Licentiate Thesis in Machine Design

Driverless trucks in the Swedish freight transport system

An analysis of future impacts on the transport system and the emerging innovation system

ALBIN ENGHOLM

Stockholm, Sweden 2021
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Abstract

A large-scale introduction of driverless trucks could start taking place during the next decade. While this could bring several economic benefits for freight transport actors and society, it may also change the freight transport system and exacerbate the negative effects of road transport. This thesis aims to increase the understanding of how an introduction of driverless trucks could materialize and impact the freight transport system in Sweden. Two overarching issues are addressed. The first is how freight transport patterns will change due to the impacts of driverless trucks on road transport supply. This is addressed in Paper 1 and Paper 2. The second issue, which is studied in Paper 3, is what factors are shaping the ongoing development towards an introduction of driverless trucks in Sweden.

In Paper 1, the impact of driverless trucks on the costs for long-distance road freight transport is studied through a total cost of ownership analysis which shows that driverless trucks could enable cost reductions of around 30%-40% per ton-kilometer. A key determinant of the cost reduction is to what extent reduced driver costs will be offset by other forms of human labor that may be required for driverless truck operations. Other factors, including changes to the truck acquisition cost, have marginal importance. The cost-saving potential provides a strong motivation for freight transport actors to develop and adopt driverless trucks.

In Paper 2, the impacts of driverless trucks on road transport demand, utilization of different truck types, modal split, and total logistics costs are studied by using the Swedish national freight transport model Samgods. Two scenario types are studied, one in which driverless trucks substitute manually driven trucks and one where driverless trucks capable of operating between logistics hubs are introduced as a complement to manually driven trucks. The analysis shows that in both scenarios, driverless trucks could reduce total costs for Swedish freight transport in the range of billions of SEK per year. Road transport demand and truck traffic volumes may increase significantly through modal shifts from rail and sea. This could lead to increased societal costs through, for instance, increased CO2 emissions and congestion which are, however, not quantified in the study.

In Paper 3, an analysis of the innovation system of driverless trucks based on an interview study with actors involved in the development and introduction of driverless trucks in Sweden is presented. The findings suggest that there are several favorable factors for a successful introduction of driverless trucks, but also that the innovation system is characterized by a high degree of uncertainty related to what infrastructure will be required and available, what business models will be emerging, and which actors will be able to capitalize on the development and which actors that become marginalized in a future with driverless trucks.

The findings from this thesis can be of interest for policymakers since it highlights potential benefits and challenges associated with driverless trucks from a transport-system perspective and the provided indicative quantitative estimates on system-level impacts offer a glimpse into a future freight transport system with driverless trucks. Also, the thesis highlights critical challenges for the innovation system of driverless trucks which could guide efforts to improve its performance.

Keywords: Driverless Trucks, Automated Driving, Total Cost of Ownership, Freight Transport Modeling, Innovation Systems
Sammanfattning


I Artikel 1 görs en analys av hur förarlösa lastbilar kan påverka kostnaden för långväga lastbilstransporter. Denna visar att förarlösa lastbilar kan minska den totala ägandekostnaden med runt 30-40% per tonkilometer jämfört med konventionella lastbilar. Avgörande för hur stor kostnadsbesparingen blir är i vilken utsträckning minskningar i forerkostnader vägs upp av andra lönekostnader som uppstår vid användning av förarlösa lastbilar. Andra faktorer, inklusive förändringar av inköpspriset på lastbilar, har endast marginell påverkan. Den potentiella kostnadsbesparingen utgör ett tydligt motiv för godstransportaktörer att införa förarlösa lastbilar.


I Artikel 3 presenteras en analys av innovationssystemet för förarlösa lastbilar som bygger på en intervjujustidie med aktörer involverade i utvecklingen och införandet av förarlösa lastbilar i Sverige. Resultaten indikerar att det finns flertalet gynnsamma faktorer för ett framgångsrikt införande, samtliga som innovationssystemet i flera avseenden karakteriseras av en låg mognadsgrad och stora osäkerheter kopplade till infrastrukturfrågor, vilka affärsmodeller som kommer uppstå samt vilka aktörer som kommer gynnas eller missgynnas av utvecklingen.

Resultaten från denna avhandling kan vara av intresse för beslutsfattare då de belyser potentiella nyttor och utmaningar med förarlösa lastbilar från ett transportsystemperspektiv och de indikativa systemeffekter som kvantifieras ger en fingervisning om hur ett framtida godstransportsystem med förarlösa lastbilar kan se ut. Avhandlingen belyser också viktiga utmaningar för innovationssystemet för förarlösa lastbilar vilket kan vägleda eventuella ansträngningar för att förbättra det.
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A large portion of the work with this thesis has been performed under special circumstances during the Covid 19 pandemic. I would never have been able to finalize this thesis without the significant efforts and support from my family and parents, thank you! Linnéa, Rakel, and Baby, I love you.

Albin Engholm
Stockholm, May 2021
Included papers

Paper 1

Paper 2
Engholm, A., Kristoffersson, I. and Pernestål, A. ‘Impacts of large-scale driverless truck adoption on the freight transport system’, Under review, submitted in February 2021

Paper 3

Contribution statement

Paper 1
Albin Engholm had the main responsibility for all research stages including research design, literature review, calculations, analysis, and writing

Paper 2
Albin Engholm had the main responsibility for all research stages including research design, input data calculations, model implementation, analysis, data visualization, and writing

Paper 3
Albin Engholm initiated the study, participated in the research design, performed a minor part of the data collection, had a leading role during the analysis, and had the main responsibility for writing the paper
Automated driving is when the driving task is performed by an automated driving system. Automated driving system is the onboard software and hardware system(s) capable of performing the driving task in either a limited specific operational design domain with or without the need for a human fallback, or in all domains. This is equivalent to SAE levels 3-5.

Automated truck is a road vehicle used for transporting goods equipped with an automated driving system with a restricted or unrestricted operational design domain. This term encompasses trucks at SAE levels 3-5.

Automated vehicle is a road vehicle for passenger or freight applications equipped with an automated driving system with a restricted or unrestricted operational design domain. This term encompasses vehicles at SAE levels 3-5.

Connected truck is a truck that is communicating data with other entities such as other vehicles, the roadway infrastructure, a central service center, etc. The data communication could be for cooperative purposes and/or for enhancing the operations of the own vehicle, for instance through remote support.

Cooperative truck is a connected truck that collaborates with other vehicles and/or the roadway infrastructure to enhance the performance of several vehicles, for instance by cooperative sensing or cooperative maneuvering. One example of a cooperative truck application is platooning.

Driverless truck is an automated truck operated without an onboard driver but that may receive remote support. Thus, driverless trucks are a subset of automated trucks. A driverless truck is either SAE level 4 or 5.

Driverless vehicle is an automated vehicle operated without an onboard driver but that may receive support from a remote human operator. Thus, driverless vehicles are a subset of automated vehicles. A driverless vehicle is either SAE level 4 or 5.

Driving task consists of the operational and tactical aspects of driving i.e. lateral vehicle control, longitudinal vehicle control, monitoring the environment, maneuver planning, signaling, etc.

Effective operating domain - EOD is the operating domain for a driverless truck when accounting for the operational design domain of the automated driving system, any additional capabilities through remote support that extends the operating domain, and any legal constraints that may limit the operating domain (e.g. automated driving may only be allowed at certain road types even though the automated driving system has a broader ODD).

Freight transport flow is vehicles (or vessels) transporting goods between an origin and a destination. This term is used broadly and is used to describe both complete transport chains and individual legs in a transport chain.

Heavy truck is a truck of maximum permissible weight of more than 3.5 tons.

Light truck is a truck of maximum permissible weight of less than 3.5 tons.
Manually driven truck is a truck without an automated driving system for which the driving task is performed by an onboard driver, although parts of the driving task may be automated. This is equivalent to SAE levels 0-2.

Operational Design Domain - ODD is the “operating conditions under which a given automated driving 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, p. 14). See SAE International (2018) for a full definition.

Operating model is a set of broad operational characteristics for how driverless trucks are operated which is partly determined by their effective operating domain. For instance, a limited EOD may result in that driverless trucks are only used for freight transport flows between a set of fixed terminals and/or at specific road types.

Remote operation is the subset of remote support functions that are used for extending the EOD of driverless trucks when operating outside the ODD or during non-nominal conditions (e.g. sensor failures, severe transport infrastructure disruption, or extreme weather). Remote operations could include a range of activities such as the provision of decision support (e.g. giving go or no/go for a maneuver requested by the driverless truck) or direct remote driving. Remote operations could either be planned (for instance always used during a given stretch of a driverless truck route) or unplanned.

Remote support refers to any sort of human support provided remotely to a driverless truck to support its operations. This includes, but is not limited to, functions such as fleet management, transport mission planning, access management, load surveillance, supervision, and/or marshaling during loading and unloading, and remote operations.

SAE levels of automated driving classify the capabilities of automated driving systems. SAE level 3 is when the automated driving system performs the entire driving task in a restricted ODD with a human driver as a fallback. SAE level 4 is when the automated driving system performs the entire driving task in a restricted ODD without the need for a human driver as a fallback. SAE level 5 is when the ODD is unrestricted. See SAE International (2018) for details.

Ton kilometer - TKM is a metric for transport activity and is defined as moving one ton of payload one kilometer.

Transport application is a set of transport tasks with similar characteristics that constitute a certain type of transport (e.g. long-haulage line-transport or timber transports).

Transport chain is the transport leg or legs used for transporting a shipment from a production location to a consumption or warehousing location. A transport chain could be either multi-modal (e.g. road-rail-road) or unimodal (e.g. road).

Vehicle kilometers traveled - VKT is a metric for traffic volume and describes the total number of vehicle kilometers (i.e. one vehicle driving one kilometer) performed within a given system.
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The prospects of developments within automation, digitalization, and electrification have had a significant influence on both the public and academic discussion about future transportation systems (Paulsson and Sørensen, 2020). Claims have been made that a new transport paradigm based on the combination of driverless, electric, connected, and shared vehicles will bring a more efficient and safe transport system (Arbib and Seba, 2017; Fulton et al., 2017; Jaller et al., 2020) and a common narrative in the Swedish transport policy discourse is that these technologies will transform transport systems for the better and thereby improve society (Henriksson et al., 2019). However, the literature has highlighted that there are vastly different future scenarios compatible with the introduction of these technologies and that there are risks for undesirable outcomes and lock-ins to unsustainable mobility paradigms in addition to the potential benefits (Fulton et al., 2017; Gössling et al., 2018; Sovacool and Assen, 2018; Townsend, 2014). Scholars have argued that for these new technologies to change transport systems in a desirable direction that is compatible with societal goals, there is a need for active public governance (Docherty et al., 2018; Paulsson and Sørensen, 2020).

There is a growing number of publications analyzing the potential implications of driverless vehicles on a transport system level and societal level (Cavoli et al., 2017; Gandia et al., 2019; Milakis et al., 2017b). This literature has shown that driverless vehicles could indeed generate significant benefits for vehicle owners as well as the users and producers of transport services through reduced (generalized) transport costs, improved safety and accessibility benefits (Meyer et al., 2017; Milakis et al., 2017b; Scanlon et al., 2021; Wadud, 2017) which could bring substantial benefits to society (Andersson and Ivehammar, 2019; Fagnant and Kockelman, 2015). However, the impacts of driverless vehicles on a transport system level and societal level are uncertain and complex to predict since they are highly dependent on the introduction dynamics and the societal and technological context (Cohen et al., 2020; Engholm et al., 2018a; Milakis et al., 2017a; Pernestål et al., 2017b; Scanlon et al., 2021; Wadud, 2017). One concern raised in the literature is that driverless vehicles may generate negative effects resulting from increased road transport demand which could lead to a net increase in energy use and negative externalities such as congestion even if driverless vehicles are “more efficient” on a vehicle level compared to manually driven vehicles (Gruel and Stanford, 2016; Pernestål et al., 2020b; Taiebat et al., 2018; Wadud, 2017). So far, research on the impacts of driverless vehicles on the transport system and society has primarily been focused on driverless vehicles for passenger transport applications and not on freight transport. This thesis is an effort to start closing the research gap on the impacts of driverless vehicles in freight transport applications by examining the development towards, and the impacts of, an introduction of driverless trucks in the Swedish freight transport system.

