructure readiness include quality of mobile internet, 4g coverage, quality of roads, technology infrastructure change readiness, logistics infrastructure and density of charging stations (KPMG, 2019). The reasoning for including the density of EV chargers and logistics infrastructure is according to KPMG (2019) that AVs will mostly be EVs and that AVs will likely be used for freight transport in the beginning.

The requirements of infrastructures are not standardised and this is partly due to the difference of internal technologies that AVs use (European Commission, 2019). To solve the standardisation problem European Commission (2019) suggest for OEMs, road operators, users and traffic managers to cooperate and define these infrastructure requirements. The area of infrastructure adjustments need further research before decision-making and investments in this area (European Commission, 2019), even though future CAV may require additional infrastructure needs, and that they may not be covered until after 2030 (European Commission, 2019). According to the Research Institutes of Sweden (RISE), making adjustments of the infrastructure to fit the current levels of autonomy would both be costly and be inflexible (Jelica et al., 2019). Instead, Jelica et al. (2019) recommends to standardise the infrastructure requirements and implement some kind of minimum requirements for both physical and digital infrastructure, that the AV development can adjust to. The reasoning for not fully adapting to the current technology is due to the fast development of technology used for autonomous driving, including sensors and positioning technology (Jelica et al., 2019; Yu, Li, Murray, Ramesh, & Tomlin, 2019).

The European Commission (2017) argue that changing the physical infrastructure of the roads will not be necessary, however, improvements of road signs and lane markings could be beneficial for both AV and human driving. Instead, digital maps will be important, and issues regarding interoperability may become more important (European Commission, 2017, 2019).

2.5.1 Physical infrastructure

While some manufacturers claim that their vehicles can operate on any road without any modifications, some conditions need to be fulfilled (Kockelman et al., 2016). Possible changes include making dedicated roads for AVs (Blanco et al., 2016), monitor quality of signs (Kockelman et al., 2016) and lane markings (Broggi et al., 2013; Faisal et al., 2019; Farah, Erkens, Alkim, & van Arem, 2018), adjust speed limits (Blanco et al., 2016) and to change the position of traffic signals (Blanco et al., 2016; Kockelman et al., 2016; Sebanja & Megherbi, 2010). There are many functions of AV that is either partly or fully dependent on infrastructure changes in order to become a reality, including lane departure warning, lane-keeping, left turn assist, auto-valet parking and highway platooning (Kockelman et al., 2016). In order to estimate what these changes require and how much they cost, Kockelman et al. (2016) summarised them according to table 2.4. However, Farah et al. (2018) argue that there is a research gap regarding physical infrastructure and that the requirements found concerns 100% adoption of AVs.

Table 2.4: Infrastructure requirements needed for specific changes (Kockelman et al., 2016)

Function	**Needed adjustments**	**Cost of adjustments**
Lane departure warning Left turn assist Lane keeping Traffic jam assist	Lane markings	Low
Traffic sign recognition High speed automation Highway platooning	Traffic lights, lane marks	Moderate

Road layout

The road layout is an important aspect to consider for implementation of AVs, and there is a need to standardise the layouts to simplify the circumstances for the AV (Galbas & La Torre, 2020; Petriaev, 2019). Using a dedicated lane for AVs is not necessary, but it can accelerate the AD development, however, it could be necessary for urban environments (Dokic, Müller, & Meyer, 2015). This is the case since the complexity of urban driving is significantly higher than when driving on a highway, which makes highway driving a simpler implementation (Antonio Loro Consulting, 2016; Watzenig & Horn, 2016). Farah et al. (2018) found that protected lanes, such as HOV or bus lanes, could also be a good way of first testing AVs due to their comparatively limited interaction with other traffic, while Huggins et al. (2017) mentions the need for hard shoulders or lay-bys on roads that are travelled by AVs, as they need to be able to safely come to a complete stop if a problem arises and not block the road as they are doing so. Furthermore, Ehrlich and Hautière (2016) state that tunnels, especially long and curved ones, presents issues for positioning systems, which can require additional infrastructure to mitigate.

Intersections

Intersections is another important aspect to consider since these also need to be standardised (Galbas & La Torre, 2020; Petriaev, 2019). The most difficult intersections to handle are the ones without traffic lights (Isele, Rahimi, Cosgun, Subramanian, & Fujimura, 2018; Song, Xiong, & Chen, 2016), but in order to overcome many of the difficult intersections, these could be changed to roundabouts (Petriaev, 2019) or signalled intersections (Levinson et al., 2011), since this would lower the complexity for the AV. Furthermore, flyovers and other types of grade-separated highway intersections can both reduce and increase complexity (Antonio Loro Consulting, 2016; De la Fortelle & Qian, 2016; Ehrlich & Hautière, 2016; Friedrich, 2015). According to Friedrich (2015), the separation of traffic flows and the reduction of conflict with other traffic have positive effects on the overall flow of traffic. At the same time, Antonio Loro Consulting (2016) argues that placing flyovers and off-ramps too close together will increase the complexity of the traffic situation as vehicles are required to change lanes more often. Furthermore, Ehrlich and Hautière (2016) mentions that complex highway intersections in multiple levels might confuse the positioning systems on the AV. A solution to reduce complexity for AVs is according to Farah et al. (2018) to have protected crossings for pedestrians and bicyclists, since this reduces the interaction between AVs and pedestrians.

Signs

Other than the placement of signs, the condition is important (Kockelman et al., 2016) but also the lighting, since some technologies used in AVs, mainly cameras, have a lighting requirement (Huggins et al., 2017; Kockelman et al., 2016) in order to ensure readability of signs (De la Escalera, Armingol, & Mata, 2003). Similarly, the U.S. Department of Transportation (2018) argue that good preparation for AVs are for road owners to increase the quality of signs, roads and road markings, even though AVs are being developed to function with the existing infrastructure. According to Huggins et al. (2017) variable smart signs can be difficult for AVs to reliably detect visually, and Huggins et al. instead proposes to use other technology to send the same information directly to the AV.

Maintenance

Huggins et al. (2017) highlights the need for routes intended for traffic by AVs having higher maintenance standards, as they currently have difficulties avoiding potholes and other obstacles in the road. Another reason why maintenance is important is due to too precise positioning within the lane which causes rutting, which is when the pavement is worn down in specific spot (Farah et al., 2018; Steyn & Maina, 2019). However, one benefit with this reduced wandering in the lane is the possibility to make the lanes more narrow (Farah et al., 2018). According to Farah et al. (2018), highways currently consisting of two lanes could be changed to three lanes without an expansion of the current road, and where the third lane could be dedicated to either platooning or AVs that could operate in higher speeds.

Duvall, Hannon, Katseff, Safran, and Wallace (2019) state that basic preparations for AVs are to keep existing infrastructure in good condition, eliminating any potholes, lacking road markings, and other maintenance issues that can lead to issues for AVs. Furthermore, Duvall et al. argue that continuous maintenance is of the essence to not have any issues with the infrastructure on a longer time horizon and that preventive maintenance must be a priority. One way of measuring the quality of the road, according to CEN (2017), is to use the IRI.

Lane markings

Regarding lane markings, these need to be standardised and continuous (Farah et al., 2018; Huggins et al., 2017), and reflectors (Duvall et al., 2019; Huggins et al., 2017) or other "sensor friendly" infrastructure markings (Yousuf, Dailey, Sundararajan, & Kandarpa, 2016) could be used as a complement to lane markings for AVs to distinguish them better. Furthermore, in order to be able to operate AVs in bad weather, the infrastructure needs to be adapted so that lane markings and signs are visible in conditions where visibility can be limited (Neumeister & Pape, 2019). Furthermore, Faisal et al. (2019) and Farah et al. (2018) also stress the need for clear lane markings, and that repainting some roads might be required in order to be able to operate AVs on them.

2.5.2 Digital infrastructure

There is still a long way until vehicles are fully autonomous, but in order to support the development of them, infrastructure is important (Carreras, Xavier, Erhart, & Ruehrup, 2018). Autonomous vehicles are according to Skarbek-Zabkin and Szczepanek (2018) adjusting to the physical infrastructure currently in place, but they require new digital infrastructure. However, Farah et al. (2018) argues that it is unclear whether the sensors in the vehicle will be sufficient or if sensors will need to be a part of the infrastructure (Farah et al., 2018). CARTRE (2018) state that digital infrastructure will become necessary for reaching higher levels of autonomy, but adds that it is unclear what infrastructure adjustments are necessary for which levels. Watzenig and Horn (2016) is somewhat less optimistic about the role of digital infrastructure, stating that it may not be necessary but that it can be beneficial. However, CARTRE (2018) adds that it is important to assess which changes that are really needed. The aim of AV is to not be dependent on external information and therefore also infrastructure, but in the progression towards higher levels of autonomy, the use of infrastructure support could enhance the pace of the development (Carreras et al., 2018). Contrary to this Dokic et al. (2015) argues that in order to achieve higher levels of autonomy V2V and V2I is needed, and therefore also a standardisation of this communication, and that this should be solved by 2025.

In order to achieve all the benefits of AVs, they need to be connected to the infrastructure (Farah et al., 2018). Important for this connectivity is sensors, digital maps, positioning technology and communication technology (Farah et al., 2018). According to Coppola and Silvestri (2019) it is researchers and not the industry that is the most interested in connected autonomous vehicles (CAV) that communicate with other entities, but Carreras et al. (2018), Grush and Niles (2018) and Coppola and Silvestri (2019) state that the digital infrastructure requirements of AV are still unclear and there is a need for further research in this field. In order to make the definitions of infrastructure requirements more clear, and to reduce the need to communicate every detailed characteristic of a road, Carreras et al. (2018) suggest a standardisation of infrastructure support for AV.

Digital maps

Vehicles of autonomy level 4 and 5 are dependent on localisation data, making tunnels and other areas with insufficient connection difficult to operate in (Carreras et al., 2018; Ehrlich & Hautière, 2016), but redundant technologies are emerging, making the loss of Global Navigation Satellite System (GNSS) or Inertial Navigation System (INS) more acceptable (Yousuf et al., 2016). According to Meng et al. (2018), techniques such as Simultaneous Localisation and Mapping (SLAM) can be used in conjunction with GNSS-based systems to improve redundancies and improve positioning further. Englund et al. (2018) describes that there is a symbiotic relationship between positioning, mapping, and localisation that directly influences the performance of the navigational system of the AV. Physical information like directions and speed limit does not have to be noticed by the AV since this information often is stored in digital maps that are commonly used by AVs (Carreras et al., 2018; Parsons et al., 2018). Duvall et al. (2019) mentions the need for a continuously updated and accurate 3D map of roads so AVs are able to predict what is ahead, especially where the road design is complex. In order to access high-resolution maps to increase the positioning of the GPS, 4G/5G connection is necessary (Jelica et al., 2019). Heineke et al. (2017) state that there are two main approaches to mapping, *Granular high-definition maps* and *Feature mapping*. The granular HD maps are created using LiDAR scans and data from cameras that are placed on a specially equipped vehicle that drives the route that the AV is intended to operate along, while feature mapping mainly uses cameras to map features such as signs and other objects at a much less detailed level (Heineke et al., 2017).

The digital map, or road database as it is also called, is the most fundamental part of digital infrastructure (Farah et al., 2018). In order to increase the quality of these maps, they should contain 3D information that is of high precision, rich of information and preferably updated in real-time to include road maintenance or construction (Farah et al., 2018). Yousuf et al. (2016) also covers the topic of mapping, and states that high-quality maps are useful for use in SLAM techniques for use in foul weather. In order to standardise different levels of digital traffic information, CARTRE (2018) categorised it in four different levels, which can be seen in table 2.5.