1.1 Motivation

Road freight transport is important for several reasons. It is an integral part of modern economies since it enables commodities to be available for citizens in the right place at the right time and makes it possible to separate the locations of production and consumption and thereby enabling economic specialization (National Academies of Sciences, Engineering, and Medicine, 2011). Without road freight transport, many critical supply chains would break down within a few days (McKinnon, 2006). For Sweden, which is an industry-heavy and export-dependent economy, a well-functioning freight transport system is regarded as critical for the economy (Regeringskansliet,
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In 2014, trucks carried 381M tonnes of goods which amounts to 65% of the total Swedish freight volume (Trafikanalys, 2016a). This is more than 100kg per Swedish citizen per day. Road freight transport is itself a large economic sector that employs more than 67 000 persons in Sweden (Trafikanalys, 2016b). On the other hand, purchasing freight transport services is a substantial cost post for Swedish companies (Trafikanalys, 2016a), and improving the cost-efficiency of road freight transport is from this perspective desirable. Furthermore, road freight transport generates several negative societal effects (Engström, 2016) with one of the most severe being large amounts of greenhouse gas emissions. In 2018, heavy trucks generated 20% of all Swedish transport-related greenhouse gas emissions, and around 6% of total Swedish territorial greenhouse gas emissions (Naturvårdsverket, 2019a, 2019b). On a global level, the demand for freight transport is expected to increase substantially in the coming decades due to increased trade and consumption resulting from population growth and economic development. In their baseline scenario, ITF (2019) estimate that global road freight transport demand will increase by 200% in 2050 compared to 2015. This would result in an increase of global CO2 emissions from road transport by 88% with current transport climate policy ambitions (ITF, 2019). Freight transport demand is expected to increase also in Sweden. In the current official Swedish freight transport forecast, it is estimated that the total freight demand in terms of tons will grow by 44% between 2016 and 2040 (Trafikverket, 2020). It is also expected that the freight transport sector will be subject to significant technological change in the coming decades (Tavasszy, 2020) since there are several potentially high-impact emerging innovations in the area, with driverless trucks being one of those (Melander et al., 2019; Toy et al., 2020).

There may be significant benefits for freight transport actors with automated driving. From the perspective of producers and buyers of freight transport services, there are several potential benefits of driverless trucks. In Sweden, the largest cost post for road freight operators is driver-related costs (The Swedish Association of Road Transport Companies, 2020) which typically constitute around 40% of total costs (Trafikanalys, 2017). Therefore, there is an opportunity for significant cost savings by introducing driverless trucks as they could substantially reduce labor costs (Fagnant and Kockelman, 2015; Gandriz et al., 2020; Wadud, 2017). Driverless trucks may further reduce costs through more energy-efficient driving (Kristoffersson and Pernestål Brenden, 2018; Manyika et al., 2015). Another potential benefit is to increase the utilization rate of trucks (Chottani et al., 2018; DHL, 2014), for instance by not having to adhere to hours of service regulations (Short and Murray, 2016), which could also reduce transport lead times (Chen and Lu, 2020). Furthermore, the potential to improve road safety (Andersson and Ivehammar, 2019; Bernard Bracy et al., 2019; Fagnant and Kockelman, 2015) and to alleviate the challenge with a growing shortage of truck drivers (ITF, 2017) are expected benefits.

A large-scale introduction of driverless trucks could start within this decade. While various forms of driverless vehicles have been used for logistics and freight transport applications in confined areas for several decades (Flammig, 2016), there are currently no large-scale commercial operations of driverless trucks on public roads. There are technological, legislative, and operational challenges related to the introduction of driverless trucks (Kristoffersson and Pernestål Brenden, 2018; Neuweiler and Riedel, 2017) and it may take several decades before automated driving systems that are capable to operate in all environments at all times (i.e. SAE level 5) are developed (Shladover, 2018). However, it is plausible that driverless trucks at SAE level 4 may become widely commercially available for certain transport applications within the coming decade (ERTRAC, 2019).
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and several such pilot projects are ongoing or announced both internationally (Ackerman, 2021; Zarif et al., 2021) and in Sweden (AB Volvo, 2019; Jensen, 2021; Kristensson, 2019). Full penetration of driverless trucks across the whole truck fleet and for all transport applications may take decades (Simpson et al., 2019) if it is ever reached, but the adoption for specific transport applications may be rapid once driverless trucks with appropriate capabilities become available since they may bring significant competitive advantages (Engström et al., 2019; Fritschy and Spinler, 2019).

Driverless trucks could have significant impacts on the transport system and society but these have barely been studied. Introducing driverless trucks would require adaptations to logistics processes since the driver typically performs several other tasks than driving which need to be handled in other ways (Flämig, 2016). The limited currently available literature suggests that driverless trucks may likely also result in wider changes to the freight transport system. For instance, changes in road transport demand through modal shifts (Andersson and Iveshammar, 2019; Bao and Mundy, 2018; Huang and Kockelman, 2020), resulting from reductions in road freight transport costs (Ghandriz et al., 2020; Wadud, 2017) and through changed trade patterns (Huang and Kockelman, 2020) are expected. Also, driverless trucks could impact traffic flow (Erlandsson, 2020) and affect the labor market (Gittleman and Monaco, 2020; ITF, 2017). It has also been discussed that the introduction of driverless trucks at SAE level 4 may bring structural changes to how freight transport is organized through segmentation of road transport where driverless trucks operate some parts of the road network and manually driven trucks complement those in other areas (Monios and Bergqvist, 2019). Even though a commercial introduction of driverless trucks on public roads may happen rather soon and that this may generate significant impacts on the transport system, few studies have systematically studied the impacts of driverless trucks from a transport system perspective. Out of the total literature on driverless vehicles, only a few percent addresses non-technological issues (Gandia et al., 2019) and out of the literature on societal impacts of driverless vehicles, only a small fraction covers freight transport topics (Cavoli et al., 2017). In particular, almost nothing is known on the system-level impacts of operating models in which driverless trucks with limited operating domains are used only for specific transport applications (e.g. only performing transport between logistics hubs) which is the type of operating model that is expected to be introduced first (Engström et al., 2019; Kristoffersson and Pernestål Brenden, 2018).

The lack of knowledge on the impacts of driverless trucks is problematic from a policy and planning perspective. In general, there is a lack of literature on the policy impacts of new freight transport innovations (Tavasszy, 2020), and this is also the case for driverless trucks. The need for knowledge on how an introduction of driverless trucks could materialize and affect the transport system can be important for policymakers for several reasons. For instance, such knowledge is needed to evaluate if and how the introduction of driverless trucks should be managed or supported, predict demand changes as a basis for infrastructure planning, or examine the need for policies and interventions for driverless trucks to steer the development towards societal targets. Also, given the long planning horizons for transport infrastructure, and for implementing or changing transport policies, an argument can be made that more and better knowledge on the system impacts of driverless trucks is not only valuable but that it is also urgent. Several researchers have expressed the need for a more pronounced position in the policy domain for non-technical research that could bring a “broader” systems and societal perspective to the development and impacts of driverless vehicles (Cohen et al., 2020).
1.2 Aim, objectives, and research questions

This thesis aims to improve the understanding of how an introduction of driverless trucks could materialize and impact the freight transport system in Sweden. This is broken down into two objectives and three research questions, as illustrated in Figure 1. Each of the included papers addresses one of the research questions.

![Figure 1 Overview of the aim, objectives, research questions, and the included papers.](image)

The first objective is to analyze the impacts of driverless trucks on the freight transport system in scenarios where driverless trucks are widely available and in use. This objective is approached from a transport economic perspective. Two research questions that follow a sequential logic are addressed for this objective.

**Research question 1**

*How will automated driving impact the total cost of ownership for trucks?*

Transport cost is a key determinant for freight transport and logistics decisions (Holguín-Veras et al., 2021). Therefore, to be able to study the impacts of driverless trucks on a system level, it is key to assess how driverless trucks will impact the costs of road transport which is done in Paper 1.

**Research question 2**

*How will the freight transport system respond to large-scale adoption of driverless trucks?*

Research question 2 is addressed in Paper 2. The cost reduction of road transport that could result from large-scale adoption of driverless trucks may yield far-reaching consequences for the transport system. Changes in transport supply resulting from driverless trucks are however not only a result of changed road transport costs but also of what type of transport applications driverless trucks are capable of performing which depends on their effective operating domain – EOD. Therefore, both
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scenarios where driverless trucks directly substitute manually driven trucks and scenarios in which driverless trucks can only be used for specific transport applications and complement rather than substitute manually driven trucks are studied.

The second objective is to analyze the current development towards introducing driverless trucks in the freight transport system. This is approached from a sociotechnical perspective where the development of driverless trucks is understood as a complex process resulting from the interactions among multiple actors with various goals and that is shaped by economic, technical, and social factors. The following research question is addressed for this objective.

Research question 3

What are the key factors characterizing the innovation system of driverless trucks?

Research question 3 is addressed in Paper 3. The sociotechnical innovation system focused on developing, diffusing, and utilizing driverless trucks in Sweden is analyzed based on the technological innovation systems framework. This research helps understanding how the development towards an introduction of driverless trucks in Sweden is shaped by various forces and factors and also what the main perceived challenges and uncertainties are among the actors.

1.3 Reflections on the research process and other publications by the author

In this section, a reflection on my process for defining the research aim and focus for this thesis is presented along with a list of other publications that I have contributed to in parallel with developing this thesis.

When initiating my PhD project, the idea was not to focus on freight transport but instead on the transport planning and policy implications of driverless vehicles in general. However, after performing an initial literature review (Engholm et al., 2018b, 2018a) I was surprised by the lack of studies on freight transport applications, especially as many publications noted that freight transport may be the area where driverless vehicles have the most “potential” in short-term. During the same period, the interest in driverless trucks grew within the industry and more attention was given to it in the media and grey literature. Almost a year into my PhD project I decided to focus my licentiate thesis on how driverless trucks could impact freight transport systems. A result of this decision was to initiate the master thesis project that later turned out to form the main empirical basis for Paper 3.

My idea at this point was to perform an impact assessment of driverless trucks through a system-level modeling study. I was inspired by the large body of literature with model-based case studies of driverless vehicles in passenger transport (Pernestål and Kristoffersson, 2019; Soteropoulos et al., 2019). At the time, equivalent studies on driverless trucks were non-existing. When I started reviewing the available freight transport model systems, it soon became clear that the Swedish national freight transport model Samgods was a suitable candidate for my research. Not only was the model suitable for representing and capturing the impacts of driverless trucks (see Section 4.3.2 and the discussion in Section 5.2), but it also aligned well with the partners in my research project since The Swedish Transport Administration (Trafikverket) who are the project financier are also the owner and primary user of the Samgods model and The Swedish National Road and Transport Research Institute (VTI) who are a research partner in the project have leading expertise in the Samgods model.
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During the planning stage for the modeling study, it became evident that the work related to selecting, deriving, and calculation input data (e.g. driverless truck costs) for the modeling study was a significant research effort in itself. Therefore I decided to separate the work into two distinct parts which resulted in Paper 1 dealing with the modeling inputs and Paper 2 presenting and analyzing the modeling results.

In addition to the papers included in this thesis, I have also been contributing to the following publications in parallel with the work with this thesis.


1.4 Outline of the thesis

This thesis is a compilation thesis that consists of a kappa which is an introduction and synthesis of the research, and the three included papers. The remainder of the kappa is organized as follows. In Chapter 2, a contextual backdrop for the research is given through an overview of current trends in the development of driverless trucks, and an overview of the Swedish freight transport system. In Chapter 3, a review and summary of the literature on driverless trucks is provided. The research approach including research focus, research design, and methodologies is presented in Chapter 4. The key findings and a discussion relating the results to previous literature are presented in Chapter 5. In Chapter 6, concluding remarks are given in the form of a brief discussion on policy and planning implications, conclusions, and suggestions for future research. Reading of the included papers is recommended to be done in the following order: Paper 1-Paper 2-Paper 3, or Paper 3-Paper1-Paper2.
2 Driverless trucks: developments and context

In this chapter, a backdrop for the research in this thesis is provided through an overview of the current status of driverless truck development (Section 2.1) and an overview of the Swedish freight transport system (Section 2.2).

2.1 Driverless trucks development trends

Driverless vehicles have been used for logistics operations in confined areas for several decades. Examples of such applications include automated guided vehicles within industrial and logistics facilities, port areas, and similar environments and driverless haul trucks used in mines, quarries, and other raw material sites (Flämig, 2016; Parreira and Meech, 2011). There have been ideas on how vehicle automation applications can be used for truck transport on public roads, for a relatively long time, primarily as various forms of platooning applications (Shladover, 2010). During the last decade, technological advancements within automated driving systems have increased the feasibility of driverless truck applications on the public road network (Daduna, 2020). While it has not yet been any large-scale commercial operations of driverless trucks on public roads, both investments and the technological progress for driverless trucks have accelerated (Ackerman, 2021) along with a growing number of pilot projects (Zarif et al., 2021) during recent years.

Chan (2017) outlines broad types of development approaches towards achieving driverless vehicles with unrestricted ODD that are useful also for understanding the development of driverless trucks. One is an evolutionary approach in which there is a gradual development and deployment of automated driving technology. This starts with driver assistance systems which are then followed by an introduction of automated driving systems of increasing sophistication. Here, the purpose of the automated driving technology is primarily to support and enhance the human driver that is still intended to be present in the vehicle to perform the driving task (Kirschbaum, 2015). The focus for this approach is primarily to develop automated but not driverless trucks although, at some point in the future when automated driving technology has matured significantly, the need for a human driver may be eliminated. The other approach is an “everything somewhere” approach where the focus is on developing trucks without the need for an onboard driver but that, initially, will only capable of operating in a limited environment. Over time, when automated driving technologies develop, driverless trucks can be deployed to more and more environments and be used for more transport applications. Based on Engström et al. (2019), the efforts to develop driverless trucks within the vehicle industry, and in particular, for the established OEMs, can be understood as initially having been focused on pursuing the evolutionary approach but that during the last years, the focus has shifted towards the “everything somewhere” approach. In particular, this is the focus for many startup companies that have entered the area.

It will possibly take several decades before automated driving systems that are capable to safely enable driverless trucks to operate in all environments at all times (i.e. SAE level 5) have been developed, if it ever happens (Shladover, 2018). Furthermore, the introduction of driverless trucks is not only a matter of technological maturity but also requires adaptations to legislation such as aligning traffic law so it allows for driverless truck operations and to specify testing procedures for vehicle certification (Litman, 2021). However, it is plausible that driverless trucks at SAE level 4 may become commercially available for certain transport applications on public roads within the coming decade. In particular, two applications are often discussed as being technologically and
operationally achievable, commercially attractive, and feasible from a legislative perspective in an initial phase. The first one is to use driverless trucks for short-distance, repetitive transport flows between logistics facilities such as factories, warehouses, harbors, etc. where the route is taking place in relatively simple traffic environments, for instance within industrial areas. Typically, these flows are between fixed locations where processes for loading, unloading, and handling of the goods can be standardized and adjusted to the fact that no driver is present to assist. In the roadmap for heavy truck technologies by ERTRAC (2019), driverless trucks for this type of transport applications are expected to be commercially available around 2027. Several pilot projects within this application are ongoing or announced in Sweden (AB Volvo, 2019; Kristensson, 2019). The other type of application is driverless trucks with ODD’s that enable automated driving at highways or other major roads with a relatively controlled traffic environment which could make driverless trucks feasible for many long long-haulage transport applications. One example is line-haul transport between terminals in parcel and logistics networks of a hub-spoke character. For transport flows originating and/or ending in locations that are not located close to the highway network and that therefore cannot be reached by using automated driving, several solutions have been proposed. One is to use remote operations when the driverless truck operates outside its ODD (Viscelli, 2018). Another is that manually driven trucks tow trailers to/from driverless truck transfer terminals located in direct connection to the highway network where a “trailer swap” is performed between the manually driven truck and a driverless truck, which then performs the long-haulage leg (Hu et al., 2020; Monios and Bergqvist, 2019; Viscelli, 2018; Zarif et al., 2021).

It is within the automated driving industry widely believed that the ODDs required for automated driving in industrial areas and at highways and similar environments are less demanding compared to driving in urban environments which presents more complex and unpredictable traffic conditions (Engström et al., 2019). This is a view also expressed in both academic and grey literature (Gittleman and Monaco, 2020; Hu et al., 2020; Meldert and Boeck, 2016; Monios and Bergqvist, 2019; Müller and Voigtländer, 2019; Viscelli, 2018). Several driverless truck technology companies have stated that they primarily pursue driverless trucks for highway operations and there are and have been numerous pilot projects for this type of transport application in the U.S. (Ackerman, 2021). In Sweden, Scania recently got legal permissions to commence a pilot project for long-distance highway driving with driverless trucks (Jensen, 2021). In 2020, a representative of the driverless truck technology company TUSimple stated that the company will perform driverless operations on highways without a safety driver in 2021 (Bishop, 2020). ERTRAC (2019) estimate driverless trucks for long-haulage applications to be available at around 2030.

Since driverless trucks will, at least initially, not have unlimited EODs, the introduction of driverless trucks will likely happen step-wise, use-case by use-case where initially, the focus will be on applications with simple traffic environments and straightforward business cases (e.g. singular routes with high freight volumes in a repetitive flow with the route being in a controlled traffic environment with a single actor involved) and later more complex operations with more refined solutions and business models can be achieved (Engström et al., 2019; ITF, 2017; Viscelli, 2018).

2.2 Road freight transport in Sweden: an overview and key figures

Road transport is in several ways a dominant transport mode for freight transport in Sweden, in particular for domestic transport flows (between an origin and destination that are both located in Sweden). In 2014, around 88% of the goods of domestic freight transport flows were carried by heavy trucks according to Trafikanalys (2016a). For import and export flows, which constitute
around 40% of the total Swedish freight volume measured in tons (Trafikverket, 2020), sea transport is the dominant mode, and heavy trucks carried 14% of the volume (Trafikanalys, 2016a). All in all, this means that 65% of the total Swedish freight transport volume was transported by heavy trucks, which amounts to 381 M tonnes of goods that were transported by performing roughly 28 million heavy truck trips (Trafikanalys, 2016a).

In 2019, heavy trucks performed 53 B ton kilometers (TKM) on Swedish territory (Trafikanalys, 2020a). As shown in Figure 2, the TKM per mode and the modal split have been rather stable on the national level during the last 20 years (the time-series discontinuity for sea transport in 2015 is due to a change in the calculation method). The total TKM performed on Swedish territory by all transport modes has during the period fluctuated between roughly 100 B TKM to 120 B TKM. In the wake of the financial crisis in 2008, there was a decrease in demand for all modes.

![Figure 2 TKM performed on Swedish territory per mode and year since 2010. The figure is based on data from Trafikanalys (2020a). In 2015 the calculation method for Sea transport was changed which is the reason for the time-series discontinuity.](image)

The use of different transport modes varies significantly between different types of commodities. Figure 3 shows the TKM performed on Swedish territory for different commodity types and transport modes according to the Swedish national freight transport model Samgods. For instance, road transport is the dominant mode for "timber" and "food and beverages" while having a smaller role for "metal ores", "refined petroleum products" and "transport equipment". A large share, around 40%, of total road TKM is performed for the two commodity types for which the largest volumes of road transport are performed, namely "wood, pulp, paper", and "timber".
Driverless trucks: developments and context

Figure 3 Annual TKM per mode per commodity type in 2017 in Sweden. The data for the figure is obtained by the author from the 2017 reference scenario of the national Swedish freight transport model Samgods (which is the baseline scenario for the current national Swedish freight transport forecast (Trafikverket, 2020)).

In 2020 there were in total 680,000 trucks registered in Sweden that were in use, of which 84,000, 12%, were heavy trucks (Trafikanalys, 2021). During the last decade, there has been a large increase in the use of light trucks and the use of the heaviest types of trucks (> 26 tons maximum permissible weight) while the use of trucks ranging from 3.5 tons to 26 tons has decreased (Takman et al., 2020). However, the average amount of loaded goods per heavy truck has been rather stable at around 11 tons during the same period (Takman et al., 2020). Sweden is one of few European countries allowing trucks heavier than 40 tons. Since 2015, trucks up to 64 tons are allowed at the public road network, and also, trucks up to 74 tons are allowed at around 12% of the road network (Asp et al., 2019).

Most trips performed by Swedish heavy trucks are less than 100 kms, but in terms of VKT and TKM, trips over 100kms represent more than 75% of total VKT and TKM (Trafikanalys, 2019a). Trips over 300kms represent around 40% of total VKT and TKM (Trafikanalys, 2019a). A recent analysis of data of truck movements in Sweden suggests that 20% of heavy trucks currently drive at least 50% of their total distance on highways and other larger roads (Trafikverket, 2021).

Swedish road freight transport is in itself a large economic sector which in 2019, consisted of around 8,700 registered limited liability companies that collectively employed more than 67,000 persons and generated total revenues of 142 B SEK (The Swedish Association of Road Transport Companies, 2020). It is estimated that in 2019, Swedish companies spent 135 B SEK on freight transport which is roughly 2% of the total spending of Swedish companies (Trafikanalys, 2019a). Also, Sweden has a large vehicle industry that directly employs well over 60,000 persons and around twice as many if suppliers and consultants are counted (Statistics Sweden, 2017). The vehicle industry contributes to around 13% of the total value added to BNP from the Swedish manufacturing industry (Statistics Sweden, 2017).
Sweden’s current transport climate target is a 70% decrease of direct emissions (i.e. “tank to wheel”) from domestic transport in 2030 compared to 2010 (SOU 2016:47). This covers emissions from road, rail, and domestic sea transport while air transport is not included since it is covered by the EU emissions trading system EU ETS (Takman et al., 2020). This target is set as a milestone toward the overarching Swedish climate target of reaching net-zero emissions in 2045 (SOU 2016:47). Figure 4 shows territorial greenhouse gas emissions from the Swedish transport sector from 1990. Passenger and freight transport activities performed at Swedish territory did in 2018 emit 16.4 MTCO2eq which is around 32% of total Swedish territorial greenhouse gas emissions (Naturvårdsverket, 2019b, 2019a). Road transport emissions were almost 15 MTCO2eq, which is 92% of total domestic transport emissions. Out of these, road freight transport generated 4.7 MTCO2eq which is 31% of road transport emissions, 28% of all transport emissions, and around 9% of total Swedish territorial greenhouse gas emissions. Heavy trucks emitted 3.2 MTCO2eq in 2018, which is around 70% of truck emissions and 6% of total Swedish emissions (Naturvårdsverket, 2019a, 2019b).

Reaching the 2030 climate target would mean that annual transport emissions decrease to 6.1 MTCO2eq in 2030. A linear trajectory from 2010 to the 2030 target level would require an annual decrease by 3.5 percentage points. However, the decrease from 2010 to 2018 has on average been 2.4 percentage points per year, 18% in total (Naturvårdsverket, 2019b). The 2030 target is not broken down into domain or mode-specific targets (e.g. for freight transport, road transport, or similar) but if the 70% reduction target is applied to the heavy trucks segment, it is equivalent to a decrease from 4.5 MTCO2eq in 2010 to 1.3 MTCO2eq in 2030. For heavy trucks, the decrease between 2010 and 2018 has been 28.4% which is equivalent to an average annual decrease of slightly above 3.5 percentage points.
Figure 5 shows how CO2 emissions, VKT, and TKM have developed for light trucks and heavy trucks in Sweden since 2010. VKT increased for light trucks by 23.8% and for heavy trucks by 4.3% (Trafikanalys, 2020b). Total TKM for heavy trucks increased by 0.9% during the same period (Trafikanalys, 2020a), no official statistics on TKM for light trucks are available. The average emitted CO2eq per VKT (i.e. the average carbon intensity) decreased by 28% for light trucks and by 31% for heavy trucks. This indicates that the difference in the development of total CO2 emissions between heavy trucks and light trucks in this period is primarily a result of different developments in VKT rather than different developments in average carbon intensity. The reduction in CO2 per VKT for trucks achieved so far is probably mainly explained by the increasing use of biofuels, primarily through the policy of mandated admixture of biofuels in diesel, and possibly also through a decrease in energy intensity (Takman et al., 2020).

Figure 5 Changes in CO2 emissions, VKT, and TKM (only for heavy trucks) for light and heavy trucks in Sweden between 2010 and 2018 indexed to 2010 levels (2010=100). Own calculations based on data from (Naturvårdsverket, 2019b; Trafikanalys, 2020a, 2020b) inspired by a similar figure in (Takman et al., 2020).