Table 2.5: Levels of traffic information used by CARTRE (2018)

Levels	Function	Example
Static	Basic Map Database	Digital cartographic data, topological data, road facilities
Semi-static	Planned activities and forecast	Traffic regulations, road works, weather forecast
Semi-dynamic	Traffic Information	Accidents, congestion, local weather
Dynamic	Information through V2X communication	Surrounding vehicles, VRU, traffic
	Driving recommendations	Lane change, distance gap, speed

V2I & I2V

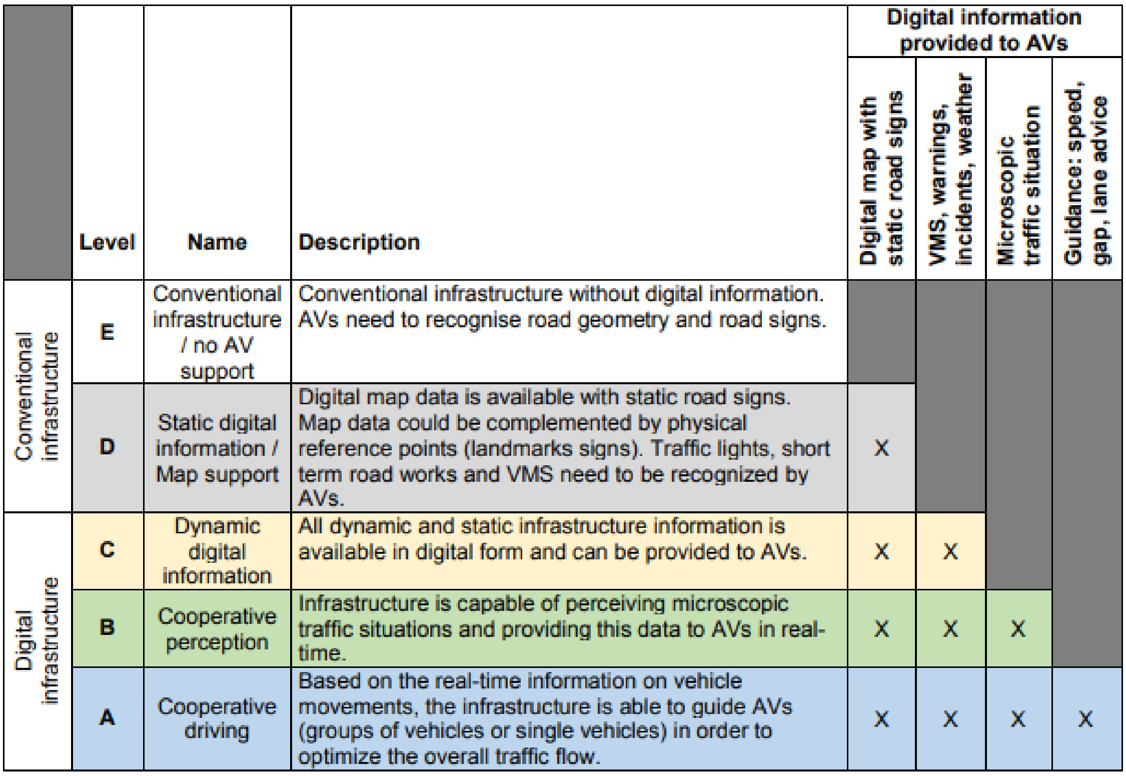
The European Commission (2019) and Ravipati et al. (2019) explain that AVs connected to the digital infrastructure will increase the overall positional awareness of the vehicle. These I2V sensors communicating with the vehicle would increase the knowledge of the road ahead (Carreras et al., 2018; Toledo-Moreo et al., 2018) and could be used in intersections and other complex situations (Carreras et al., 2018; Rebsamen et al., 2012). The V2I and I2V can enable the use of permanently placed sensors that could help the vehicle in areas or situations where GPS/GNSS connections are limited (Yousuf et al., 2016), to detect blind-spots around corners, or to further improve the AI to better predict pedestrian movement (Dubbert, Müller, & Meyer, 2008). The use of infrastructure sensors would also lower the responsibility of the vehicle manufacturer, and could according to Gopalswamy and Rathinam (2018) increase the rate of development for SDV.

Tettamanti et al. (2016) further argue that communication between cars and infrastructure will become a part of the normal daily driving and that for example physical traffic lights can be replaced by digital traffic lights over time. Dokic et al. (2015) also argues that connectivity is necessary for AVs in order for them to operate safely while ERTRAC (2019) and Alonso Raposo et al. (2019) argue that more benefits will be able to emerge if the vehicles are connected to the infrastructure (V2I), which could be by a 5G connection. One of the reasons why 5G would be beneficial compared to 4G is the low latency (ERTRAC, 2019; European Commission, 2019), and 5G is, therefore, a key enabler for AD (European Commission, 2019) and will improve the success rate of an AV implementation (Steyn & Maina, 2019).

Faisal et al. (2019) found that ITS features such as smart signs and radio information messages regarding traffic conditions might still be useful in the future, dependant on how and if other methods of V2I and I2V technology is implemented. Furthermore, Faisal et al. also states that traffic signals might have to be equipped with dedicated short-range communications (DSRC) in order for all AVs to reliably be able to detect and distinguish what signal is shown. In order to create an efficient system of AVs Monios and Bergqvist (2019) state that V2I and I2V communications are important as information handling can become centralised and benefit more than one road user. In a network context, Rau et al. (2019) argue that I2V technology enables the use of centralised control which can make coordination more efficient, as well as enable the AVs to travel at higher speeds and closer distances as information relating to road conditions and intentions of other vehicles can be easily shared. Duvall et al. (2019) state that traffic signals and signs will need to be able to communicate directly with the vehicles, as the systems used for identification today have limitations regarding reliability and readability. Similarly, Wagner, Baker, Goodin, and Maddox (2014) argue that DSRC will be needed in order for I2V and V2V communication to work, but it is uncertain who should cover the cost for this infrastructure to be installed.

Sight is a hindrance for AVs, but I2V connection could help solve this problem as it can communicate information that the car can not see, or information that it missed (Farah et al., 2018). For vehicles to be able to reliably identify their position, Yousuf et al. (2016) suggests the use of connected, static infrastructure points to enable easy I2V and V2I information sharing. Yousuf et al. argue that the use of such static infrastructure points could improve the safety of AVs in several areas, such as work zones, intersections and near schools. Unless AVs use I2V connectivity they need approximately the same line of sight that a human needs in order to safely travel at the same speeds (Farah et al., 2018). Meng et al. (2018) further highlight the needs for accurate positioning of AVs using a concept called Required Navigation Performance (RNP) that is originally used in aviation that states four main criteria that the positioning system should fulfil. The criteria are *integrity* which means that the information collected by the positioning system is reliable, *continuity* that is that the positioning system can be trusted to continuously function independently of the main function of the vehicle, *availability* that is the up-time of the system, and *accuracy* which is the difference by the measured position and actual position (Meng et al., 2018).

In order to standardise the digital infrastructure support, Carreras et al. (2018) developed a framework for the classification of roads. Infrastructure support levels are not meant to cover large areas but rather segments of the roads (Carreras et al., 2018). For example, when driving on a highway without intersections, the need for this support is lower than in an intersection contains mixed traffic (Carreras et al., 2018). The levels A-D are sometimes required to have connectivity since they are retrieving information from the infrastructure, but for level D, this need is periodical since the maps presented in table 2.6 is rather static (Carreras et al., 2018). As explained by Carreras et al. (2018), when using the support levels A-B, the latency of the communication must be low since the information is used to guide the vehicles. Pilot studies with supportive infrastructure of level B and C are currently ongoing in Austria and Spain respectively (Carreras et al., 2018). However, the drawback mentioned regarding connected infrastructure is that this would be expensive to implement (European Commission, 2019).



	Level	Name	Description	Digital information provided to AVs			
				Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
Conventional infrastructure	E	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs.				
	D	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs.	X			
Digital infrastructure	C	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs.	X	X		
	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time.	X	X	X	
	A	Cooperative driving	Based on the real-time information on vehicle movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow.	X	X	X	X

Table 2.6: Levels of infrastructure support (Carreras, Xavier, Erhart, & Ruehrup, 2018)

2.6 Conceptual framework of infrastructure requirements

The following framework is based on section 2.5 and is constructed by the authors of this paper.

The literature review resulted in five main categories for physical infrastructure, including; road layout, intersections, signs, maintenance and lane markings. Three categories of digital infrastructure did also emerge, including; digital maps, V2I/I2V communication, and connectivity. All categories but connectivity is a separate sub-chapter, but connectivity is interrelated to both digital maps and V2I/I2V and is therefore not distinguished from them in terms of a sub-chapter. These main infrastructure characteristics resulted in the construction of a conceptual framework, which can be seen in 2.5. In order to be able to evaluate these different parameters, the framework was divided into subcategories. The subcategories were found in the literature review can be seen in table 2.7.

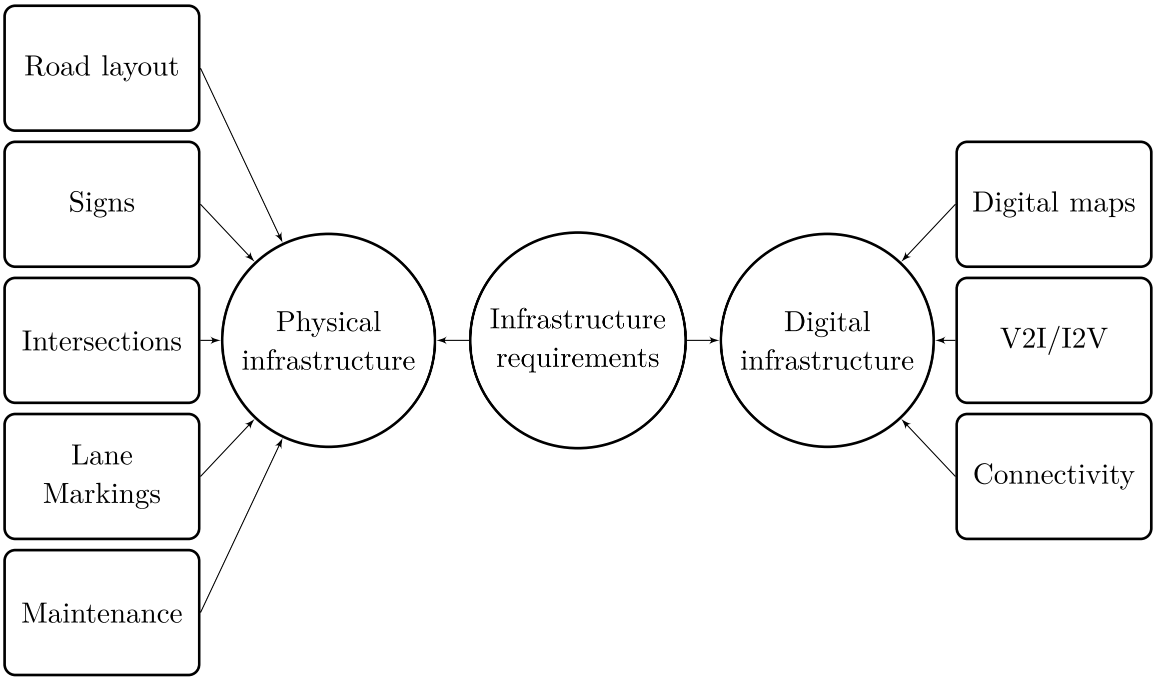


Figure 2.5: Conceptual framework of infrastructure requirements

Table 2.7: Subcategories of identified infrastructure categories

Group	Category	Subcategory
Physical infrastructure	Road layout	Dedicated lanes
		Protected lanes
		Tunnels
		Hard shoulders and lay-bys
	Intersections	Roundabouts
		Flyovers
		Traffic lights
		Separated pedestrian crossings
	Signs	Condition
		Lighting
		Placement
	Maintenance	Road pavement quality
	Lane markings	Condition
		Reflectors
Digital infrastructure	Digital maps	Detail
		Update frequency
	V2I & I2V	Sight
		Traffic info
	Connectivity	Positioning
		Latency
		Coverage

3

Methodology

The report is an exploratory study (Bryman & Bell, 2011) that consists of three phases. The *first phase* is including data collection through a literature review. The collected data of infrastructure characteristics are then compiled to create a framework used for route evaluation. The *second phase* is a multiple-case study consisting of interviews and gathering of data on routes. The qualitative interviews with researchers and industry professionals were conducted to gather as much up-to-date data as possible, and the internal documents provide information about the selected routes. In the *third phase* the framework was applied to the different routes for analysis and comparison of the cases, to be able to find the most suitable route for AV implementation.

3.1 Methodological approach

According to Dubois and Gadde (2002), abduction is a commonly used research approach when starting with a theoretical framework and then making adjustments to the framework based on a case study. This is similar to this study, where the case serves as both a confirmation of the conceptual framework and further development of it. An abductive approach is especially suitable for theory building (Dubois & Gadde, 2002). According to Awuzie and McDermott (2017) an abductive approach is used in qualitative research when neither the inductive nor the deductive approach is suitable for the research purpose. Corbin and Strauss (2015) states that a qualitative literature review is suitable for discovering variables for later quantitative testing, which is in alignment with this project.

3.2 Data collection

The main purpose of the data collection phase was to gather enough data to be able to construct a model from several criteria regarding the characteristics of route and requirements for infrastructure to support the vehicles. The literature review was conducted to analyse what already has been researched and what emerging technologies that exist, regarding autonomous vehicles and road infrastructure characteristics. A case study was also conducted, with different actors interviewed to gain additional information from other data collection methods than a literature review.

3.2.1 Literature review

A literature review is described as a suitable method for data collection in qualitative research by Bryman and Bell (2014). According to Bryman and Bell a literature review is one of the main steps in qualitative research and is crucial for the initial data collection and to get a good overview of what you are researching.

A literature search was conducted by using databases of academic papers, such as the libraries of the Technical University of Eindhoven and Chalmers University of Technology, and Google Scholar. Keywords used for the literature search include *Autonomous vehicle, self-driving vehicle, autonomous vehicles infrastructure, autonomous transit, automated transit & autonomous bus.* To supplement the academic papers several books and popular science articles were used as well. Furthermore, news articles and press releases from different sources were also used to get an overview what the industry currently is working on, and what is coming in the near future in the form of trials, projects, and product releases.