For a more comprehensive and in-depth analysis of the current state in the Swedish freight transport system, the reader is referred to Trafikanalys (2016a) and Takman et al. (2020).
3 Literature review

The scientific literature studying driverless trucks from a transport system- or societal perspective is relatively scarce. A scientometric analysis of the literature on driverless vehicles by Gandia et al. (2019) shows that the field has been dominated by technical subjects with only a few percent of the publications addressing non-technical issues. Within the research field of impacts of automated driving, freight transport is not a common topic. Cavoli et al. (2017) performed a systematic literature review on the societal impacts of automated vehicles and found that less than 5% out of around 400 identified publications covered freight transport aspects. Within the literature on automated vehicle applications in freight transport, platooning has received quite some attention (Alam et al., 2015; Muratori et al., 2017; Noruzoliae et al., 2021; Paddeu and Denby, 2021; Sivanandham and Gajanand, 2020; Tsugawa et al., 2016) while driverless truck applications and impacts have been addressed to a lesser extent.

Before turning our attention to the scientific literature on driverless trucks, it is worth mentioning other types of publications that can provide useful information and that are often cited in academic papers. Driverless trucks have been the subject of many consulting and industry reports (Chottani et al., 2018; DHL, 2014; Keese et al., 2018; Manyika et al., 2013; Nowak et al., 2018; Roland Berger, 2016; Shanker et al., 2013; Zarif et al., 2021). These reports do provide insights by speculating on potential developments, applications, impacts (primarily in the form of potential benefits), and “barriers” for driverless trucks. However, there are reasons to take a critical position towards the claims expressed in these publications as these actors may have economic interests shaping their viewpoints (Shladover, 2018). Besides the consulting and industry reports, there is a body of “grey literature” comprising policy reports and review reports that provide an overview of opportunities and challenges of automated and driverless trucks (Bao and Mundy, 2018; Center for Global Policy Solutions, 2017; Després et al., 2018; Gittleman and Monaco, 2020; Groschen et al., 2018; ITF, 2017; Jaller et al., 2020; Kulmala et al., 2019; Litman, 2021; Mehta and Levy, 2020; Meldert and Boeck, 2016; Short and Murray, 2016; Slowik and Sharpe, 2018; Trafikanalys, 2019h; Viscelli, 2018; Waschik et al., 2021). There are also a few publications summarizing discussions and learnings from conferences on automated trucks (Engström et al., 2019; Poorsartep and Stephens, 2015).

The remainder of this chapter summarizes the scientific literature on driverless trucks along with findings from a selection of the grey literature relevant to the scope of this thesis.

3.1 Perceptions on driverless trucks and their impacts among freight transport actors

One topic in the literature is how various actors in logistics and freight transport perceive driverless trucks and how it could affect their business. Müller and Voigtländer (2019) perform an interview study with high-level managers at German logistics and freight transport companies in their role as potential future buyers and users of automated trucks. A key finding is that driverless trucks are seen as significantly more attractive compared to automated trucks that would still have an onboard driver. This is primarily since driverless trucks can target important challenges for the industry by alleviating the driver shortage and reduce costs which could increase profit margins. Anderhofstadt and Spinler (2020) present a choice-based conjoint analysis among freight transport companies in Germany. The findings show that freight organizations perceive automated driving as an attractive feature of future trucks but that it is less prioritized than other factors such as long driving range and low operating costs. Furthermore, driverless and automated trucks are seen as more attractive
than manually driven trucks but the data reveal no difference in preference between automated and driverless trucks. Kristofferson and Pernestål (2018) assess the perceived benefits, costs, drivers, and barriers for driverless trucks among freight and logistics experts in Sweden. The findings suggest that the experts foresee a potential for driverless trucks to reduce transport costs and increase vehicle utilization but raise concern over cyber-security issues and how to deal with load handling, and delivery processes. Long-distance highway transport between major logistics nodes is seen as a plausible initial type of transport application for driverless trucks but concerns are expressed that there might be issues with international cross-border transport which is important for this application. Fritschy and Spinler (2019) perform a Delphi study among German freight and automotive experts on how driverless trucks will impact business models in the automotive and freight transport industry. The results show that driverless trucks are expected to be associated with higher degrees of industry cooperation both vertically between suppliers, OEMs, and logistics companies to develop driverless truck solutions but also horizontally between logistics companies to increase resource utilization by sharing driverless truck capacity. Other possible developments are that OEMs may own driverless truck fleets and offer transport capacity as a service, that driverless trucks becomes a highly standardized product, and that there may be a consolidation of the logistics industry.

The impacts of driverless trucks on business models and the structure in the freight transport sector are further discussed by Monios and Bergqvist (2020). They argue that driverless trucks may lead to the traditional business models of truck OEMs to sell trucks to road carriers will vanish and be replaced by a transport as a service model. This will lead to a need for a new type of actor with a new business model focused on operating transportation networks with driverless trucks and providing driverless truck services directly to the transport buyer. The authors speculate that the new network operator role could be taken by either existing truck OEMs or logistic service providers, or by a new entrant. Furthermore, the authors claim that this development will change the role of several key actors in the current road freight transport system. For instance, road carries may become outcompeted in certain market segments by the network operator.

3.2 Market uptake
Several publications in the grey literature provide assumed scenarios for the “penetration rate” of driverless trucks over time, primarily to enable an analysis of potential impacts (ITF, 2017; Litman, 2021; Waschik et al., 2021). In the academic literature, only Simpson et al. (2019) have assessed the market uptake dynamics systematically. They use the theory of diffusion of innovation to model the adoption of driverless trucks among freight transport companies by estimating model parameters based on adoption patterns of previous innovations in the road freight transport sector. Depending on the assumptions for how driverless truck technology improves over time, the public perception, and market factors, the market penetration of driverless trucks in 20 years after market introduction range from less than 20% to more than 95%. In a subsequent paper, Simpson and Mishra (2020) propose an alternative methodology based on modeling peer effects which allow for simulating the uptake of driverless trucks resulting from competition and communication in networks of freight transport actors.

3.3 Impacts on transport costs
While there are multiple industry and consultancy reports that make claims about how driverless trucks will change the cost of road freight transport operations, there are only two examples in the academic literature of such analysis. Both are based on a total cost of ownership (TCO) approach.
Literature review

Wadud (2017) investigates how automated driving may affect TCO for trucks of various sizes in the United Kingdom. Results for the scenario intended to represent the “most likely” assumptions show reductions in TCO in the range of 15%-22% per year with the relative TCO reduction being larger for smaller truck types and vice versa. Ghandriz et al. (2020) use an optimization approach to minimize TCO for driverless battery-electric trucks and driverless internal combustion engine trucks for different types of transport routes by varying vehicle and infrastructure configurations. Their findings suggest that TCO can be reduced by 33-41% for driverless battery-electric trucks compared to manually driven battery-electric trucks and 22%-33% for driverless internal combustion engine trucks compared to manually driven internal combustion engine trucks depending on trip distance.

3.4 Impacts on logistics and freight transport systems
Flämig (2016) provides an overview of possible developments and impacts of automated trucks and highlights that introducing driverless trucks would require changes to logistic activities upstream and downstream of driving as well as adaptation of non-driving related driver tasks, for instance, administrative tasks such as document handling.

Chen and Lu (2020) study how logistics managers should adjust shipment sizes in a situation where driverless trucks would require increased upfront costs due to an assumed increase in truck acquisition cost but, on the other hand, reduces transport lead times compared to conventional trucks. The analysis is based on the economic order quantity model and concludes that driverless trucks would increase the optimal shipment size compared to manually driven trucks in this situation.

A broader perspective on how logistics and freight transport networks may change is provided by Monios and Bergqvist (2019). They anticipate that the introduction of driverless trucks with EODs restricted to highway driving in combination with truck electrification will change the structure and transport geography of road freight transport. Road freight transport networks may develop into a model similar to multimodal transport networks with driverless trucks performing long-haulage between fixed logistics terminals located close to the highway network, and with manually driven electrified trucks performing the pre-and post-haulage for these transport flows.

Bao and Mundy (2018) examine how driverless trucks and platooning combined could decrease relative costs for road transport compared to rail and thereby result in modal shifts from rail to road. Their findings suggest that road transport costs can be cut by approximately 40% which greatly increase the transport distance at which road transport is cost-competitive against rail transport. The resulting decrease in rail demand is estimated by using two methods, an elasticity-based method suggesting an effect of 45% and a cost-curve-based method which suggests an effect of around 20%.

Huang and Kockelman (2020) study the impacts of driverless trucks on freight transport patterns in the U.S. by using a multi-regional input-output model with a random-utility-based mode-choice model including rail and road transport (the “RUMBRIQ” model). For the assumed reduction in road freight transport costs per TKM by 25%, it is estimated that road-TKM increase by 11%, partly explained by a modal shift from rail and partly by changes in origin choice. The use of trucks increases for all but one commodity type and all distances except for the longest distances (+4 800km).
Erlandson (2020) studies the traffic flow impacts of driverless trucks by performing a microsimulation-based case study of a highway section in Sweden. The study considers two types of driving styles for driverless trucks, a passive style, and an aggressive style. The simulations show that introducing driverless trucks with a passive driving style leads to statistically significant increases in travel times and reductions in total CO2 emissions in the system. Driverless trucks with an aggressive driving style do not increase travel times but yield smaller CO2 reductions.

Noorvand et al. (2017) study the effect of driverless trucks on pavement rutting and fatigue by assessing the potential for driverless trucks to be distributed more uniformly across the whole road lane and thereby distribute the wear and tear across a larger road area. The findings suggest that this would be a beneficial strategy to reduce road infrastructure deterioration from truck traffic. However, this would limit the potential to “free up” road capacity by allowing driverless trucks to drive closer to each other than what is possible with manually driven trucks.

### 3.5 Wider impacts

Questions related to how driverless trucks will affect energy and greenhouse gas emissions on a transport-system level are addressed by Wadud et al. (2016) and Taiebat et al. (2018). Wadud et al. (2016) examine impacts on energy and carbon emissions from automated vehicles at a transport system level by combining vehicle and network-level effects. The study includes both passenger vehicles and trucks. The analysis shows that the total road transport energy demand depends on the combined impacts of automated vehicles on energy intensity and travel demand, and a key finding is that it is plausible for increasing transport demand to outweigh energy intensity reductions and result in a net increase in total energy demand and emissions. Taiebat et al. (2018) perform a literature review and analysis of energy, environmental, and sustainability impacts of automated vehicles. They highlight the complexity arising from interactions of impacts on vehicle-, transport system-, and societal levels and stress the need for holistic energy and sustainability assessments on impacts of automated vehicles on the societal level.

There have been a few efforts to study the wider economic and socio-economic impacts of driverless trucks. Lunkeit et al. (2019) develop a system dynamics model to simulate the impacts of an introduction of driverless trucks in Germany on an aggregated system level. They find that road transport demand could grow significantly due to reduced truck operating costs which would lead to a net increase in total fuel consumption and transport costs on a system level. Pernestål et al. (2020b) use system thinking to link vehicle-level effects and transport system effects resulting from an introduction of driverless vehicles and suggest that driverless trucks will shift the system equilibrium to a state of higher VKT and that there may be a potential to reduce the truck fleet size (for a given transport demand).

Fagnant and Kockelman (2015) estimate some of the potential societal benefits of automated vehicles for passenger and freight applications in the U.S for various penetration rates of automated vehicles. The analysis includes aspects such as improved road safety, traffic flow, and fuel economy and estimates annual societal benefits to around $3300 per automated vehicle. Bernard Bracy et al. (2019) discuss to what extent driverless trucks could reduce traffic accidents and whether these benefits would motivate additional infrastructure investments to support driverless truck operations by improving lane markings and/or investing in V2I solutions. Clements and Kockelman (2017) assess the impacts of automated vehicles (passenger and freight) across multiple industrial sectors.
in the U.S. and conclude that the road freight transport sector is the single sector with the largest economic gain from automated vehicles, mainly due to productivity gains.

Andersson and Ivehammr (2019) apply a cost-benefit analysis framework to estimate the societal costs and benefits in speculative scenarios on the usage and impacts of automated trucks in Sweden in 2025 and 2040. Their indicative calculations show that automated trucks could generate substantial net benefits to society, which for 2040 are estimated in the range of 1B€, with almost 90% of the total benefits being driver cost reductions. An important finding is that the vast majority of benefits accrue to the buyers and producers of road freight transport services and not to other actors in society and that therefore “there is no reason for giving subsidies to the industry producing automated vehicles or to the consumers buying them” (Andersson and Ivehammr, 2019, p. 141).