Gandia et al. (2019) conducted a bibliometric review and found that within the area of AVs, there was a relatively high number of conference proceedings, which they attributed to the novelty of the area. Gandia et al. also found that 0.70% of all sources contribute 33% of the content, which they state could be related to the highly localised developments within the area.

As described by Bryman and Bell (2011), in exploratory studies the authors are not sure what they will find. The literature review is often used to gain a first view of the topic, and that the research questions are later adapted to fit the existing literature (Bryman & Bell, 2011), which was the case in this project. The data collected is used to create a framework of the most commonly appearing themes and requirements.

3.2.2 Case study

The case study was conducted using a methodological approach described in Meckstroth (1975) and Przeworski and Teune (1970) that is called ”most different systems design”. The method is based on selecting study objects with different attributes to make sure that systemic factors do not play a role in the comparison. As such, the results obtained should be able to see if the selected routes are suitable for operations of autonomous buses, and by extension, if the framework developed is suitable to use.

Interviews

According to Corbin and Strauss (2015), unstructured and semi-structured qualitative interviews provide the most amount of data for use in theory building, which supports the choice of conducting semi-structured interviews. It is also stated that since the participants can speak more freely the interview method is suitable for when the interviewers have limited knowledge in the area (Corbin & Strauss, 2015). The choice of semi-structured interviews is further supported by Yin (2018) who argues that unstructured or semi-structured interviews are more suitable for case studies since the interviews allow for more in-depth knowledge and theory building. The interviews were conducted via phone calls, video calls and in-person and were between 30 minutes to one hour.

The sampling of respondents was based on their ability to contribute to the research, and all companies except company B is involved in projects regarding autonomous vehicles. The difference in industries interviewed was chosen to gain a breadth of the companies, which was thought after since the position of the actor could influence the answers given. The diversity of industries the companies operate, which can be seen in 3.1, was also chosen to be able to evaluate if answers differ between industries. The disclosure of the number of interviews and how the sampling was conducted is according to Bryman and Bell (2011) important to increase transparency. Furthermore, the variety of industries interviews could reduce the risk of opportunistic sampling (Bryman & Bell, 2011).

Table 3.1: Industry and position of respondents

Pseudonym	**Industry**	**Position**
A	Consulting	Senior consultant
B	Public transport	Managing director
C	Bus operation	Project manager
D	Bus operation	Project manager
E	Start-up	Project manager
F	Government agency	Lead analyst
G	Research institute	Research director
H	Research institute	Managing director
I	Research institute	Researcher
J	Automotive manufacturer	Project manager
K	Automotive supplier	Chief designer

Organisational documents

The data collection does also consist of internal documents, both within the Swedish Transportation Administration and Västtrafik. These documents are used to gain additional information about routes, that is not, or only partially available to the public. Bryman and Bell (2011) state that there is a risk that companies only provide documents that are of non-confidential status, and that this information asymmetry may affect the research. The information needed in this case study is not of confidential nature, and the risk of information asymmetry due to this reason is therefore low. The information has mainly been gathered through ERP systems and internal reports.

3.2.3 Route selection

The selection of routes for the case study was based on the ”Most different systems design” presented in Meckstroth (1975). One road of each road category in the Swedish Transport Administration’s national road database was selected. The road categories are 2-lane roads, 2-lane roads with divided traffic, 4-lane roads, and highways. The routes were selected using this approach to increase the difference in characteristics between the selected routes. The city-driving portions of the routes which are not taking place on the Swedish Transport Administrations own roads are excluded from the comparison. Therefore, the comparison between the different routes only considers the part taking place on roads managed by the Swedish Transport Administration.

The selection of routes was also based on whether the Swedish Transport Administrations list of routes prioritised for public transport, the number of vehicles that drive on the road, and if there are a significant amount of transportation demand for this route. Data for the case studies were collected from internal systems from the Swedish Transport Administration, but additional data regarding passenger numbers of selected bus routes were provided by Västtrafik. To evaluate the condition of the roads, the measures used are rut depth, International roughness index (IRI) (CEN, 2017), and groove depth as these are the measures used by the Swedish Transport Administration to evaluate the conditions of the roads. As such, was is data available for all of their roads, with a sampling interval of 20m. The Swedish Transport Administration also provides a threshold, or baseline, for what the different measures should not surpass. The threshold is used to determine if the road is in good condition for the three different measures and, if the threshold is exceeded, what percentage of the route that is above the threshold.

Other tools that were used to gather data and to evaluate the routes are geographical information systems (GIS) such as Nationell vägdatabas, *lit. National Road database* (NVDB), *Google Maps*, *Google Streetview*, as well as the internal system *LabVis*. These tools were used to gather information for some of the measurements that are used for the evaluation of the routes. To get an overview of data reception for e.g. 3G and 4G, coverage maps of different carriers were compared to determine coverage for the routes. The carrier with the best coverage was selected for the comparisons. If no real-world data was available, the relevant standard for the type of road was used, presented in Trafikverket (2020). In one case, a route that uses planned extensions of the existing infrastructure was used, however the other routes only existing data is used.

3.3 Trustworthiness

Trustworthiness is a way of evaluating qualitative research, and it consists of credibility, transferability, dependability and confirmability (Bryman & Bell, 2011).

Credibility

Credibility consists of two parts, respondent validation and triangulation (Bryman & Bell, 2011). Respondent validation is when the researcher lets the respondents in an interview confirm in the interviewer has interpreted them correctly, and serves to validate the interviews (Bryman & Bell, 2011). In this study, this was made continuously during the interviews, with questions of whether their message was understood and interpreted correctly. Regarding the triangulation (Bryman & Bell, 2011), three different data collection methods were used. Both the literature review and the interviews were used to triangulate the information regarding infrastructure requirements, future predictions and use-cases.

Transferability

Bryman and Bell (2011) describe transferability to whether the findings apply to other contexts. The research covers different categories of route categories used throughout Sweden, and are not specific to this context. The literature also aims to conduct a framework based on literature and was therefore not dependent on the case itself. This makes the framework applicable in more cases, and this is according to Bryman and Bell (2011) improving the transferability.

Dependability

Dependability could be compared to an auditing process, and Bryman and Bell (2011) states that dependability requires a clear record of the process. The authors of this project have kept track of the progress in the form of a logbook, but also the respondents of the interviews, including their names, position, company and answers. The answers to the questions were noted during the interview. Recording the interviews would be beneficial in terms of dependability (Bryman & Bell, 2011), but the interviews were not recorded since the information collective is sensitive to some of the companies.

Confirmability

Confirmability is described as the sway of research to suit the personal values of the author (Bryman & Bell, 2011). The authors of this report have no conflict of interest regarding this research topic and have no other motives to seek certain results.

3.4 Authenticity

Bryman and Bell (2011) describe authenticity as of its political impact. Authenticity is divided into fairness, ontological authenticity, educative authenticity, catalytic authenticity and tactical authenticity.

Fairness

This criterion is concerning whether the respondents are representative and convey a fair view of questions (Bryman & Bell, 2011). The respondents represent a variety of industries and companies, and this was purposely chosen to represent a broader view of the involved actors. Many of the respondents have a managerial position, but this was important since the topic of the questions are general and broad knowledge of the topic was therefore important.

Ontological authenticity

Ontological authenticity concerns whether the research helps to improve the knowledge of the members (Bryman & Bell, 2011). Many of the respondents of the interview requested the report when it is finished in order to learn more on this topic. The report is therefore likely to increase the knowledge of the involved actors.

Educative authenticity

The report further allows the different actors to see each other's view of the question. If this results in a better appreciation of the other's perspective, as educative authenticity is described (Bryman & Bell, 2011), is unclear. However, this allows for the realisation of different viewpoints and could potentially increase appreciation.

Catalytic & tactical authenticity

The Catalytic and tactical authenticity refers to whether the report has increased the engagement of the involved actors to change their circumstances and to engage in changes respectively (Bryman & Bell, 2011). If the involved actors will change is unclear, since the development of different AVs is independent of this research. The possibility of the companies to take this paper into account when conducting new pilot studies on public roads is however possible.

4

Case study

This chapter is divided into two parts, the interviews conducted and the route selection. The interview chapter includes summarised answers to the questions asked, while the route chapter consists of the selected routes and information about them gathered from internal documents and some external sources. This chapter serves a summary of the information that will later be analysed in chapter 5.

4.1 Interviews

The interviews topics are divided into three areas, namely infrastructure requirements, future predictions and applications. The answers from the different actors have been summarised in tables 4.1, 4.2, and 4.3, where the pseudonym of the company is marked next to their answer.

4.1.1 Infrastructure requirements

Regarding infrastructure requirements, the conducted interviews resulted in table 4.1. The constructed framework based on the literature review was not presented to the respondents, but the answers were categorised according to the structure of the framework.

Table 4.1 shows how the different subcategories are supported by different actors, and how the proportion of support is divided between them. Some respondents expressed the need for a category, while others were more specific and mentioned subcategories. All the respondents mentioned that traffic and pedestrians increase the complexity for AVs, but also that higher speeds increase complexity, while multiple lanes are beneficial since this enables easier overtaking of the AV. It was also stated by D and J that snow can be problematic since it can limit the lane width and that frequent snow removal is of importance, but also animal fences (J). Some requirements and themes mentioned in the literature was not a concern mentioned by the interviewees, and some categories do not have a company pseudonym next to them. A general theme is that the AV should be able to handle any situation, but that some infrastructure requirements will ease the implementation and might advance the introduction if installed. However, it was stated by one of the respondents that the AV needs to be trained in a step-by-step approach where the difficulty of the route is successively increased, since the AV needs to be challenged in order to develop further.

Table 4.1: Support for infrastructure categories

Group	Category	Subcategory	Company
Physical infrastructure	Road layout	General	
		Dedicated lanes	A, B, D, F, G, H, I, J, K
		Protected lanes	H
		Tunnels	
		Hard shoulders and lay-bys	G
	Intersections	General	C
		Roundabouts	
		Traffic lights	A
		Flyovers	
		Separated pedestrian crossings	B, F, G
	Signs	General	A, F, G, I
		Condition	
		Lighting	
		Placement	
	Maintenance	General	G
		Road pavement quality	E
	Lane markings	General	E, I
		Condition	
		Reflectors	
Digital infrastructure	Digital maps	General	A, E, D
		Detail	I
		Update frequency	I
	V2I/I2V	General	
		Sight	J
		Traffic info	G, J, K
	Connectivity	General	C
		Positioning	
		Latency	D, F, G, I, K
		Coverage	E, G, J, K

4.1.2 Future predictions

The different companies were also asked to estimate when SAE level 4 AD will be available with an ODD that can handle city traffic and highways. Some of the respondents did answer with a plus after the year, indicating that it will at least take to that year until the scenario is a reality. Other respondents did not want to answer the question, either due to low confidence in the estimation or due to lack of knowledge in this type of estimations. Furthermore, some of the respondents mentioned that is is difficult to make future predictions due to the many factors affecting the development, including social acceptance, regulatory adjustments and the technology itself. Many of the companies also mentioned hurdles that were not of a technical nature, such as legislation, company brand image, and business models, that all influences the development av AV and therefore also the future predictions.

Table 4.2: Timelines for when AVs will reach level 4 with a ODD that can handle city and highway driving

Pseudonym	**Year**
A	2025
B	n/a
C	2030+
D	2035+
E	2030
F	2030+
G	2030+
H	n/a
I	n/a
J	n/a
K	2040

4.1.3 Application

The application of autonomous buses can be made in different scenarios, and the opinions of the most suitable scenario can be seen below in table 4.3. The hub-to-hub scenario was described as a bus line between cities, interchange stops, or other major destinations, operating on a highway or other main road. The scenario of first and last-mile was described as bus line operating on a fixed route, which feeds a hub with passengers. As can be seen in table 4.3, company B, C, D, F, G, I, and J all thought that both applications would be useful and viable to implement. The application of autonomous buses in public transport will according to the manager of a public transport company (B) be most useful where it can save money, and this is by replacing frequent hub-to-hub transportation rather than first and last-mile transport. This is according to company B since there are more frequent bus departures for hub-to-hub lines and therefore more bus drivers that can be replaced.

Table 4.3: Future application of autonomous buses

Application	**Company**
First and last-mile	A, B, C, D, F, G, H, I, J
Hub-to-hub	B, C, D, E, F, G, I, J, K

4.2 Routes

The route information was gathered from internal documents from both the Swedish Transport Administration and Västtrafik, but also external sources such as Google Maps, Google Streetview and NVDB. The information is used to describe the infrastructure characteristics but also traffic volumes and public transport trips. Information regarding data coverage was collected from several mobile carriers coverage maps, as well as from the Swedish Post and Telecom Authority. An overview of the routes can be seen in table 4.4

Table 4.4: Overview of route attributes

Type of road	**Highway**	**4-lane**	**Separated 2-lane**	**2-lane**
Route	Gothenburg ↔ Borås	Gothenburg ring-road	Skövde ↔ Mariestad	Skövde ↔ Karlsborg
Route type	Node-2-Node	Loop	Node-2-Node	Node-2-Node
Route length	60km	25km	38km	45km
Max Speed limit	110 km/h	90km/h	100km/h	90 km/h
Width of lane(s)	3.5m	3.5m	3.4m	3.5m
Wildlife fence	Yes	Partially	Yes	Partially
Unobstructed view, bus stop	N/A	200m	200m	200m
Unobstructed view, intersection	200m	200m	200m	200m
Dedicated lanes	No	No	No	No
Bus lanes	No	Yes	No	No
Tunnels	No	Yes	No	No
Hard shoulder/ Lay-bys	Yes	Yes	Yes	Yes
Roundabouts	No	No	Yes	Yes
Intersections, signalled	No	Yes	No	No

Type of road	**Highway**	**4-lane**	**Separated 2-lane**	**2-lane**
Int., left turns	No	No	No	Yes
Int., no signal	No	No	Yes	Yes
Int., left turns, no signal	No	No	No	Yes
Flyovers	Yes	Yes	Yes	No
Pedestrian crossings, type	N/A	N/A	Unprotected	Unprotected
Signs, condition	Good	Good	Good	Good
Signs, placement	Standard	Standard	Standard	Standard
Signs, lighting	Reflective	Reflective	Reflective	Reflective
Rut depth, below threshold	97%	99%	40%	93%
IRI, below threshold	98%	99%	99%	99%
Groove depth, below threshold	100%	100%	100%	100%
Lane markings, general condition	Good	Good	Worn	Worn
Reflectors	In guardrail (L) Poles (R)	Partially in Guardrail (L/R)	Poles (L/R)	Poles (L/R)
Digital maps, detail	High	High	High	N/A
Digital maps, update frequency	N/A	N/A	N/A	N/A
I2V - Sight	No	No	No	No
I2V - Traffic info	No	No	No	No
Positioning - obstacles	Yes, partial	Yes	Yes, partial	Yes, partial
Data connection (Latency)	3/4G	3/4G	3/4G	3/4G
Data coverage	Very good (100%)	Very good (100%)	Basic (1%), Very good (99%)	Good (<1%), Very good (>99%)

4.2.1 Highway

This route is on a highway between Gothenburg and Borås and has 4-6 lanes with separated traffic. An illustration of the route is presented in figure 4.1. The speed limit differs along the route but is between 90-110 km/h. The route is part of Swedish trunk route 40 and has approximately 10000 vehicles per day travel in each direction. The route is in good condition, with <1% of the route being below the standard for rut depth, IRI and depth of grooves. The route is currently used by Västtrafik's line 100 between Gothenburg and Borås, as well as line 101 that stops at several towns along the way, most notably Bollebygd. Long-distance buses also use this route between Gothenburg and Stockholm, stopping in Borås and at Landvetter Airport, which is the second-largest airport in Sweden. With both Gothenburg and Borås being major cities, the need for transportation between the two high, with approximately 95000 trips in each direction only on bus line 100 each week. The current frequency for line 100 is 3 departures per hour per direction, increasing to 12 departures per hour during rush-hours. On weekends the frequency is 2 departures per hour in each direction. Line 101 has a departure frequency of 1 per hour, and a departure every other hour on weekends in each direction. Since the route is classified as a highway it is protected from wild animals by wildlife fences. The route can be classified as a hub-2-hub route since it has major destinations at its endpoints. A high-speed railway is planned along the route, with stops at Gothenburg, Landvetter Airport and Borås, continuing to Stockholm. The railway project is scheduled to begin construction between 2025-2027.

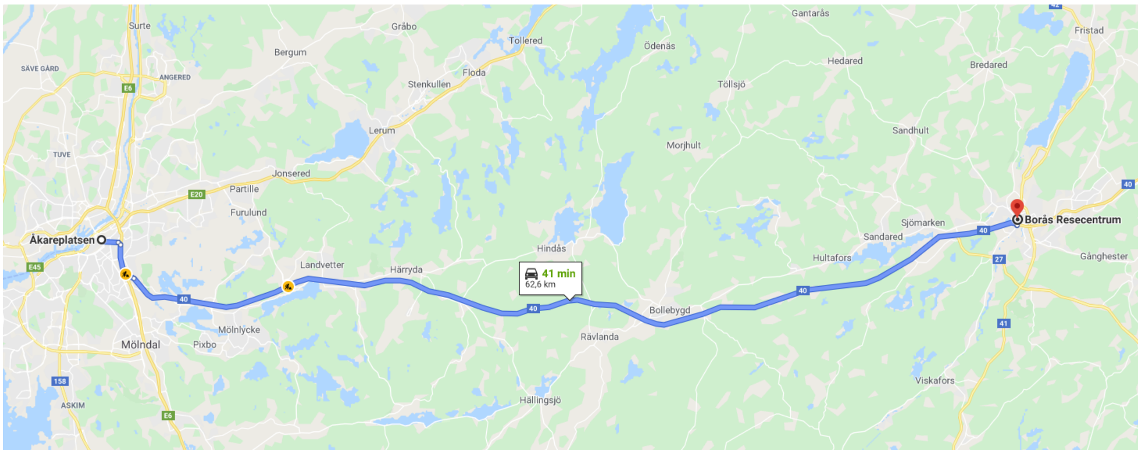


Figure 4.1: Route between Gothenburg and Borås

4.2.2 4-lane road

This route extends along a four-lane road with separated traffic around the city of Gothenburg. Speeds limits are ranging from 70 to 90 km/h, and some parts of the route are located on a highway, although with a lower speed limit than the national standard. A proposed route is presented in figure 4.2 with an alternative routing being plotted using a red dotted line. The same route is currently being used by Volvo cars in their DriveMe project for trials with their own AVs (Svensk, 2018). The route is characterised by high traffic levels and has frequent bus service for multiple bus lines, however, the traffic and service differ between segments of the route. The average volume of traffic is around 23000 vehicles per day and direction, with some bottlenecks showing much higher traffic levels. The route is one of the proposed "ring routes" in Next Stop 2035 (Västra Götalandsregionen, 2018) with proposed route located on the mainland, with an alternative routing over the island Hisingen. The map presented in figure 4.2 also include other proposed lines within the metro-bus concept presented in Västra Götalandsregionen (2018), marked in blue. The metro-bus proposal would mean that almost the entire route would have dedicated bus lanes and easily accessible stops and stations along the route. The purpose of the route would be to offer a high-frequency circular service to break up the current hub-and-spoke model, which concentrates most routes to a single point. While this route is not a node-2-node or a last-mile application, it instead partly similar to both concepts. The circular and feeder nature of the route is similar to the first and last-mile application, as well as making certain journeys shorter. At the same time, the route covers several hubs, and the route can be viewed as several hub-2-hub routes combined into a single loop. Currently, parts of the route are undergoing major construction, and future projects are planned to increase traffic flow and eliminate choke-points.

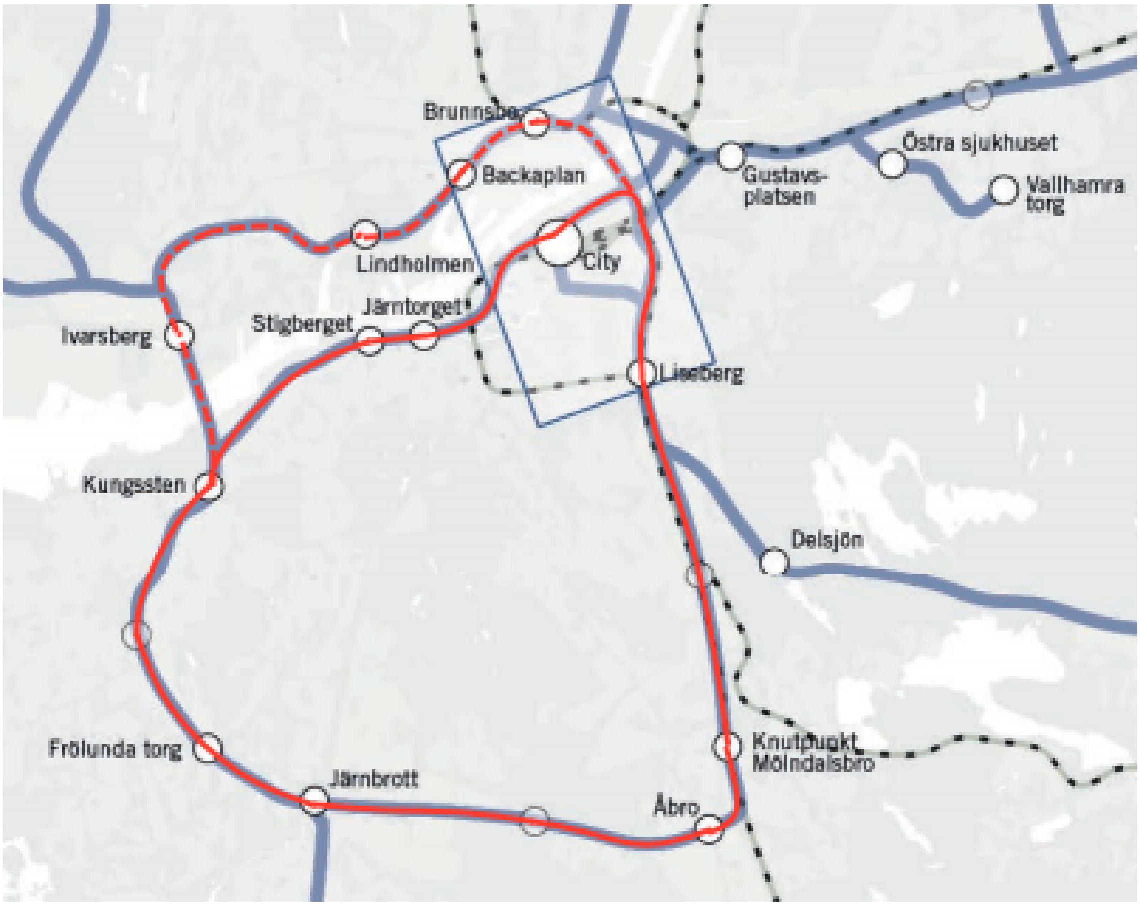


Figure 4.2: Proposed route map overlayed on the proposed Metrobus network (Västra Götalandsregionen, 2018)

4.2.3 2-lane road with divided traffic

This is a road in a 2-lane or 2+1 lane configuration with separated traffic and extends along parts of Swedish trunk road 26, between the cities of Skövde and Mariestad. There are approximately 3500 vehicles per day that travel this route, and around 3000 trips by public transit each week. The frequency for line 500 which currently operates along the route is 1 departure per hour, increasing to 4 departures per hour in the peak per direction. Around 60% of the road is above the threshold for rut depth, but almost entirely within the standard limits for IRI and groove depth. The road also contains several lay-bys evenly spaced along the route, as it lacks a continuous hard shoulder. The width of the road varies according to the 2+1 configuration. Lane markings are for the most part in good condition, with small sections where it is worn down. These sections usually are located in the vicinity of intersections. The intersections along this route are either unsignalled "conventional" level intersections or roundabouts. At some of the bigger intersections, there are bus-stops located on the far ends of the intersection in the direction of travel. It is necessary to use some city streets at both ends of the route to reach the intended endpoints. In Skövde the route would start at the bus- and train station, connecting to local and regional modes of travel. In Mariestad the route would stop at the bus- and train station, providing more connections. The route would also pass near Skaraborgs' hospital, just outside Skövde, which could be a major source of passenger demand. An illustration of the route can be seen in figure 4.3.

Figure 4.3: Route between Skövde and Mariestad

4.2.4 2-lane road

This route stretches 45km between Skövde and Karlsborg, with several smaller villages along the way among which Tibro is the largest, illustrated in fig. 4.4. The entire route is a 2-lane country road with the maximum speed limit of 90 km/h. The road between Skövde and Tibro is one of the most used 2-lane roads in Västra Götaland. Major destinations along this route are Skövde station, a few industrial areas around Tibro, and the fortress of Karlsborg which is an old military base.

The road is in generally good condition, except some sections where the rut depth is above the threshold value. Public transit along this route consists of two lines, 400 and 401 which complements each other. The combined passenger statistics for these two lines are around 5100 passengers per week in each direction. The departure frequency varies between 4 to 1 departures per hour between the two lines. Between Skövde and Karlsborg there are about 4000 vehicles travelling each day, while on the route Skövde to Tibro there is about 8800 vehicles each day.