Waschik et al. (2021) use a dynamic computable general equilibrium model (the “USAGE-Hwy” model) to study the macroeconomic impact of a gradual introduction of driverless trucks for long-haulage road transport in the U.S. Three scenarios with varying driverless truck adoption pace are studied. The main finding is that driverless trucks would generate macroeconomic benefits through improved productivity in the road freight transport sector resulting from driverless trucks which would increase GDP, capital, employment, and wages. Another important finding is that although the net hiring of truck drivers will decrease when driverless trucks are introduced, it does not lead to lay-offs in the road transport sector in the slow and medium scenarios (assuming current turnover rates) while there are lay-offs in the long-haulage truck-driver workforce in the fast adoption scenario. Several other reports have studied the impact of driverless trucks on the labor market, in particular for the U.S., and primarily from the perspective of whether driverless trucks will lead to job loss among truck drivers. The conclusions differ significantly between publications with some estimating that millions of jobs lost in the freight transport sector if a rapid introduction of driverless trucks take place (Center for Global Policy Solutions, 2017; Groshen et al., 2018) while other claims the effect is much smaller although some types of road transport jobs, primarily long-haul drivers can be severely affected (Gittleman and Monaco, 2020; Viscelli, 2018). The discrepancy between the studies is mainly due to different assumptions on what type of driver jobs (and tasks) could be “replaced” by driverless trucks, how demand for road transport will develop, and how fast driverless trucks will be introduced. A study by the International Transport Forum (2017) highlights that the current and anticipated future shortage of truck drivers need to be accounted for in the analysis but still estimates that more than two million truck drivers may be displaced in the EU and the U.S. combined if driverless trucks are introduced rapidly.
4 Research approach and methodology

4.1 Research focus

Table 1 provides an overview of the research focus and key assumptions of this thesis. In addition to the delimitations discussed in this section, Section 4.2 discusses system boundaries, and Section 4.3 discusses specific delimitations and assumptions for each paper.

Table 1 Overview of key focus areas and assumptions for the thesis.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Focus and key assumptions</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck type</td>
<td>Heavy trucks (&gt;3.5 tons)</td>
<td>All papers</td>
</tr>
<tr>
<td></td>
<td>SAE level 4-5</td>
<td>All papers</td>
</tr>
<tr>
<td></td>
<td>No driver present in the truck</td>
<td>All papers</td>
</tr>
<tr>
<td></td>
<td>Internal combustion engine trucks</td>
<td>Paper 1 and Paper 2</td>
</tr>
<tr>
<td>Type of transport applications and activities</td>
<td>Transport on public roads</td>
<td>All papers</td>
</tr>
<tr>
<td></td>
<td>Long-haulage transport</td>
<td>All Papers</td>
</tr>
<tr>
<td></td>
<td>The driving task is in focus, changes to upstream and downstream processes such as loading, unloading, etc. are not studied.</td>
<td>Paper 1 and Paper 2</td>
</tr>
<tr>
<td>Geographical</td>
<td>Sweden</td>
<td>All papers</td>
</tr>
<tr>
<td>Temporal</td>
<td>A point in time when driverless trucks are widely available and in use</td>
<td>Paper 1 and Paper 2</td>
</tr>
<tr>
<td></td>
<td>The situation as of 2018 and short- to mid-term developments</td>
<td>Paper 3</td>
</tr>
<tr>
<td>Other</td>
<td>Equivalent operating profiles for driverless trucks and manually driven trucks</td>
<td>Paper 1</td>
</tr>
<tr>
<td></td>
<td>Inelastic demand for material flows</td>
<td>Paper 2</td>
</tr>
</tbody>
</table>

4.1.1 Implications of the definition of driverless trucks for the scope of the thesis

The definition of driverless trucks is an important aspect for defining the scope and focus of this thesis. Furthermore, the term “driverless” does not have a generally accepted definition and has been used for describing a wide range of automated driving-related concepts in both the literature and in the public discussion leading to confusion around the term (Shladover, 2018). Therefore, an elaboration on the definition of driverless trucks and a discussion of its implications on the thesis scope is presented in this section.

A driverless truck is in thesis defined as:

A truck that is equipped with an automated driving system with a restricted or unrestricted operational design domain operated without an onboard driver but that may receive remote support.

Driverless trucks are equipped with automated driving systems at SAE level 4 or 5 (SAE International, 2018). The definition of driverless trucks does not distinguish between driverless trucks with highly limited EODs that are used for highly niched transport applications (e.g. only for a specific route and carrying a specific type of cargo) or driverless trucks with unrestricted EOD that could be used for an equally broad range of transport applications as for a human-driven truck of
comparable vehicle configuration. This means that all trucks at SAE level 5 are by definition considered to be driverless trucks, but not all trucks at SAE level 4 are driverless trucks as driverless trucks are never driven by a human on-board driver. This means that the definition excludes trucks at SAE level 4 operated with a driver in the truck that “checks out” from the driving task when the automated driving system is engaged. The definition allows driverless trucks to use remote support for enhancing transport operations or for extending the EOD (Zhao et al., 2020).

There are other vehicle-related aspects that are not specified in the definition of driverless trucks but for which important delimitations are made. The thesis is delimited to heavy trucks, i.e. trucks of more than 3.5 tons of maximum permissible weight. Heavy trucks constitute a heterogeneous category of vehicles which includes several types of truck configurations such as rigid-body, rigid and trailer, tractor and trailer, etc. (ACEA, 2016). There is no explicit delimitation to specific truck configurations other than that the scope is limited to vehicles intended to carry goods (i.e. not fire trucks, crane trucks, etc.). Since certain types of transport applications, primarily various forms of long-distance transport flows, are the focus of this thesis not all types of vehicle configurations are relevant. Another aspect is whether if and to what extent, driverless trucks are connected and/or cooperative, see Figure 6. Although most driverless trucks will likely be connected and/or cooperative it is, according to the definition, possible that they will be neither, i.e., autonomous. However, for a driverless truck to be able to receive remote support it also needs to be a connected truck. A related concept is platooning, which in this thesis is regarded as a collaborative driving mode that driverless trucks may utilize in some situations due to fuel-saving opportunities or other benefits. However, platooning capabilities are not a prerequisite for meeting the driverless truck definition, and platooning is not accounted for in the thesis other than that it is considered as one factor that may influence the operating costs of driverless trucks in Paper 1.

Figure 6 Schematic illustration of the relationships between the concepts of automated, driverless, connected, and cooperative trucks and platooning in the thesis. The figure is an adapted and simplified version of Fig. 4 in Engholm et al. (2018b).
Research approach and methodology

4.1.2 Transport applications studied
The focus of this thesis is on transport applications that take place on the public road network. Therefore, driverless truck applications operating only on private grounds, such as in harbors, fenced industrial areas, mines, etc. are not studied. However, it is acknowledged, and also discussed in Paper 3, that these types of use cases may be important stepping stones towards driverless truck applications on public roads. Urban first-mile applications and last-mile applications (e.g. parcel deliveries) are not in the scope of this thesis. This is mainly due to three factors. First, driving in urban areas is, in general, diverse and complex and is, therefore, a challenging ODD. Second, using driverless trucks for these use cases has many operational challenges since typically there are many interactions with the senders/receivers (e.g. picking up/dropping off parcels). Finally, the Samgods model used for the study in Paper 2 does not model pick-up and distribution operations in sufficient detail to represent and analyze such applications.

4.1.3 Freight transport activities studied
The focus of the thesis is on the automated driving aspect of driverless trucks. However, as previously discussed, the introduction of driverless trucks may result in changes in other freight transport activities apart from the driving task such as loading, unloading, document handling, and load securing. These could likely be handled in many different ways through (combinations of) various adaptations such as re-designing processes, having tasks performed by other personnel (e.g. by employees at the sending/receiving/terminal location), automation, digitalization, etc. Assessing these adaptations is not in focus for this thesis. Therefore, for the calculations in Paper 1 and scenario inputs in Paper 2, no changes in load handling processes are assumed for driverless trucks compared to manually driven trucks. However, in Paper 3, non-driving-related transport activities are aspects that are discussed by the interviewees.

4.2 Systems under study
Two systems are studied in this thesis: the (Swedish) freight transport system which is studied in Paper 1 and Paper 2, and the (Swedish) driverless truck innovation system which is studied in Paper 3. The framework in Figure 7 conceptually outlines these systems, and their relationships to each other and other relevant related systems.
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The freight transport system is linked to other societal systems. For instance, there is a reciprocal relationship with the economy and land-use systems which are ultimately determining the demand for freight transport but are conversely affected by the capabilities of the freight transport system. The freight transport system also interacts with the passenger transport system, primarily through the use of common infrastructure. Also, the freight transport system is interacting with the driverless truck innovation system and other innovation systems of new freight transport solutions and technologies. One way of understanding this relationship is that the actors constituting the supply side in the road freight transport system (e.g. road transport operators, logistics service providers) represent the demand side (or end-users) in the driverless truck innovation system. The driverless truck innovation system is also affected by developments in other societal systems. Furthermore, there are global trends (technological, cultural, demographic, social, etc.) influencing all systems.

4.2.1 The freight transport system
The freight transport system is in this thesis broadly defined as:

*The physical objects (e.g. vehicles, terminals, and infrastructure), information, actors, and institutions (e.g. regulations, norms, practices, standards, business relations, etc.) collectively enabling, planning and performing the movement of goods, materials, and products.*

The freight transport system consists of several transport modes such as road, rail, road, sea, and air. The focus of the thesis is on the Swedish freight transport system. Freight transport decisions are in this thesis understood as resulting from the interaction between actors on a transport market. 

Figure 7 A framework for the systems directly or indirectly related to this thesis. The systems that are studied are white, while grey systems are having an indirect relation with the inquiry in the thesis.
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where transport buyers having a demand for moving materials, goods, or products ("demand for material flows" in Figure 7) interact with transport operators that provide transport services either directly or via logistics service providers. A key theoretical approach in this thesis is that actors on the freight transport market are understood as rational agents that are seeking to minimize total logistic costs for each freight transport flow (Ben-Akiva and de Jong, 2013) according to the principles of inventory theory (Combes, 2014). It is assumed that this is the underlying principle for actors’ freight transport decisions such as the use of consolidation and distribution centers, shipment size, transport chain (including mode and vehicle choice), etc. (Ben-Akiva and de Jong, 2013) which are understood to be made through a collaborative interaction between the transport buyer and the transport operator (Holguín-Veras et al., 2011).

The focus in Paper 1, is on quantifying the impacts driverless trucks could have on the cost of road transport and thereby change the supply side of the freight transport system. The delimitation to Sweden means that the cost impacts of driverless trucks are calculated by using a Swedish baseline for truck costs provided by ASEK (Trafikverket, 2018) which is intended to reflect average truck operating costs in Sweden.

In Paper 2, the response of the Swedish freight transport system for different scenarios for changes in road transport supply due to large-scale adoption of driverless trucks is studied under the assumption of an inelastic demand of material flows. The delimitation to the Swedish freight transport system is for this paper based on the system representation in the Swedish national freight transport model Samgods. A detailed description is given in Bergquist et al. (2020) but in short, it encompasses all freight transport infrastructure and all transport activity at Swedish territory, and all transport flows either originating and/or ending or transiting in/through Swedish territory. In other words, transport activities resulting from material flows that are starting and ending in Sweden, import, export, and transit flows are modeled.

4.2.2 The driverless truck innovation system

The (Swedish) driverless truck innovation system is defined as:

*The sociotechnical innovation system focused on the generation, diffusion, and utilization of driverless trucks in Sweden.*

This system consists of a range of actors, networks, and institutions and is conceptualized by applying the theoretical framework Technological Innovation Systems (TIS) (Bergek et al., 2008). The focus in Paper 3 is to perform a descriptive analysis of the driverless truck innovation system in Sweden. The TIS framework is described in Paper 3 along with references to relevant literature and a summary of the TIS framework is provided in Section 4.3.3. The driverless truck innovation system interacts with the freight transport system and does also partly consist of actors directly involved in the freight transport system. The Swedish focus means that actors operating in Sweden and with the ambition of introducing driverless trucks in Sweden are the focal point of the analysis. However, important aspects are that many of these actors are international or global players that are also targeting other markets and that the Swedish driverless truck innovation system is linked with, and affected by, international developments.

4.3 Research design and methodologies

This thesis is based upon a mixed-methods approach combining quantitative analysis of the total cost of ownership (Paper 1), freight transport modeling (Paper 2), and a qualitative interview study
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(Paper 3). The overall research design can be described as a convergent parallel mixed-methods approach where the qualitative and quantitative research is performed in parallel and the respective findings are used as complementary to gain a comprehensive understanding of the research problem (Creswell, 2014).

Paper 1 and Paper 2 are closely related since the findings in Paper 1 are used as input for Paper 2. These studies are also based on the same theoretical foundations and compatible methods and assumptions. Paper 3 is methodologically and theoretically independent of the other two papers, and addresses a different research question, from a different perspective. An important aspect of the research design is that different time perspectives are studied in the papers. Paper 1 and Paper 2 are prospective analyses of driverless trucks at some future point in time when driverless trucks are widely available and in use. Paper 3 is an analysis of the current state of the innovation system and the development of driverless trucks in the near term.

4.3.1 Paper 1: Total cost of ownership analysis

The analysis of the impacts of driverless trucks on road transport costs in Paper 1 is performed by using a total cost of ownership (TCO) approach. A TCO analysis intends to capture all costs for owning and operating a vehicle during the vehicle lifecycle and is a method commonly used to compare the cost performance of alternative vehicle technologies (Ghandriz et al., 2020). In Paper 1, the TCO is analyzed for four different truck sizes (16-ton, 24-ton, 40-ton, and 64-ton) for three driverless truck scenarios reflecting pessimistic, intermediate, and optimistic assumptions on economic impacts of driving automation based on current literature. The calculations in the paper are based on the TCO framework and cost data for Swedish manually driven trucks by ASEK (Trafikverket, 2018), see Figure 8. This TCO framework considers TCO from the perspective of the vehicle owner and does therefore not include externalities or cargo-related costs (e.g. value of time costs). By using the ASEK TCO model, the results from Paper 1 can be used for the input parameters related to driverless truck costs required for the analysis in Paper 2 using the Samgods model.

![Figure 8 Cost components considered in the total cost of ownership model used in Paper 1.](image)

The focus in Paper 1 is primarily on calculating the relative difference in TCO for driverless trucks compared to a baseline for manually driven trucks. Absolute costs levels are of lesser interest. The methodological procedure follows four main steps.

1. Review the literature and map the discussed effects of driverless trucks on transport costs to the components of the TCO model.
2. Set assumptions for the three cost scenarios for driverless trucks per TCO component expressed as a relative change compared to the manually driven truck baseline (see Table 2 in Paper 1).
3. Calculate the TCO components for the baseline and the three driverless truck cost scenarios.
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4. Convert the results from step 3 into TCO per TKM to enable comparison within and between truck types.

For step 4, an aggregated approach intended to represent an “average truck” within each truck type is used. This includes assuming an average mission profile per truck type (e.g. average trip distance, the mix of commodity types carried, etc.) intending to be representative for long-distance transport. For this purpose, official statistics for inter-regional truck trips are used. The transport mission profile per truck type is assumed unchanged between the manually driven truck baseline and the driverless truck scenarios but the number of trips per year may vary due to changes in truck utilization rates. The average truck approach means that the findings can provide useful indications for the overall cost development for different truck types but since truck transport applications are heterogeneous, this method is not suitable to evaluate the cost impacts of driverless trucks for specific truck owners or transport applications.

4.3.2 Paper 2: Transport-system impacts analysis using Samgods

In Paper 2, the Swedish national freight transport model Samgods v.1.2 (Bergquist et al., 2020) is used to analyze the impacts of driverless trucks on the transport system. Samgods is typically used for freight transport analysis such as freight demand forecasting, evaluation of potential infrastructure investments, and policy analysis. In this thesis, Samgods is extended to the analysis of driverless trucks which is a new application domain of the model. Samgods is based on the aggregate-disaggregate-aggregate freight transport model approach which is described by Ben-Akiva and de Jong (2013). The zonal structure is at the municipal level in Sweden and a rougher level in other countries. The Samgods model represents the demand and supply side of the Swedish freight transport system and simulates the decision-making at the transport market (see Section 4.2) for individual shippers under the principle of minimization of total logistics costs for each freight flow. In Samgods, the definition of total logistics cost \( C \) for a transport flow is defined as in Eq. 1, where \( O \) is the cost for placing transport orders, \( T \) is the transport cost (including costs for driving, loading, unloading, and, if any, transfers between vehicles), \( Y \) is the capital cost of goods during transport, \( I \) is the inventory cost, and \( K \) is the capital cost of inventory (de Jong and Baak, 2020, p. 11).

\[
C = O + T + Y + I + K \quad \text{(Eq. 1)}
\]

The cost minimization is done by evaluating all possible freight transport solutions for all freight transport flows. The freight volume is split between the two cheapest solutions for each freight transport flow based on the relative difference in total logistics costs between those two solutions. Minimizing the total logistics cost by adjusting freight transport decisions involves a trade-off between different cost elements. For instance, increasing the shipment size tends to decrease transport costs and order costs but increases inventory costs and vice versa. The optimization method used in Samgods for the minimization of logistics cost is described by de Jong and Baak (2020).

An important feature in the Samgods model is that transshipment (transferring goods between different modes) and consolidation are modeled explicitly. This is crucial to properly model how the economy of scale effect of freight transport (i.e. that transport costs per ton tend to decrease with increasing shipment sizes as larger vehicles that carry more goods can be used) and the complementing roles of different transport modes impact freight transport decisions. It is also a
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useful feature to represent certain types of driverless truck operating models. An illustration of this is provided by the example in Figure 9 which is inspired by de Jong and Ben-Akiva (2007). For transporting a shipment from A to B, there are several options. Option (1) is to perform a direct road transport chain. Option (2) is to use consolidation and distribution in a transport chain consisting of three road transport legs using small truck (AC) - large truck (CD) – small truck (DB). This is feasible if the cost savings enabled through the use of a larger truck during leg CD outweighs the costs for the consolidation at C and de-consolidation at D. Option (3) is to use a road (AE) - rail (EF) - road (FB) transport chain. Similarly to option (2), there is here a trade-off between cost reductions for the rail transport between EF and the costs for the transfers at E and F.

![Figure 9 Example of various transport chain options between A and B by either using a direct road transport chain (1), consolidation and distribution (2), or transshipment to rail (3).](image)

The analysis of driverless trucks in Paper 2 revolves around two uncertainties that may be key determinants for the impacts of driverless trucks. The first uncertainty is the extent of the driverless trucks’ EOD and what transport applications driverless trucks can be used for as a result of that. Two main scenarios are created that represent two different alternatives, as illustrated in Figure 10.

![Figure 10 Overview of the scenarios analyzed in Paper 2. The black boxes represent the two main scenarios and the grey boxes represent sensitivity scenarios.](image)
The All trucks driverless scenario (AllDL) represents a future where driverless trucks are a direct substitute to manually driven trucks and there is full penetration of driverless trucks across the whole truck fleet. In this scenario, there are no restrictions to the driverless trucks’ EOD, which is denoted as the all roads operating model. The Hub-to-hub scenario (H2H) represents a situation where driverless trucks have a restricted EOD and are capable of operating between fixed logistics hubs in the transport network in the form of terminals (e.g. road terminals, rail terminals, harbors, airports, etc.) but cannot be used for the first or final transport leg in a transport chain. Therefore, for a shipment to “access” driverless trucks, it first has to be transported to a terminal (e.g. by a manually driven truck) where it can be transferred to a driverless truck (compare with consolidation and transshipment as outlined in Figure 9). This is denoted as the hub-to-hub operating model. In the H2H scenario, a 40-ton driverless truck type is introduced as a complement to the existing manually driven truck fleet. Variations of the AllDL and H2H main scenarios are studied in a sensitivity analysis. For H2H, two variations of the driverless truck network are analyzed. In H2H main roads, the road network that driverless trucks can operate is further restricted to only the international E-road network and closely located hubs. In H2H SE only it is assumed that the driverless truck network is only present on Swedish territory. The second uncertainty used to define the scenarios is the degree of cost savings that driverless trucks enable. The effects of this are analyzed for both H2H and AllDL in the sensitivity analysis by varying the driverless truck cost inputs between a low-, mid-, and high level (which are based on the optimistic, intermediate, and pessimistic cost scenarios in Paper 1).

The scenarios are evaluated from several perspectives such as modal shifts and changes in transport activity per mode and the use of various types of truck types. Also, changes in transport- and total logistics costs on a system level are analyzed. Externalities, e.g. changes in CO2 emissions, congestion, road safety, noise pollution, are not quantified. The driverless truck scenarios are compared against a baseline without driverless trucks and compared against each other.

As when using any transport model system outside the application domain for which it was originally developed, great consideration needs to be taken to if and how the studied phenomena can be properly represented and if, and how well, relevant impact mechanisms are modeled. Without going into technical details, the Samgods logistics decisions module is primarily sensitive to supply changes in the form of changes in relative costs between vehicle types and modes (the interested reader is referred to De Jong and Baak (2020) for details). Since changed road freight transport costs are a clear (and possibly the most important) direct effect of driverless trucks, the Samgods model is, at least in principle, well suited to capture the response of the freight transport system to driverless truck induced cost changes. Furthermore, driverless trucks can rather straightforwardly be represented in the Samgods model by altering the characteristics of the existing vehicle types and the hub-to-hub operating model can be represented since transport chains are modeled. However, there are anticipated effects of driverless trucks which currently cannot be represented in Samgods, such as reduced transport lead times. See Paper 2 for a more detailed discussion on the limitations of the Samgods model structure for representing driverless trucks.

4.3.3 Paper 3: Technological Innovation System analysis
The Technological innovation system (TIS) framework is used for the study of sociotechnical innovation systems for emerging technologies (Bergek et al., 2008). The TIS framework was originally proposed as an approach for increasing the relevance of innovation system studies for policymaking by providing a scheme of analysis and a framework for describing the structure and...
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dynamics of innovation systems (Bergek et al., 2008). Often, TIS studies are used for identifying and analyzing current or potential shortcomings in an innovation system's capabilities to successfully develop, diffuse and generate a specific technology and based on that, identifying suitable policies for improving the system (Markard et al., 2015).

The TIS analysis in Paper 3 is based on the framework by Bergek (2008) and conceptualizes TIS’ as consisting of three types of structural components, namely actors, networks, and institutions that need to successfully perform a set of functions (i.e. key processes) to achieve the system goal, see Figure 11 for an overview.

![Figure 11 The driverless truck technological innovation system conceptualization used in Paper 3.](image)

The focus in Paper 3 is primarily on performing a descriptive analysis of the Swedish driverless truck TIS, i.e., to outline the structural components and analyze how the TIS functions are performed. There is a bearing also on assessing the TIS capabilities and shortcomings, primarily through identifying critical uncertainties about the future development of driverless trucks that are perceived by the involved actors.

The methodology for the study is summarized in Figure 12. In total, 20 expert interviews were conducted with 23 respondents from 16 different organizations during the autumn and winter of 2018. The interviewees represented various types of actors from both the public and private sector such as public authorities, truck OEMs, road carriers, transport buyers, etc. (see Table 1 in Paper 3). The majority of the data collection and initial data processing was performed by two of the paper co-authors as a part of their master thesis project. The interview data collection and data processing followed standard practices for semi-structured interviews that are summarized in Paper 3 and presented in detail in the master thesis report (Björkman and Joelsson, 2019).
4.3.4 Research design considerations from an uncertainty perspective

A fundamental methodological and theoretical issue for studying the (future) impacts of driverless trucks is the range of uncertainties this research problem is associated with. Any efforts to predict the “impacts of a yet to be diffused technology on society” raises fundamental questions about the nature of how society and technology interact and to what extent these impacts at all can be predicted (Nye, 2006, chaps. 2 and 3; Rosenberg, 1998; Smith and Marx, 1994). Walker et al. (2003) present a useful perspective for discussing uncertainty in the context of model-based research intended for policy guidance. They define uncertainty as *any departure from the (unachievable) ideal of complete determinism*. Their view means that uncertainty is not the same as the lack of knowledge, as, for instance, getting more knowledge on a subject may reveal further uncertainties that were previously not known and thereby increases the level of uncertainty. Walker et al. (2003) distinguish between two types of uncertainty which are different in their nature: *epistemic uncertainty* which is uncertainty resulting from poor knowledge that is reduced through more empirical information and *variability uncertainty* which is uncertainty resulting from inherent variability and complexity in real-world systems.