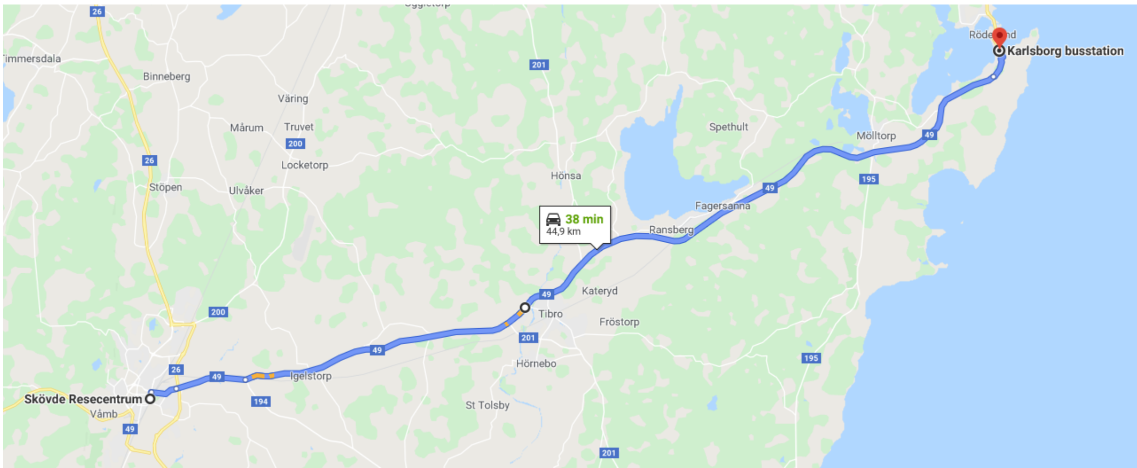


Figure 4.4: Route between Skövde and Karlsborg

5

Analysis

This chapter contains the analysis of the data obtained in the literature review and combines it with data collected in the case study. Analysis of the made route choices is based on the infrastructure characteristics of the route in combination with the traffic and number of public transport passengers.

5.1 Infrastructure requirements

The infrastructure categories from the conceptual framework in figure 2.5 will in this section be evaluated and analysed. The different subcategories will later be evaluated based on their effect on the complexity for the AV.

5.1.1 Evaluation of road infrastructure

The literature review resulted in a conceptual framework consisting of many categories and subcategories of infrastructure requirements. The categories and subcategories are in the literature not compared or weighted, making a prioritisation between them difficult to assess. To get some initial weighting of the parameters, the answers to infrastructure requirements from the interviews will be used. The frequency of how many respondents that mentioned a category could be used to evaluate the importance of that category. Some of the subcategories found was not confirmed by the interviews, but that does not make that specific subcategory unnecessary or redundant, instead, that indicates that this category is not seen as a requirement by the interviewed actors. As can be seen in table 2.5, road layout was the most frequently mentioned category by the 11 respondents with 9 companies mentioning it, followed by connectivity (8), intersections (5), signs (4), digital maps (4), maintenance (4), and lane markings (2). The importance of the different infrastructure characteristics among the interviewed companies can therefore be established. This could also be used as an indication of the general infrastructure requirements. The importance of requirements can be divided into three categories, which is visualised in table 5.1. The decision of using three levels of importance was made since the number of companies that mentioned the different categories naturally could be arranged into three levels. However, it appears that some of the answers are not fully unified between the companies, which indicates that there are different needs for different applications or AVs. The categories marked as being of high importance can therefore be categorised as that on a general level, but i.e. lane markings, which is categorised as being of low importance, could be the most important for specific actors.

Table 5.1: Importance of infrastructure categories

Characteristic	**Importance**
Road layout	High
Intersection	Medium
Signs	Medium
Maintenance	Medium
Lane markings	Low
Digital maps	Medium
V2I & I2V	Medium
Connectivity	High

The interviews can further be used to validate the framework, as the categories are confirmed by the respondents. A difference found between the interviews and the literature review is that the interviews mentioned the need for animal fences (1), wider lanes (1) and multiple lanes (3) while this was not stated in the literature review.

The framework regards the general infrastructure characteristics and some of the characteristics is not necessary for all types of AV. The requirements are dependent on the internal technology of the AV, but also on the approach. The AVs currently operating in SAE level 0-3 with the evolutionary have a driver that is ready to take over control of the vehicle if necessary, while some of the ones taking the transformational approach are dependent on the vehicle being remotely controlled. The transformative approach does in this example require low latency data connections while the evolutionary examples do not require as low latency. Furthermore, some companies have predefined the traffic rules and speed limits of the routes, and is therefore not as dependent on sign recognition, but instead digital maps, either pre-existing or gathered by the company operating the AV. The literature review did also find that some authors think that no infrastructure adjustments will be required, but that in the developing phases many of the characteristics may reduce complexity and therefore be required for the current capabilities of AVs.

Physical infrastructure

Road layout was mentioned by most of the interviewees as something that could ease the implementation of AVs, since reduced ODD complexity will decrease the difficulty of operating a vehicle. Furthermore, inherent characteristics of certain types of roads make them easier or more difficult to operate AVs on, but with certain trade-offs. For instance, a highway is considered by many of the interviewees and some of the authors in the literature review to be the easiest to operate an AV on, since the traffic is separated, the flow is relatively even, and highways are overall of a generally high infrastructure standard. However, the high speed limits on highways are challenging for the vehicle's sensors as they need to have longer range due to the higher speeds in order to respond safely if a potentially dangerous situation occurs. There are comparatively to highways few articles in the literature regarding AVs on country roads, and the interview respondents rarely mentioned this application either. The main topics that were covered in both the literature review and during the interviews were city driving and highways, but there were a few themes that are applicable to the road characteristics of a country road, such as the use of unprotected intersections. Unprotected left turns at intersections that require the AV to anticipate other drivers behaviour and being able to view oncoming vehicles from far away is presented as a major challenge, unless the vehicles are connected and communicating to each other. Something that differed between the literature review and the interviews is the required width of the lanes. Some authors argue that the use of AVs could reduce the width of the lanes, while some of the interviewees stated that they think the lanes will have to be slightly wider to allow for more leniency as the technology matures. This could be due to the research talking about AVs in the future, while the respondents referred to the current capabilities of AVs.

The road layout should, according to both literature and interviewees, minimise the interaction between different modes of travel, such as pedestrians and cyclists, since every interaction makes the AV application more complex. One aspect of the problem is that AVs in all cases predict the worst-case scenario for all situations and therefore have to lower its speed in certain areas. This results in another problem if all vehicles are not autonomous, namely frustration among other drivers that an AV always drive slower than others. Due to this issue, it is likely, according to answers from the interviews, for AVs to require own lanes or at least multiple lanes in each direction. Dedicated lanes were frequently mentioned in the interviews as something that will be required by AVs, but it might be sufficient with protected lanes, or even multiple lanes since this decreases complexity and allows for overtaking as well.

Reliability of the systems aboard the AV is also affecting the infrastructure requirements of the road layout, and therefore also what adjustments that are needed. The vehicle must be able to put itself into a minimal risk state if a problem arises, and in most cases that is to safely stop the vehicle away from other traffic. In many cases, this requires a hard shoulder or a lay-by that is placed along the route. Furthermore, tunnels are something that is covered in the literature that wasn't directly mentioned in the interviews. The literature review does also mention that long tunnels could present issues for positioning systems, while the consensus of the interviews is that the AV should be able to deal with every situation it is presented with and that if the AV can not safely respond to the situation it is in, it should not have been there in the first place. The issue with tunnels can therefore be considered a link between the road layout and physical infrastructure that directly impacts the navigational systems, and therefore might require additional digital infrastructure to overcome the issue.

Multiple characteristics are deemed to be of medium importance, one of which is the intersection characteristic. Both answers from the interviews and the literature review are in consensus on that the more distinct and clear a situation is, i.e. the better the input is, the easier the AV will have to judge a situation. Hence it is why intersections are of interest, as they in many cases present a situation where the AV will be exposed to a certain degree of unpredictability and other vehicles acting indecisive. The situation that is considered to be the most difficult by many actors is an unprotected left turn. However, the higher the proportion of AVs that are in traffic, the easier it will become for the AVs since they act more predictable than a human driver. The difficulty increases even more if the intersections allow higher speeds, but the use of traffic control measures, such as traffic lights are helpful to the AV, as it makes the behaviour of vehicles at intersections more predictable. Another way of reducing the difficulty of intersections with unprotected left turns is by changing them to roundabouts. It was apparent in the literature review that roundabouts are easier for AVs to operate than an unprotected intersection, but more difficult than an intersection with traffic lights. However, the inherent characteristics of a roundabout with clear rules and traffic calming measures that makes the traffic slow down are things that most likely will make things easier for AVs. Flyovers are another area which can make it either easier or more difficult for an AV dependent on the situation. Grade-separated intersections make it easier for the flow of vehicles to remain at a steady level, and significantly reduces conflict zones with other vehicles from other directions. However, complex flyovers with lanes on multiple levels require more sophisticated navigation equipment to not get confused about where the vehicle is and where it is headed.

Pedestrians do also present an increase in the complexity of the traffic situation for AVs. To clearly mark, or even better, to separate the pedestrian crossings will make the implementation of AVs easier. However, there have also been some concerns raised about making roads more of a barrier than they are today for pedestrians. As previously mentioned, AVs does not take any unnecessary risk and if not separated from other modes of transport the speeds would naturally have to be lowered.

Signs are another area which requires some attention, and based on the answers in the interviews it is classified as being of medium importance. There are two main approaches to gather the data from signs, either the vehicles use a camera-based system to visually read signs, or the signs are placed as digital markers in the AV's navigation system. The vision-based system, used in many vehicles with ADAS today, seems to be the approach of most automotive manufacturers but the downside of using this system seems to be that the condition, lighting, and placement of the sign comes into consideration for the AV to be able to read the signs. If the sign is worn in any way, or if the paint has begun to peel off, the vision-based system can have problems determining what information the sign is conveying. Similarly, if the lighting is poor or the placement of the signs are so that it can be obscured there is a risk that the AV will miss the information and continue as before. The signs could be especially difficult to detect during certain weather conditions such as snowfall or fog. The alternative approach is more related to the digital infrastructure, as the rules are pre-programmed into the navigation data on-board the AV. This approach seems to be more suited for vehicles travelling on a limited number of routes, at least in the early stages of implementation as every sign needs to be covered. However, if there is any difference between the digital map and the reality, for example during road maintenance, this could entail risks.

The maintenance of the road is another factor that was assessed to be of medium importance. Both literature and interviewees seem to agree that the better the condition the road is in, the easier it will be for the AV to operate. One of the factors that were mentioned was that AVs can have difficulties detecting and avoiding potholes, and similar road defects, which can cause issues such as punctures, drive-train and suspension damages, and in the worst case scenario crashes. A pothole on a highway can therefore have catastrophic consequences, but the risks are the same no matter how the vehicle is controlled. As such, the road standard can have a direct safety impact on the operations of the vehicle. AVs are also susceptible to causing certain road damage themselves, and according to the literature review, especially relating to rutting. This highlights the need for increased maintenance since both AVs and manual vehicles are going to benefit from it, and increase the safety on the roads.

The last of the physical infrastructure based requirements is the lane markings, and the literature and interviewees are quite divided on this topic. Lane markings were sparsely mentioned in the interviews and not presented as a major problem, but in the literature, lane markings are presented as a major issue with AVs. The interviewees seemed not to be very concerned as the vehicles can use navigational sensors and systems to determine position without the use of visually detecting lane markings. The literature review resulted in lane markings being quite critical to a safe operation of the AV, were potential issues with worn road markings, ”ghost marks”, and temporary lane markings were mentioned. As for the previous infrastructure categories, the clearer and more predictable a situation are presented to an AV, the easier it will be for the AV to operate. This implies that the better condition the lane markings are in, the easier and safer the implementation of AV operations will be. However, lane markings seem to not be crucial for safe operations, as the AV have methods to detect the edge of the lane or road in other ways. Another factor that is covered in the literature is reflectors as a complement to the lane markings. The reflectors have the advantage of being more visible in the dark, and from a longer distance, which makes the input more reliable when it is dark. In addition to reflectors marking the side of the road, the literature makes the argument for reflectors embedded in the road surface in conjunction with markings to make the lanes extra clear to all vehicles. The reflectors were however not mentioned in any of the interviews.

Digital infrastructure

Digital maps are classified as part of the digital infrastructure and are based on the interviews assessed to be of medium importance among the infrastructure requirements. According to both literature and interviewees, digital maps are very useful to AVs in order for them to navigate to a destination, no matter what technological approach is selected for that particular application. For AVs using the evolutionary approach, the detail of the digital map is not as important as the coverage of it. AVs using the transformational approach rely much more on detailed, preferably laser-scanned, maps that reflect the immediate surroundings as well as the path they are travelling on. One of the interviewees implied that the automated shuttles that operate today are more or less locked to a pre-programmed track that it can not deviate from unless a manual operator overtakes the control. It was also stated in the interviews that certain information was in some cases pre-programmed into the digital map, to not be dependent on the AV to be able to read the signs 100% of the time in order to adhere to the traffic regulations for that road. Furthermore, it was mentioned during the interviews that there is a possibility of using the sensors on the AVs to continuously update the digital maps, although that is currently not being performed today. Instead, a vehicle specially equipped with scanners drive along the planned route to collect data for that specific route, which can limit the update frequency of the maps depending on how large the network operated is. Due to infrastructure changes, there is a need for continuously updated maps, and these are important for a safe operation of the AV. Unfortunately, since the practice of updating the precise digital maps are not performed on the routes for the case study, it is difficult to comment on how it will affect the AV.