The impacts of driverless trucks are associated with several significant uncertainties that are categorized into four uncertainty domains in Table 2. This is not intended to be a comprehensive or a fully systematic analysis of those uncertainties but is rather intended to illustrate that there is uncertainty in several domains related to driverless trucks. In all of the uncertainty domains, there are both epistemic and variability uncertainty meaning that although more knowledge can be obtained for these topics through generating both theoretical and empirical progress, there will still be fundamental uncertainties for each of these areas from variability uncertainty (Epting, 2019; Porter et al., 2018).
### Table 2 Areas of uncertainty related to the future impacts of driverless trucks.

<table>
<thead>
<tr>
<th>Uncertainty domain</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) The timeline, phases, and dynamics of the development, introduction, adoption, and usage of driverless trucks</td>
<td>It is uncertain when (if ever) automated driving systems will be technologically mature for operating on public roads and related to this, when and under what conditions legislation enabling driverless trucks will be in place. It is currently not possible to specify with any high accuracy when different use cases of driverless trucks will be available on the market and how the adoption and use of those will develop.</td>
</tr>
<tr>
<td>2) The societal development influencing freight transport.</td>
<td>There are many uncertainties in how social, political, regulatory, economic, and technological factors will develop which shape the need for freight transport (for instance the economic activity, industrial structure, land use patterns, and consumer behavior). This sets the frames for the freight transport system and will therefore have an indirect effect on driverless trucks and their impacts.</td>
</tr>
<tr>
<td>3) Other developments within the freight transport system.</td>
<td>There are multiple technological, organizational, and structural changes to the freight transport system which could materialize in parallel with the development of driverless trucks which are driven and shaped by complex sociotechnical processes and whose impacts are virtually impossible to predict in detail with any certainty (e.g. “physical internet” and changed supply chain and logistics paradigms).</td>
</tr>
<tr>
<td>4) The response to, and impacts of driverless trucks.</td>
<td>Although standard freight transport modeling approaches can be used to generate more knowledge of the responses to driverless trucks, it is also possible that there will be unforeseen responses resulting from the complex dynamic between actors in the logistic and freight transport system for which there is currently a lack of theory. Also, there may be “unobservable attributes” related to aspects such as reliability and the (perceived) service quality level of driverless truck services which are not possible to estimate with any certainty before actual usage and experiences with driverless trucks can be studied.</td>
</tr>
</tbody>
</table>

The uncertainties described in Table 2 are interdependent through complex causal dependencies which add to the complexity and therefore increase variability uncertainty. For instance, the development and introduction of driverless trucks are dependent on the societal development and the response to, and impacts of, driverless trucks depend on the dynamics and structure of the development and introduction of driverless trucks. Moreover, uncertainty domain 2 and 3 describe the uncertainty related to what context driverless trucks will be introduced and used within which means that it is uncertain what scenarios and what impact mechanisms should be considered. Further adding to the uncertainty is that while it is known that freight transport decisions are interdependent on a broad range of other logistics decisions there is yet a lack of modeling approaches that comprehensively and appropriately represents these dependencies (Tavasszy et al., 2020).

This situation is what in the modeling literature is referred to as deep uncertainty which can be understood as when not only the model parametrization for representing the future is uncertain but also the model structure itself (Kwakkel et al., 2010; Marchau et al., 2010). In other words, this is
when the researcher or modeler is “being able to enumerate multiple possible futures or specify multiple alternative model structures, without being able to specify their likelihood” (Kwakkel et al., 2010, p. 12).

From an uncertainty perspective, this thesis is an effort to reduce the epistemic uncertainty for uncertainty domain 1 by outlining some of the dynamics of the development and introduction of driverless trucks in Paper 3, and for uncertainty domain 4 through the studies of driverless truck impacts in Paper 1 and Paper 2, while acknowledging that deep uncertainty resides.

The research design for Paper 1 and Paper 2, which deal with future impacts of driverless trucks, is based on several uncertainty-related considerations. Since it is uncertain what driverless truck applications will be available on the market at what time, and how fast the market uptake of these applications will be, it is chosen not to situate the studied scenarios within a specific timeframe (e.g. 2040). Instead, the temporal setting of the studied scenarios is only loosely defined as a period when “driverless trucks are available and in use”. However, some possible temporal relationships between the scenarios in Paper 1 and Paper 2 can be outlined within this period. The three scenarios for different cost levels of driverless trucks in Paper 1, could be interpreted as representing increasing maturity stages of driverless truck technology and therefore describing various points in time. Similar interpretations can be made for the scenarios in Paper 2 where the H2H scenarios may be plausible before the AllDL scenarios. Furthermore, the sensitivity scenarios varying the cost levels for driverless trucks (reflecting the pessimistic, intermediate, and optimistic cost scenarios in Paper 1) could also describe temporal variations between these scenarios in the same way as in Paper 1.

The scenarios in Paper 1 and Paper 2 are designed so that all other factors than the introduction of driverless trucks are fixed and represent current Swedish conditions. Some of the most important consequences related to this assumption are that the need for (and costs of) human labor during loading/unloading of trucks is assumed to be equal for manually driven trucks and driverless trucks (Paper 1 and Paper 2), driverless trucks are assumed to be powered by internal combustion engines (Paper 1 and Paper 2) and other scenario and model parameters (e.g. transport demand, infrastructure supply, location of terminals, costs for other modes, calibration parameters, etc.) are fixed between the baseline scenario and the driverless truck scenarios (Paper 2). This aspect of the research design has both positive and negative aspects. On one hand, it enables the impacts of automated driving to be “isolated” from effects of concurrent developments and it reduces the complexity of the analysis. This is preferable from the perspective of improving the understanding of the underlying impact mechanisms. Furthermore, there are practical reasons for choosing this approach related to limitations imposed by the limited flexibility (e.g. in terms of available vehicle types and vehicle transfer types) and long set-up and run times of the Samgods model. On the other hand, the analysis does not account for trends and developments which are likely to occur (e.g. changes in freight transport demand from forecasted demographic and macroeconomic development), potential technological development in both road transport and other modes, and this approach could therefore be criticized for studying driverless trucks are in an unrealistic context since one may argue that, in this case, the present is a poor estimate of the future.
5 Key findings

This chapter presents the key findings of the thesis. For each research question, the main results are presented followed by a short discussion on the relation to previous literature.

5.1 Research question 1: How will automated driving impact the total cost of ownership for trucks?

Paper 1 shows that driverless trucks will, in a technologically mature stage, enable a significant reduction in road freight transport costs. Figure 13 shows the total cost of ownership (TCO) in the driverless truck scenarios normalized to the manually driven truck baseline per truck type. The cost reduction is 12%-23% in the pessimistic scenario, 29%-45% in the base scenario, and 43%-58% in the optimistic scenario depending on the truck type. There is a clear relationship between truck size and relative cost savings with smaller truck types having larger relative cost savings while the relative cost savings are smaller for larger truck types. This suggests that driverless trucks may slightly counteract the economy of scale benefit that larger trucks have in terms of cost per TKM even though there is a significant economy of scale effect also for driverless trucks (see Figure 2 in Paper 1).

![Figure 13 Total cost of ownership per TKM normalized to the manually driven truck baseline per truck type. Note MD=Manually Driven truck.](image-url)

The obtained cost reductions are primarily a result of eliminated driver costs. This is shown in Figure 14 which provides a breakdown of cost changes for the 40-ton truck type compared to the manually driven truck baseline. Driver cost is a time-related cost and is practically independent of the truck size which explains why smaller truck types foresee larger relative cost reductions than larger trucks. The cost for remote operations required for driverless truck operations is, as shown in Figure 14, an important cost component. Currently, the available literature provides little guidance on “how much” remote operations will be required (i.e. how many trucks one operator can handle on average), the labor costs per operator, technology costs, and how these factors will develop over time with increasing maturity of automated driving systems. For the 40-ton truck type in the driverless truck base scenario, it would require that remote operations are used during 60% of the...
truck's operating time (with the assumed 2x cost for a remote operator per hour compared to a truck driver) to fully offset the TCO savings.

A key finding is that if driver costs can be eliminated, the reduction in TCO is not very sensitive to increased truck acquisition costs resulting from technology costs for the automated driving system. For instance, truck acquisition cost would have to increase by 230% compared to the manually driven truck baseline to fully offset the TCO savings in the base scenario for the 40-ton truck.

Figure 15 shows the cost structure for the 40-ton truck. In all scenarios, the relative share of node costs (i.e. costs for loading and unloading) increase compared to the manually driven truck baseline. This is a direct result of the assumptions of fixed labor and process costs for loading and unloading but highlights that node costs may constitute a significant share of road transport costs also in a driverless future. Another key effect on the cost structure is that time costs are significantly reduced (by around 75% in the base scenario) while distance costs are only marginally reduced (around 5% in the base scenario) and even slightly increased in the pessimistic scenario.
Key findings

Figure 15 Cost structures for the 40-ton truck type in the various scenarios. Note MD=manually driven truck, DL-truck=driverless truck.

To sum up, the findings in Paper 1 illustrate that driverless trucks could lead to significant reductions of production costs for road freight transport services through reduced TCO. Therefore, a large-scale introduction of driverless trucks would, under the assumption of a functioning competitive market, lead to reduced prices for road transport.

Compared to the similar studies by Wadud (2017) and Ghandriz et al. (2020), Paper 1 estimates slightly larger reductions in TCO (in the driverless truck base scenario). Probably the main reason for this is that both other studies assume higher costs for human labor for supporting driverless truck operations (e.g. through remote support and loading/unloading) than was done in Paper 1.

The relative cost savings estimated in Paper 1 should be reasonably transferable for markets with similar cost structures for road transport as in Sweden. However, for other markets with other cost levels and cost structures for road transport compared to Sweden, for instance, lower labor costs, the impacts on TCO from automated driving may differ significantly, which has been shown for commercial vehicles for passenger transport by Becker et al. (2020).

5.2 Research question 2: How will the freight transport system respond to large-scale adoption of driverless trucks?

Paper 2 shows that a large-scale adoption of driverless trucks would have substantial impacts on the freight transport systems by altering the cost of road transport relative to other transport modes which would change freight transport decisions. The magnitude of these effects is dependent on the assumed cost reduction for road freight transport and what type of driverless truck operating model being used. The key findings in Paper 2 on an aggregate system level are summarized below, with related key values presented in Table 3.

- Driverless trucks lead to modal shifts from rail and sea to road in both the AllDL scenarios and the H2H scenarios. The increase in road TKM is approximately twice as large in AllDL as in H2H. The decreases in rail and sea TKM are in absolute terms roughly equally distributed between the two modes. In the H2H scenarios, there is a shift from manually driven trucks to the DL-truck type although manually driven trucks (primarily the 60-ton truck type) still perform the majority of domestic road TKM.
Key findings

- There is a larger relative increase in road VKT than road TKM. This is mainly because that the average truck size decreases in the driverless truck scenarios. One reason for this is that the increased use of road transport for import and export flows means that there is a larger amount of small trucks (up to 40-tons) operated in Sweden since 60-ton trucks are not allowed outside of Sweden and Finland.
- There are substantial reductions of annual total logistic costs on the system level in all scenarios but H2H SE only. The cost savings result from the reduced road transport operating costs enabled by driverless trucks.
- In the H2H scenarios, restricting the driverless truck type to only the international E-road network as in H2H main roads does not limit the competitiveness of driverless trucks compared to H2H. However, if driverless trucks are restricted only to Sweden as in H2H SE only there is not much benefit on a system level. This may however primarily be a result of that the 40-ton truck type is used for the driverless trucks and not the 60-ton truck type.

Table 3 Summary of results from Paper 2. All values represent domestic values (i.e., transport activities on Swedish territory) except for total logistics costs which also include international costs.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Road TKM [M TKM]</th>
<th>Road share of total TKM</th>
<th>Road VKT [M VKT]</th>
<th>DL-truck usage (H2H) [M TKM]</th>
<th>DL-truck share of road TKM (H2H)</th>
<th>Total logistics costs for all flows [M€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>30 200</td>
<td>48%</td>
<td>2 700</td>
<td>N/A</td>
<td>N/A</td>
<td>22 400</td>
</tr>
<tr>
<td>AllDL</td>
<td>61 200</td>
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<td>3 700</td>
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<td></td>
<td>+22%</td>
<td>+12pp</td>
<td>+35%</td>
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<td>AllDL high DL costs</td>
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<td>54%</td>
<td>3 100</td>
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<td>+6pp</td>
<td>+15%</td>
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</tr>
<tr>
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<td>2 800</td>
<td>5 800</td>
<td>11%</td>
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<td>+29%</td>
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<td>36 100</td>
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<td>21 200</td>
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<tr>
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<td>+12%</td>
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<td>+2pp</td>
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<td>N/A</td>
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In Figure 16, a geographical overview of the changes in annual transport flows in tons per mode for AllDL and H2H compared to the baseline without driverless trucks is provided. The most substantial increase in road transport is in both scenarios along the main road corridors. In AllDL there is also increasing road transport on many other parts of the road network. Import and export freight flows using rail and sea are to a large degree replaced with road transport. The growth in international road transport is associated with significant growth in road ferry transport connecting Sweden with the neighboring countries.
Figure 16 Changes in transport flows (in tons) in AllDL (left) and H2H (right) compared to the baseline without driverless trucks.