V2I infrastructure, and by extension I2V infrastructure, is classified as having medium importance of the digital infrastructure. The consensus among both those interviewed and the literature seemed to be that to have an efficient system of AVs, V2I and I2V is advised to be used. Information about road conditions and traffic congestion could be shared among AV and traffic control, which then could be communicated to non-AVs via radio, smart signs or other communication channels. Furthermore, safety can significantly be improved through additional information such as cameras being placed at obscured intersections to extend the line of sight, or to convey the information that there is a vehicle approaching. However, relying on V2I and I2V infrastructure could be problematic if it is required for AVs to be operated safely, partly because connectivity will not be available everywhere and partly because the vehicles must be able to safely operate if there is a power outage or similar that prevents the I2V system from functioning properly.

Connectivity is according to the interviewees considered to be the most important of the digital infrastructure, as positioning is something very important to AVs in order to make them operate. To be able to position itself on a map, the AV needs to be connected to some kind of positioning system, and according to the interviews and the literature review, GNSS is the preferred way of doing so. The upside of using GNSS is that the vehicle can be positioned with high accuracy and keep the tracking accurate through most situations, while the downside concluded by the literature review is that the signals from the satellites can be interrupted by e.g. tunnels or canyons. An issue with determining the RNP is that different systems behave differently when dealing with lacking coverage or obstructions. As such it is difficult to measure the performance of the navigation systems without knowing what technology is being used for that particular application. The alternative measure to analyse the routes is therefore if there are any obstruction or geographical feature that potentially can hinder the GNSS from achieving the RNP. The other subcategories of connectivity are the coverage and latency of the connections to and from the vehicle, which is connected to the ability to remotely control the vehicle. If the vehicle is to be operated from a control centre there are higher demands on low latency, but high bandwidth could potentially be required depending on the number of cameras and the quality of the video that is being sent to the control centre. If there is no remote controlling of the vehicle, but instead orders or commands such as accepting a request from the AV to deviate from its path to navigate around an obstacle, the required bandwidth is likely low. This was supported by most respondents, where most stated that the current data network infrastructure and technology should be sufficient, but that remote controlled AVs could potentially require 5G which has lower latency and higher bandwidth. It was also stated that lower latency and high bandwidth could be beneficial, but it seemed only to be required in cases where a vehicle is remotely controlled, which is similar to what was found in the literature review.

5.1.2 Effects of subcategories

To evaluate routes and to be able to make comparisons, the impact of the subcategories has to be explicit. The effects of the different subcategories can be positive or negative, but is sometimes more complex. For the measurements that are in percentages, they do in this application become more positive the higher the percentage is, meaning that the best scenario would be if e.g. rut depth would be 100%. All subcategories except the subcategories of intersections are strictly positive or negative, but the subcategories of intersections are more complicated. The reason for this is that least complex scenario would be it there is no intersections or pedestrian crossings at all, resulting in a road between two destinations with no connecting roads. This is a somewhat unusual scenario and the subcategories will instead in many cases have to be compared to each other. The literature resulted in intersections with traffic lights being less complicated for AVs than roundabouts, while intersections without traffic lights being the most complicated, especially if there is a left turn. This indicated that the best scenario is when there is no intersection followed by an intersection with traffic lights, roundabouts, and unprotected intersections. Regarding flyovers, they could be used to reduce the complexity of a situation, but could still be challenging depending on the placement of them. Protected pedestrian crossings are less complex than unprotected pedestrian crossings but more complex than no crossings at all. The list of all subcategories and their effects can be seen in table 5.2.

5.2 Future predictions

The future predictions differ among the respondents, but also among researchers. One of the difficulties includes the lack of standardisation, which means that different technologies have to be taken in to account. The literature review also showed two main approaches to self-driving, which further complicates the future predictions. The difficulty of predicting future development was also why four of the respondents choose to not answer the question regarding future predictions, since they found no

Table 5.2: Effects of subcategories

Subcategory	**Measurement**	**Effect**
Dedicated lanes	Yes	+
Protected lanes	Yes	+
Tunnels	Yes	+/−
Hard shoulders/ Lay-bys	Yes	+
Roundabouts	Yes	+/−
Intersection, signalled	Left turn	+/−
	Yes	+/−
Intersection, unsignalled	Left turn	−
	Yes	−
Flyover	Yes	+
Separated ped. crossing	Yes	+/−
Sign condition	Good	+
Sign lighting	Good	+
Sign placement	View distance	+
Road Pavement Quality	Rut 100%	+
	IRI 100%	+
	Groove depth 100%	+
Marking condition	Good	+
Reflectors	Yes, L/R	+
Digital maps, detail	High	+
Dig. maps, update frequency	High	+
I2V sight	Yes	+
I2V traffic info	Yes	+
Connectivity, latency	3G/4G/5G	+
Cellular coverage	Good	+

value in a speculating. It is noticeable that researchers tend to be somewhat more restrictive in their estimations, and two of three did not make any estimation. This could, however, be a random occurrence due to the low number of respondents, but the results are interesting nonetheless. One notable difference between the predictions in the literature review and the interviews is the significantly more deviating estimates in the literature. This could, however, be due to a difference in capability between different estimations. SAE level 4 could be simple if operating on a very limited ODD, but complex when operating in a larger ODD, and lastly, the extreme level 5 with an unlimited ODD, which many researchers and respondents argued to be impossible.

The most optimistic respondent estimated that AVs would be able to operate in the specified ODD by 2025, but most of the responses estimated that it will not be available until after 2030. The exact year is therefore not clear, but this indicates that it will not be available anytime soon. These inconsistencies in predictions make it more difficult for actors like the Swedish Transport Administration to make infrastructure adjustments since the infrastructure adjustments take time, and infrastructure requirements could be changed due to rapid technology development. If infrastructure adjustments are made to fit the current capabilities and requirements, it may have to be changed again due to technology changes, which would be costly for the road owner. However, the conducted literature review showed that many of the authors believe that the technology will be ready in about 10 years, and this is fairly similar to the respondents from the interviews.

The reason behind that some estimate that the technology is going to be available before 2030 could possibly be due to the fact that many of the predictions were made near the peak of inflated expectations in the Gartner hype cycle, which could result in over-ambitious estimations. An interesting aspect that was mentioned during the interviews is that the brand image of the companies developing AV could be damaged if releasing a product or feature that is not completely safe, which in the literature was referred to as being in ”the danger zone”. Any accidents could damage the company brand and this did hinder the speed of development for this actor. This implies that it is not just the technology itself, and the regulations surrounding it that might influence the estimations, but the reputation of the companies developing them as well. This could indicate that start-up companies could be more likely to taking risks by releasing new features in the danger zone, since they do not have any legacy to protect.

5.3 Application of autonomous buses

The literature review resulted in two main areas for the application of autonomous buses. These are hub-to-hub transportation between two nodes and first and last-mile transportation between a hub or node and the starting or final destination. There are arguments for both types of applications, and some authors argued for a combination of the two application called a transit fusion network. This combines the high capacity transportation between hubs, with a lower capacity transport for the first and last-mile. A first and last-mile bus application can operate either on a fixed route, even though it is not between hubs, or as some type of taxi service. However, the application of public transport as a situation similar to a taxi, usually called an SAV service, is rather unlikely in the early stages. This is due to the increased complexity for the AV and the fact that for a service that responsive there would naturally be few passengers per vehicle.

The literature review indicates that fully autonomous vehicles are still quite far in the future, but many authors seem to believe that fixed or dedicated routes seem to be the area where AVs will first be implemented. Since public transit systems often operate on fixed routes and with high operating costs, public transport seems to be a good application for AVs in order to lower operating costs, and therefore be able to either increase the number of departures with the current budget or be able to decrease the budget while operating the current number of departures. The literature mainly covered smaller shuttles, and in a comparison of them and traditional modes of transit, such as LRT, it was found that it is possible to achieve the same capacity as traditional systems with smaller shuttles, but that it would require a substantial amount of vehicles. However, the shuttle vehicles would most likely offer a higher comfort to its passengers in terms of space and frequency of departures, but would take up a considerably larger amount of physical space. The literature was not nearly as extensive in regards to the automation of larger vehicles. A factor that was mentioned in the literature was that buses tend to not be prioritised for automotive manufacturers that also manufacture other vehicles, and that the technology adoption for buses is similar to the trickle-down effect from its other vehicles. This will likely provide an opportunity for start-ups that solely focus on the application of autonomous buses, but that might only have the resources and capability of producing smaller vehicles at an initial scale. As the benefits of autonomous buses emerge and the technology becomes more mature, it is possible that buses will become a focus for automation.

The interviews resulted in something similar to a transit fusion, with seven out of eleven respondents indicating the usefulness of both applications. Regarding a single application, both applications were supported by nine of the companies. There have also been two needs mentioned in both the literature and the interviews, i. e. the ability to increase service for routes with high demand, and to offer service to routes with a demand that is currently not economically defensible. The interview with the managing director of the public transport company (B) stressed the need for AVs to be justifiable from an economical perspective, and that hub-to-hub transportation is likely to be the most justified from this perspective. This is a logical conclusion, but depending on the goal of public transport, it is not necessarily the best option. Alternatives to this could be if other routes are partially subsidised, and therefore also profitable. The limitation of this project largely limit the availability of routes, since the road must be owned by the Swedish Transport Administration, and they mainly own roads between cities and not many within cities. This did indirectly exclude the application of first and last-mile, which is the reason why it is not among any of the suggested routes. The interviewed companies are all but company B involved in projects regarding autonomous vehicles, but when analysing if their own projects had any correlation with the suggested application, no correlation was found.

5.3.1 Evaluation of routes

The routes were selected for their different traits and characteristics, in combination with passenger flows. There are no routes are exactly alike and the evaluation is mainly a way to find general difficulties or requirements that are present for all routes and to discover if there is any difference between characteristics for the different road types. The evaluation will not aim to suggest which route is the best option for an implementation of AVs. The routes are evaluated according to the framework and subcategories presented in table 5.3. The recommendation of a route would be problematic since this is highly dependent on the capability of the specific AV. If the specific AV is dependent on a specific type of connectivity, one route may not be suitable, but if the connectivity is not necessary, the route may be suitable. The situation is similar for the different characteristics and a suggestion is therefore not possible, but rather an evaluation of the different characteristics on each route without making a recommendation.

The conceptual framework is broken down into evaluable units in order to be evaluated and analysed. The breakdown of the categories can be seen in table 5.3, and the effects of the different subcategories can be seen in table 5.2.

Table 5.3: Measurements for identified infrastructure sub-categories

Category	**Subcategory**	**Measurement**
Road layout	Dedicated lanes	Y/N
	Protected lanes	Y/N
	Tunnels	Y/N
	Hard shoulders/ Lay-bys	Y/N
Intersections	Roundabouts	Y/N
	w. traffic lights	Y/N
		Left turns (Y/N)
	w./o. traffic lights	Y/N
		Left turns (Y/N)
	Flyovers	Y/N
	Pedestrian crossings	Y/N
Signs	Condition	Bad/Good
	Lighting	Bad/Good
	Placement	View distance
Maintenance	Road pavement quality	Rut depth (%)
		IRI (%)
		Groove depth (%)
Lane markings	Condition	Worn/Good
	Reflectors	Y/N (L/R)
Digital maps	Detail	High/Low
	Update frequency	N/A
V2I & I2V	Sight	N/A
	Traffic info	N/A
Connectivity	Positioning	Potential obstructions
	Latency	3G/4G/5G
	Coverage	Basic/Good/V. Good

Highway

The route between Gothenburg and Borås does in terms of road layout seem fairly good with hard shoulders for the entire route, however, no protected lanes or dedicated lanes exist. There is during most of the distance two lanes in each direction but in some parts more, which simplifies overtaking by other vehicles. This is something frequently mentioned in the interviews, since this allows for AVs operating in speeds slower than the maximum speed of the road without as much interference of the traffic flow, which may be especially important during the development phases. The route does not have any tunnels which further reduces complexity.

In terms of intersections, the conditions are as good as possible, since there are no at-grade intersections or pedestrian crossings. This reduces complexity since the AV does not have to operate among pedestrians, were the AV has to predict the human behaviour, and there are also no difficulties with intersections due to there not being any. However, this route does have flyovers, but these are rather simple and only likely to decrease complexity.

Regarding signs, the signs are of generally good condition, and they are all reflective, increasing the ease of reading them, which also corresponds to the lighting of them. Furthermore, the placement of signs follows a standardised placement with a criterion of distance from where it can be seen.

The pavement quality can be measured in three different ways, the rut percentage, the IRI and the groove. These are measured by the percentage of the road that is within the acceptable values of the rut, IRI and groove. As can be seen in table 5.4, almost all of the route is in good condition, and the pavement quality can therefore be considered good.

Lane markings can be divided into two subcategories, condition and whether or not reflectors exist. For the Gothenburg-Borås route, the condition is considered good and reflectors exist on both sides of the lanes. The existence of reflectors and good quality lane markings is also as good as it could be in the category lane markings.

Digital maps are also of importance and were categorised as having a medium effect on AVs, and for this route, detailed LiDAR scans of the route exist. This is beneficial since companies can use this already existing scan when operating on the route, but a clear drawback is that these scans are not frequently updated and have only been scanned once. It could therefore be problematic if the existing scan is no longer correct due to construction or other changes to the route.

There are currently no V2I on this route, but the data connectivity coverage is rather extensive. The coverage is very high, and almost all of the route has 4G service. This is beneficial since this could allow for some remote controlling of the vehicle, but also more frequent updates of digital maps or other traffic information. However, there are some potential obstructions in terms of hillsides that could affect the positioning. An overview of the route attributes can be seen in table 5.4.

The large amounts of vehicles that travel between these destinations are both positive and negative. The introduction of autonomous buses could help to reduce the large amounts of vehicles, but at the same time, the more vehicles there is on the road, the more complex it is for the AV. Furthermore, there is already a large demand for transit between these cities, and there is a potential to either cut costs or increase the frequency of departures for the 95000 trips that are made in each direction each week. In addition, the planned high-speed railway between Gothenburg and Borås might reduce the demand for end-to-end trips when finally constructed. This can reduce the traffic between the destinations, which also decreases complexity, but at the same time also reduce the possible benefits of an AV implementation. However, the AV could instead be used by the communities along the route that the train bypasses, and also as a feeder to the railway stations.

Table 5.4: Attributes of the Gothenburg to Borås route

Category	Subcategory	Measurement
Road layout	Dedicated lanes	No
	Protected lanes	No
	Tunnels	No
	Hard shoulders/ Lay-bys	Yes
Intersections	Roundabouts	No
	w. traffic lights	No
		No left turns
	w./o. traffic lights	No
		No left turns
	Flyovers	Yes
	Pedestrian crossings	No
Signs	Condition	Good
	Lighting	Good
	Placement	Standard
Maintenance	Road pavement quality	Rut depth 97%
		IRI 98%
		Groove depth 100%
Lane markings	Condition	Good
	Reflectors	Yes (L/R)
Digital maps	Detail	LiDAR Scan
	Update frequency	N/A
V2I & I2V	Sight	N/A
	Traffic info	N/A
Connectivity	Positioning	Hillsides
	Latency	3G/4G
	Coverage	Very Good

4-lane road

This route and its characteristics are based on a future scenario and some of the characteristics presented in 5.5 does only partly refer to the actual situation. For instance, it is planned that there will be bus lanes for the entire route in the future, with dedicated stops integrated into the network, which is not present today. It is also not completely decided yet if there is to be any major reconstruction of some of the intersections that might change the characteristics of the route. The future scenario is expected to be finished by 2035, however, this scenario is still interesting to analyse due to it being under development and since it is still possible to make adjustments to the infrastructure for it to be suitable for AVs. The entire route is subject to heavy traffic that can further complicate the case for implementation of AVs, but with the proposed adjustments to the route, it should be a relatively minor issue.

The road layout does consist of multiple lanes, which allows for overtaking, but there will also be protected lanes in terms of a bus lane that will be beneficial since this can lower the complexity of the otherwise complex city traffic. Furthermore, there are hard shoulders which further lower complexity, but tunnels making the ODD more complex for the AV since it can lose connectivity or get confused regarding its positioning in the tunnels. There are two possible routes that the AV can operate on according to the suggestions, and both of them include driving through tunnels.

There are no pedestrian crossings for this route but are some intersections that are equipped with traffic lights. The intersections do not involve left turns, and in situations where crossing the other lane is required, this is handled by the use of flyovers. The fact that there are none of the most complex intersections may be especially important in city traffic since these tend to be more complex due to more lanes, traffic and signs. It is possible that the most restrictive signal-regulated intersections will be re-built into flyovers in the near future, as some parts of the route are in a phase of major reconstruction to increase traffic flow.

The pavement quality is almost as good as possible, with 99% of the route being within the tolerance limits for rutting, and 100% being within the limits for both IRI and groove depth. The road pavement is therefore not considered a constraint in any way since the quality is this high. In line with the high-quality road, is the good condition on the lane markings and the presence of reflectors, which is placed on both sides of the road.

There are also similar to the highway route, digital maps which have been collected with LiDAR. As for the highway route, the digital map has only collected at one point in time and are currently not being updated. Since this route is partly based on future infrastructure, there will also have to be an update regarding the digital maps for the information to be correct. The fact that the route is currently used for trials with AVs in the Drive Me project indicated that there could be updated data already collected, however, if this data is intended to be shared is uncertain. There are no current V2I in place, but the connectivity service is considered very good, and there is 3G/4G availability for the whole route. However, there are some potential obstructions in terms of tunnels and tall buildings that could affect the positioning.

The potential benefit of operating this route is likely high since it has already been planned for this scenario to be developed. However, the number of passengers or vehicles that travel this route is difficult to estimate, since the route is not between hubs but rather a loop. Any estimation in estimating passengers would be complicated since many of the passengers that travel from these areas, travel into the city and not around it. However, the fact that the route is included in the Next

Stop 2035 vision suggests that there is a high demand, and the system also acts as a way to alleviate some pressure on the hub-and-spoke network that the public transit system in Gothenburg is currently built upon. The ring road alternative also has the positive effect of increasing the connectivity between some of the outer areas of Gothenburg by reducing the need for transfers at a central point in the network. This helps the city move from the previously mentioned hub-and-spoke network to a more decentralised network.

Table 5.5: Attributes of the Gothenburg ring-road Route

Category	**Subcategory**	**Measurement**
Road layout	Dedicated lanes	No
	Protected lanes	Yes
	Tunnels	Yes
	Hard shoulders/ Lay-bys	Yes
Intersections	Roundabouts	No
	w. traffic lights	Yes
		No left turn
	w./o. traffic lights	No
		No left turn
	Flyovers	Yes
	Pedestrian crossings	No
Signs	Condition	Good
	Lighting	Good
	Placement	Standard
Maintenance	Road pavement quality	Rut depth 99%
		IRI 100%
		Groove depth 100%
Lane markings	Condition	Good
	Reflectors	Y/N (L/R)
Digital maps	Detail	LiDAR scan
	Update frequency	N/A
V2I & I2V	Sight	N/A
	Traffic info	N/A
Connectivity	Positioning	Tunnels, tall buildings
	Latency	3G/4G
	Coverage	V. Good

2-lane road with divider

This route does not make use of any bus lanes, apart from a few meters next to a bus stop, but it does have lay-bys that are distributed along the route. The lay-bys are important if there are any errors with the vehicles and it needs to come to a stop. Instead of blocking traffic, the AV can park itself in the lay-by which enables overtaking of the vehicle, and lay-bys or hard shoulders may therefore be especially important for roads with fewer lanes. There are long segments where there is a so-called 2+1 road, meaning that there are a total of three lanes. This results in the road having a lane for overtaking in some segments. The fact that there are only three lanes at most on the route, with segments with no lane for overtaking increases the likelihood of AVs becoming a hindrance for other traffic, however the 2+1 layouts make the overtaking less risky when possible. The route does not have any tunnels.

There are some difficulties with this route regarding intersections since there is a combination of roundabouts and intersections without traffic lights. This can be difficult for the AV, and especially when combined with the pedestrian crossings on this route. Another factor can be that in some cases there are bus stops located in the vicinity of the intersection that naturally will lower the speed of the AV as it anticipates the need to come to a complete stop if necessary, potentially making the slow-downs more accepted by passengers and other motorists since buses can be expected to move slower near bus stops. These bus stops can also be part of the issue as they increase the need for pedestrians to cross the road to access it, especially since the pedestrian crossings in some cases are unprotected. In any case, this issue is very much present today and will remain so regardless of AVs are implemented or not, unless the pedestrian crossings are physically separated from the road. However, there are some fly-overs that reduce complexity and the intersections without lights are not involving left turns for this route. The signage is of good condition with reflective signs and standard visibility, which is positive from an AV perspective, but also for human drivers.

The road pavement quality is in terms of IRI and groove of a high standard, with 99% and 100% respectively, but the rutting is not as good. There is only 40% of the route that is within the limit of the rut, indicating a bad pavement that can entail potential difficulties for AVs. In addition to this, the condition of the lane markings is worn, which further complicates the situation for the AV since the input is more difficult to interpret. However, one positive characteristic that the route posses is the reflectors on both sides of the road and in the middle fence.

This route has been mapped with a LiDAR scan that can be useful for an AV implementation, but the digital maps have so far not been updated, which will be problematic if anything has changed from the time when it was mapped to the time when it gets used. There are no V2I on this route, but the connectivity is considered good for 99% of the route, and basic for 1%. It could be problematic if the connection is good, and not very good, dependent on the requirement for coverage of the specific AV. Furthermore, the route does have 3G/4G service, but the positioning capability could be affected by the tall trees on the side of the road. An overview of the route attributes can be seen in table 5.6.

An implementation of AVs on this route could be beneficial, but the number of travellers between these hubs is not as significant as on the bigger routes. There are about 3500 vehicles that travel between the locations each day, and about 3000 that travel by public transport each week. However, the lower operating costs of the

AVs can enable a more frequent service to the same cost as today, and the frequent departures could increase the attractiveness of the service.

Table 5.6: Attributes of the Skövde to Mariestad route

Category	**Subcategory**	**Measurement**
Road layout	Dedicated lanes	No
	Protected lanes	No
	Tunnels	No
	Hard shoulder/ Lay-bys	Yes
Intersections	Roundabouts	Yes
	w. traffic lights	No
		No left turn
	w./o. traffic lights	Yes
		No left turns
	Flyovers	Yes
	Pedestrian crossings	Yes, unprotected
Signs	Condition	Good
	Lighting	Good
	Placement	Standard
Maintenance	Road pavement quality	Rut depth 40%
		IRI 99%
		Groove depth 100%
Lane markings	Condition	Worn
	Reflectors	Yes (L/R)
Digital maps	Detail	LiDAR scan
	Update frequency	N/A
V2I & I2V	Sight	N/A
	Traffic info	N/A
Connectivity	Positioning	Trees
	Latency	3G/4G
	Coverage	Basic (1%) V. Good (99%)

2-lane road

This route does not contain any dedicated or protected lanes and no tunnels, but the route has hard shoulders. The hard shoulders are important since there are only two lanes. There is no separation of the lanes, meaning that overtaking occurs in the lane for oncoming traffic. This can be problematic if the AV does not operate at the speed limit, which causes other vehicles to overtake. Frequent overtaking could be negative from a safety perspective since this occurs in the lane for oncoming traffic. However, the hard shoulders are positive since the AV can stop at it if any problem occurs, and the AV would then not stop traffic nor make other vehicles to use the lane for oncoming traffic in order to pass it.

The route does not have any intersections with traffic lights, but there are both roundabouts and intersections without signals. Furthermore, there are also unprotected pedestrian crossings, which could increase complexity and potentially be a safety concern for the pedestrians, which may be even more dangerous due to the high speeds.

The signage is similar to the other routes with reflective signs of a generally good condition and with the placement of them according to the standard requirements for sight.

The pavement quality is in terms of groove and IRI in good condition, with 100% and 99% respectively, but the rutting is somewhat worse, with 93% of the route being within the limits for rutting. This could be complicated for the AV to operate on, but the adjustments needed to fix the pavement in the needed segments is likely to manageable.

The lane markings are worn and the condition of them could be improved, which could make lane-keeping difficult for the AVs, but there are reflectors on both sides of the road, which would have a positive effect on the lane positioning. Some of the drawbacks of this route are that there are no digital maps of the route, no V2I, and trees that could limit the connectivity as especially the positioning. However, there is 3G/4G for the whole route, with 99% of it being with a very good connection. An overview of the route attributes can be seen in table 5.7.

The part of the route between Skövde and Tibro, about half of the route, is among one of the 2-lane roads in Västra Götaland with the most amount of traffic, which can increase the complexity for the AV, but at the same time also the potential benefits. The passenger statistics for the bus lines along the route is about 10000 passengers per week, which indicates that there is some demand along the route.

5.3.2 Comparison of routes

Starting with the two most important categories, road layout and connectivity, these are fairly similar for the different routes. The connectivity is at the time of this report currently only 3G/4G, and the coverage and speeds for the different routes are similar. The road layout is also fairly similar, with all routes having hard shoulders and no dedicated AV lanes. However, what differs is whether the route has a protected bus lane and if there are any tunnels. The only route with tunnels and protected lanes is the 4-lane road. The protected lane is however only partially present today, but the extent of the lane is to be expanded during the development of the road, which would be highly beneficiary due to the lower complexity it entails, even though it would not be present for 15 years. There are also tunnels on this route, which can be complicated for some AVs, increasing complexity at the present state.

As can be seen in the evaluation of the routes, none of the routes has any V2I or I2V, which was also expected since no standardisation of V2I was found in the literature review. However, one category that does differ is the availability of digital maps.

Table 5.7: Attributes of the Skövde to Karlsborg route

Category	**Subcategory**	**Measurement**
Road layout	Dedicated lanes	No
	Protected lanes	No
	Tunnels	No
	Hard shoulders/ Lay-bys	Yes
Intersections	Roundabouts	Yes
	Flyovers	No
	w. traffic lights	No
		No left turn
	w./o. traffic lights	Yes
		left turn
	Pedestrian crossings	Yes, unprotected
Signs	Condition	Good
	Lighting	Good
	Placement	Standard
Maintenance	Road pavement quality	Rut depth 93%
		IRI 99%
		Groove depth 100%
Lane markings	Condition	Worn
	Reflectors	Yes (L/R)
Digital maps	Detail	N/A
	Update frequency	N/A
V2I & I2V	Sight	N/A
	Traffic info	N/A
Connectivity	Positioning	Trees
	Latency	3G/4G
	Coverage	Good (<1%)/V. Good (>99%)

As can be seen in the evaluations for the route between Skövde and Karlsborg on the 2-lane road without a lane divider, there are currently no high-definition digital maps. This could be a hindrance if the AV that is to be implemented requires it, but the digital maps could also be scanned by the company that is to make the implementation. Since these maps have only been scanned once, there is some uncertainty if they are still correct, but if they are they would be what is called a static map and is the lowest level of digital infrastructure according to the literature review. The digital map could be useful for pre-programming the route for the AV since this is something that many of the interviewed companies did in their projects.

The types of intersections differ between the routes, where the highway is the most simple with only flyovers, which is likely positive in this context since it decreases the complexity of otherwise complex intersections. The route in Gothenburg is similar, but consists of intersections with traffic lights, and these intersections are without left turns. Both of these routes do not have any roundabouts, pedestrian crossings or intersections without traffic lights, which is positive since these are all difficult. Both the remaining routes have pedestrian crossings, intersections without signals and roundabouts, and the 2-lane route does also have left-turns in the intersections. These characteristics increase the complexity for the AV, and would increase the complexity of the ODD, and therefore make it more difficult for the AV to operate.

The signage of the roads is equal for all routes since all signs are reflective and of good quality, with standard sight requirements. This is similar to the V2I and dedicated lanes evaluations, since none of them differs between the routes. However, the reason that they can not be used to differentiate between these routes does not make them less important. The maintenance does however differ between the routes, but mostly in terms of rutting, since IRI and groove depth is within 98-100% for all routes. The rutting doe range from 93-99% with an exception of the 2-lane road with a divider where only 40% of the route is within the limits of rutting. This could make the road difficult to operate on, and since the AV can not detect potential potholes as easy as humans can, there is a risk of hitting them and losing control of the vehicle or in any other way endanger the passenger or other vehicles. The 2-lane road without a divider was in 93% of the road within the limits of the rut, which could also be problematic, even though it is far better than the 40%. Both the Gothenburg - Borås and the route within Gothenburg is of a high standard and the previous risk mentioned is considered to be small for these routes.

Lane markings were considered the least important category by the interviews but were mentioned frequently in the literature review. All of the routes have reflectors on the sides of the route, which make any comparison of this redundant for the chosen routes, since there is no difference. However, whether or not there are reflectors could impact the complexity of the route, even though lane markings are categorised as low importance. Furthermore, the condition of the lane markings is similar for the highway and the 4-lane road, which both are categorised as having lane markings of good condition, while the 2-lane roads do have worn lane markings.

One of the frequently mentioned aspects that affect the complexity for the AV to operate was the amount of traffic. This was not as apparent in the literature, but the interviews were unified in this sense. Traffic is not a type of infrastructure, but it may be as important. Another aspect that was also mentioned by the interviews is the operating speed, since higher speeds increase the complexity for the AV, which could also be of importance. These aspects are not as easily adapted by road owners, even though speed limits can be changed, it affects all the other vehicles in a way than the removal of an intersection does not. It is also important to keep the effects of induced traffic in mind, whereby just increasing the capacity of roads to alleviate the traffic situation without making dedicated AV or bus lanes, can increase the amount of traffic.

Overall, different routes have different advantages and disadvantages. No route contained only the positive characteristics that would make it the better candidate for early AV adoption and use. Furthermore, it is likely necessary to make adjustments to all routes to further decrease complexity, especially related to the digital infrastructure. It is therefore difficult to recommend a certain route, which is partly due to the reason that the capability of the AV to be used is a factor affecting the suitability of the route. All the analysed routes have potential benefits for implementing AV operations, depending on which application and type of service one are aiming to achieve.

6

Discussion & Conclusion

This chapter contains the answers to the research questions, the implications that the answers pertain, a short discussion, and finally areas of future research.

6.1 Answers to research questions

In chapter 1.5 four research questions was formulated. Through analysis of the data has the answers to these questions been formulated.

- *What application is suitable for autonomous buses?*

Any recommendation of which route that is the better one for an AV implementation is difficult to make, since many considerations have to be taken in to account. The capability of the specific AV that is intended to be used has to be considered, and therefore how well it can handle the different categories mentioned in the framework, but also take operating speed and traffic conditions into account. Furthermore, the type of route does also depend on the aim of the implementation. If the aim is to cut costs for the public transport company, then a route frequently used by their buses is likely saving the most in terms of driver costs, but if the aim is for a municipality or government to increase the mobility of its citizens, the extension on the current network would be highly prioritised.

If a route is chosen for technology development and demonstration purposes it should, according to one of the interviewees, be challenging for the AV in order to test and show the capability of the vehicle. For example, if the aim of the AV is to be used for hub-to-hub transport between cities, the bus would likely have an ODD without many complex intersections. If this AV is then to be used for routes that require the capability of navigating intersections, it should then be trained on a route containing many intersections. If the bus will be used for last-mile transport within cities, other challenges arise which should be tested according to the same principle.

- *What are the future predictions that can be made regarding autonomous driving?*

The future predictions are divided amongst researchers and the industry. There is no consistency among the predictions, but few of the researchers and respondents from the interview think that fully autonomous cars will be available before 2030. One reason for the lack of consistency could be due to the reason that capability of SAE level 4 is rather broad, even though the definition is specific. Some applications are using AVs that have a very limited ODD that by some could be categorised as level 4. At the same time, there are researchers and interviewees making the prediction that level 5 will never be available. This poses some difficulties for the question since a fairly big ODD is a rather vague term. The result of the literature review and the case study is rather than any prediction of exactly when AVs will be operating on the roads, an indication that AVs is not likely to be operating on SAE level 4 with an ODD that can drive in both cities and on highways before 2030. However, there could be development projects or partially automated vehicles in operation before 2030.

- *How can the road infrastructure characteristics be evaluated for implementation of autonomous vehicles?*

The literature review resulted in a framework consisting of physical and digital infrastructure, with 8 main categories for evaluation of infrastructure. These categories are divided into physical infrastructure which includes road layout, intersections, signs, maintenance, lane markings, while digital infrastructure includes digital maps, V2I/I2V and connectivity. These are the most important characteristics, but to evaluate them, a further breakdown was made. The breakdown into subcategories can be seen in table 2.7. These subcategories are then to be evaluated, but in order to make these evaluations, they need to be measured. The measurements of the different categories can be seen in table 5.3. Many of the measurements are whether or not these infrastructure requirements exist, but some consist of more specific measurements, such as for road pavement quality.

- *What characteristics should a route possess to make it suitable for implementing autonomous passenger vehicles?*

The literature review did also conclude some infrastructure characteristics that decrease complexity, some that could be either increase or decrease complexity, and some that increase complexity. This information was gathered from previous research but is now presented in a more holistic way covering all identified subcategories in one paper. It was apparent that the best scenarios include roads with multiple lanes, hard shoulders, good connectivity and no intersections. High condition on lane markings and signs, and the existence of digital maps and V2I is additional characteristics that are included in the best scenarios. All the characteristics and their effects can be seen in table 5.2. In general, it could be considered that less complexity makes a route a better candidate for AV implementation from a technical perspective, but not necessarily from an operational or business standpoint. The criteria for suitability does, therefore, vary depending on the purpose of the implementation and what capabilities the vehicle that is intended to be used does posses.

6.2 Implications

The findings of this paper have different impacts and implications for managers and academia, which can be seen below.

Managerial implications

The future is difficult to predict, with the predictions indicating that AVs will not become a reality until after 2030, road owners have some time for planning. The possible infrastructure adjustments are many, but if they are requirements of if they facilitate a faster development is not clear. It may therefore be reasonable to await a broader standardisation of infrastructure requirements before investing in costly and inflexible infrastructure. However, infrastructure adjustments may be needed for development projects, and the framework of infrastructure requirements can be used for a route evaluation. Regarding the application of AVs in public transport, this paper focuses on hub-to-hub transport, but the first and last-mile needs to be considered, and the best alternative is likely based on the goal of the public transport company.

Theoretical implications

The literature review did not result in any finding of a holistic and general framework for AV infrastructure requirements, and the developed conceptual framework of characteristics and measurements will therefore be extending the current research. The interviews did also provide an initial weighting of the framework on a general level, which was also not present in the current literature. Furthermore, the future predictions were collected with a broad variety of companies which complements the current predictions in the literature with up to date predictions. Furthermore, the application of AVs in public transport was not as thorough in the literature, and the potential benefits with the different approaches extended the current literature.

6.3 Discussion

One aspect to consider for the implementation of AVs that was regularly reoccurring when researching is the lack of standardisation of both technology and infrastructure. The lack of standardisation could be one of the major challenges to overcome in order for AVs to become widespread. It is likely that some large regulatory body, such as the European Commission sets a standard regarding infrastructure and requirements so that companies can develop in accordance with the standardisation. As it seems now, many companies are careful in their efforts and mainly concentrates on closed environments which are not as affected by the law as if they were to operate on public roads. It is a real risk that this uncertainty is hampering the development of autonomous vehicles, and it should be a priority for regulatory bodies or standardisation organisations to develop a standard if the industry is to innovate at a faster pace compared to today. In addition to standardisation, one aspect mentioned in both the literature review and the interviews is also the need for charging stations, since AVs is often electric. This could be characterised as infrastructure, but was excluded from the scope in this study.

Regarding the reliability of the study, it can be argued to be of high reliability, but there is a risk in this field of study that information gets outdated. The information and conclusions in this report are therefore not necessarily correct since there is a rapid development of AVs, and that the capabilities of AVs could change the need for infrastructure and that future predictions would be changed. The infrastructure framework is likely to be the same, due to the reason of the categories being general and therefore less likely to change. One thing that likely could change is the weighting of importance amongst parameters. This is highly dependent on the chosen companies, but also the position of the respondent. The distribution of different actors is therefore important and the aim of the interviews was to gain breadth in terms of industries. Furthermore, the future predictions could also be questioned. Many aspects need to be considered before making any predictions, and as could be seen, the researchers were less likely to give any predictions. What the capability of the Av should posses was what the respondents did predict, but the definition of this capability is somewhat difficult. As mentioned in the analysis, the SAE level 5 is according to some not likely to ever happen, and some argue that SAE level 4 already exist, which resulted in the need for something in between these capabilities. The number of interviewed companies could also be extended to increase reliability and to decrease the impact of any bias. Future predictions are however important for a road owner even if they are not exact, since they can indicate when the AV will be of a certain capability.

Regarding the routes, the traffic volumes, both by public transport and in terms of the number of vehicles could be questioned since this is not necessarily the data of actual public transport travellers between the hubs, since some could travel a part of the route and still be included in the data. The situation is the same for the number of vehicles, but here the number that continues past the destination is likely large. These are therefore not likely to be replaced by an autonomous bus. The numbers could, however, be used as an indication of both current demand for public transport and the number of vehicles that travel on that route.

The measurements for different subcategories could be changed, and more measurements could be added. There is also a need for more data, and data with better granularity to be able to evaluate a route more thoroughly. Furthermore, it has also been shown that the requirements of the route differ depending on which technology, or even which specific vehicle, that is intended to be used on that specific route which makes a general evaluation hard to do with high accuracy. Still, a general framework has been developed which can act as a general guide when evaluating routes at an early stage in the implementation, but as technologies and standards changes, or is implemented, the criteria in the framework are subject to change.

6.4 Future research

The literature mainly focused on the impact of service and business implications in the use of the AV, with the environmental impact left relatively unexplored. For example, comparisons of energy usage and how it differs between the modes of transportation was not found in the literature. Furthermore, the requirements that were formulated in this report is general, and the future for AVs are quite uncertain as for which technologies have the greatest potential to become widespread. When a standard has been formulated, a certain technology has become more widely used and the infrastructure requirements might have changed. Future research of the infrastructure requirements is therefore needed when the AVs become more standardised.

As for further research into infrastructure requirements, the placement of pedestrian crossings and bus stops was briefly covered in this report, but the specifics of it could be investigated further. Furthermore, since this study was performed in cooperation with the Swedish Transportation Administration, it focused on roads owned by them. By extending the scope and include more roads that are for instance owned by municipalities new demands and considerations might be found.

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