Figure 17 shows that the increase in road TKM for different commodity types differs between AllDL and H2H. For some commodity types, e.g. “coal, petroleum, gas”, “non-metallic mineral products” and “food and beverages” there is only a small difference between H2H and AllDL, while for some other commodity types, e.g. “metal ores, etc.”, “timber” and “refined petroleum products” there is a substantial difference.

Figure 17 Change in domestic road TKM per commodity type in AllDL and H2H compared to the baseline without driverless trucks. The percentages indicate the relative change in road TKM which can be compared with the total road TKM increase which is 22% in AllDL and 11% in H2H.
Key findings

The only other study that the results from Paper 2 can be somewhat directly compared against is Huang and Kockelman (2020) which is modeling a similar scenario as the AllDL scenario for the U.S. Both studies investigate the modal shift from rail to road following a driverless truck introduction. There are similar results on the relative increase in road TKM due to a modal shift from rail, although possibly with a tendency for a slightly larger effect for the Swedish system. However, detailed comparisons between the studies and the Swedish and U.S. systems are not possible as the models used for the studies are different in their approach (e.g. Samgods assumes a fixed freight demand per OD-pair and commodity type while the RUMBRO model used by Huang and Kockelman models origin choice endogenously; Samgods models transport chain choice while RUMBRO models mode choice) and scope (e.g. RUMBRO includes road and rail while Samgods also includes sea and air transport).

The study in Paper 2 contributes to the literature in several ways. First, by using the Samgods model, the impacts of driverless trucks on freight transport decisions (e.g. transport chain choice) are modeled on the actual decision-maker level (i.e. at the level of the transport buyer/operator) and not at an aggregated zone-level or through using aggregate demand elasticities as has been the approaches used in previous studies (Bao and Mundy, 2018; Huang and Kockelman, 2020). Another contribution is that Paper 2, to the author’s best knowledge, is the first study to quantify the impacts of the hub-to-hub operating model. The findings suggest that the hub-to-hub operating model might be an attractive operating model for driverless trucks although both the representation and analysis of this operating model in Paper 2 are associated with several limitations. A third contribution is that this study presents a first example of how driverless trucks could be analyzed using the aggregate-disaggregate-aggregate freight modeling framework.

5.3 Research question 3: What are the key factors shaping the innovation system of driverless trucks?

Paper 3 shows that the formation of a technological innovation system of driverless trucks in Sweden (in this section referred to as the “TIS”) is in an early formative phase with loose structures. The following general observations of the TIS can be made.

- There are significant uncertainties related to the timeline, infrastructure requirements, and regulative landscape for a widespread driverless truck deployment in Sweden.
- There is a general view among the actors in the TIS that driverless trucks are a significant opportunity for the Swedish automotive sector and the industry at large and there is a political ambition for Sweden to become both a leading supplier and user of driverless trucks.
- The development of driverless trucks is highly influenced by incumbent firms in the Swedish vehicle industry but actors from the telecom sector, energy sector, and emerging truck technology companies are also entering the area and are shaping the development. Developing driverless trucks is not an innovation process taking place only within the existing truck and road transport value chains but is characterized by a higher degree of cooperation by a broader set of actors.
- The current relatively rigid institutions for truck development and production and road freight transport will require significant alignment to adapt to driverless truck development and operations in areas such as regulations, business models, and operational practices.
The analysis in Paper 3 indicates that a key dynamic for the TIS is that it is more driven by the supply side rather than driven by the demand side. Although several actors highlight the potential economic benefits for the driverless truck users and their customers (e.g., transport buyers, logistics service providers, and road carriers) such as reduced transport costs, this demand is in general not clearly articulated by potential users and customers of driverless trucks but rather by other actors in the TIS. However, interviewees from the logistics sector highlight that driver shortage is a critical industry challenge that driverless trucks could alleviate.

One reason for the more cautious position taken by actors on the demand side might be that driverless trucks could result in a disruption to the value chain of road freight transport and that the role of the current road carries becomes marginalized when there is a reduced need for providing manually driven truck services. Several of the interviewees express a belief that driverless trucks will most likely be offered “as a service” which could put pressure on both truck OEMs and road carriers and lead to that the traditional customer-supplier relationship between road carriers and truck OEMs will change. Driverless trucks are, therefore, from this perspective, both an opportunity and a threat for several of the existing actors in the truck and road freight transport value chains while it could also provide significant business opportunities for new entrants.

Within the vehicle industry in Sweden, there are well-established capabilities and institutions for research, development, and innovation for truck technologies. However, for developing and introducing driverless trucks, there are several new types of issues and those are primarily not handled within this existing structure but through a higher degree of collaboration with other companies and public bodies. Several interviewees highlighted that the development of driverless trucks is not just a matter of solving challenging technical problems and that successful development, introduction, and diffusion of driverless trucks requires significant advancements within areas which traditionally have not been key considerations for truck OEMs. Driverless trucks require advancements in business model design, closer collaboration with transport buyers, institutional and regulatory alignments, and potentially also investments in new (digital) infrastructure that requires new ways of working and collaborating. Several publically financed innovation networks for automated driving and freight transport have emerged and provided arenas for cross-organizational collaboration on areas that are not suitable to handle within each organizations existing R&D process. Driverless trucks are by several interviewees seen as one component of an ongoing digital transformation of the entire freight transport and logistics sector. However, the needs and requirements for a (new) digital infrastructure to support driverless truck operations and a broader digitalization of freight transport is an area of large uncertainty.

The findings in Paper 3 support several of the claims made by previous literature. For instance that the development of driverless truck will be characterized by close partnerships by truck OEMs, technology suppliers, and logistic services providers (Fritschy and Spinler, 2019), will challenge existing business models for truck OEMs and road carriers (Fritschy and Spinler, 2019; Monios and Bergqvist, 2019) and that the driver shortage is a key challenge that driverless trucks could alleviate (Müller and Voigtländer, 2019). However, by performing the analysis on the level of the innovation system and not focusing solely on a specific type of actor, Paper 3 lifts several perspectives which are not covered in previous literature. For instance, the slightly different positions towards driverless trucks between the supply and demand side and the dynamics created by new types of actors entering the area.
6 Concluding remarks

This chapter concludes the thesis through a brief discussion on policy and planning implications in Section 6.1, the main conclusions in Section 6.2, and suggestions for future work in Section 6.3.

6.1 Discussion

The introduction of driverless trucks will not necessarily take place as a direct substitution of manually driven trucks since it is plausible that initially, driverless trucks with limited EODs will be deployed. This could for instance be done by using the hub-to-hub operating model which will be plausible only for certain types of transport flows, could change the structure of road transport networks, and entail a different logic for road transport operations. Therefore, driverless trucks using the hub-to-hub operating model will not directly substitute manually driven trucks but rather constitute an additional “road sub-mode” that will be complementary to manually driven trucks for some transport applications and competing with manually driven trucks for other transport applications. For planning and impact assessment purposes, it is therefore important to not by default conceptualize and model driverless trucks simply as a direct substitute to manually driven trucks and focus only on aspects such as relative costs and the penetration rate. Instead, consideration in such analysis needs to be taken also to what driverless truck operating models will be used since it has a significant effect on the impacts of driverless trucks, as this thesis shows.

Although this thesis indicates that there may be significant economic benefits of driverless trucks for producers and buyers of freight transport services, the policymaking and governance of driverless trucks need to acknowledge and consider the risks for negative externalities and unanticipated effects from the potentially substantial increase in road transport volumes as well as the uncertainties surrounding the topic. A few reasons for this are given below.

- There are significant uncertainties about what the context for driverless trucks will be. It is uncertain when driverless trucks will be in use on a large scale. It is also uncertain how other societal and freight transport trends will have developed during that time and interacted with the development of driverless trucks. Since alternative freight transport futures may come with different challenges, the role, benefits, and drawbacks of driverless trucks may differ. The impacts of driverless trucks should therefore be evaluated against the specific conditions in a broad set of alternative scenarios.
- The knowledge on the impacts of driverless trucks on the transport system and society is still on an inferior level with only a few studies have systematically assessed these questions. Significant research efforts remain to be done in this field.
- The societal costs and benefits of driverless trucks are not well-evaluated and such analysis is currently, due to the above-mentioned reasons, highly uncertain. Most current studies estimating societal costs and benefits rely on speculative assumptions on the effects of driverless vehicles and would benefit from having a broader base of impact assessments using large-scale freight transport modeling approaches to rely on.

All in all, based on the findings of this thesis and the uncertainties associated with the introduction and impacts of driverless trucks, a sound policy position towards driverless trucks could be to follow a similar approach as the literature has suggested for driverless vehicles for passenger transport in urban settings. This includes a) taking a critical position towards the dominating narratives and
visions of futures with driverless vehicles (Martin, 2021) b) viewing driverless vehicles as one of several potential transport technologies to achieve societal goals and avoid transport and infrastructure planning for driverless vehicles (Epting, 2019; Porter et al., 2018) and c) to implement a flexible policy and regulatory framework that allows for adjustments of polices over time when more is known about the impacts of the driverless trucks through experiences from real-world usage (Walker and Marchau, 2017).

6.2 Conclusions

The overall aim of this thesis has been to increase the understanding of how an introduction of driverless trucks could materialize and impact the freight transport system in Sweden. Two objectives have been targeted. The first objective was to investigate the impacts of driverless trucks on the freight transport system in scenarios where driverless trucks are widely available and in use. This is addressed through Research question 1 and Research question 2. The second objective was to analyze the current development towards introducing driverless trucks in the freight transport system which is addressed by Research question 3. The following are the main conclusions of the thesis.

Research question 1: How will automated driving impact the total cost of ownership for trucks?

Driverless trucks will most likely have a significantly lower total cost of ownership compared to manually driven trucks of comparable truck configuration. The exact magnitude of the cost reduction is subject to uncertainties related to how the capabilities and costs of automated driving technology will develop and to what extent the technologically enabled increase in performance can be realized as actual cost savings. A central aspect is to what extent the reduction in driver costs will be offset by other forms of human labor required for planning and performing driverless truck operations. Other factors, including the truck acquisition cost, have marginal importance.

Research question 2: How will the freight transport system respond to large-scale adoption of driverless trucks?

Driverless trucks will increase the demand for road freight transport. The increased cost competitiveness of road transport relative to other transport modes will result in modal shifts from rail and sea to road. This effect can be observed across all transport distances and for more or less all commodity types in all the evaluated scenarios. The increase in truck VKT is in relative terms more substantial than the increase in truck TKM. The magnitude of the increase in road transport demand will depend on the costs for driverless truck operations relative to manually driven trucks and other modes, and on what driverless truck operating model will be used. Driverless trucks might enable significant reductions in total logistics costs for Swedish freight transport in the range of billions of SEK per year.

Research question 3: What are the key factors characterizing the innovation system of driverless trucks?

The driverless truck innovation system is one hand characterized by factors that present favorable conditions for a future successful introduction (in the sense that there is large-scale commercialization) of driverless trucks in Sweden. For instance, the potential to alleviate the driver shortage in the road freight industry, the positive pressures on Swedish truck OEMs to develop driverless truck solutions, the ambitions for putting legislation that enables automated driving in
Concluding remarks

place, and political support. On the other hand, the innovation system of driverless trucks is at an immature stage and several major uncertainties reside. These issues relate to legislation, defining requirements, responsibilities, and financing models for digital infrastructure and, possibly, interventions in the physical infrastructure. Also, the adaptation of business models and the re-definition of roles and relationships in the truck manufacturing and freight transport business landscape are key uncertainties.

6.3 Future work
The work with this thesis has opened up several new questions and possible areas for future research.

Expanding the analysis of driverless truck costs to a broader logistics perspective
While the broad analysis of driverless truck costs that is presented in Paper 1 is valuable for overarching assessment, there is also a need for more case-specific analyses of transport cost impacts of driverless trucks. Road transport is heterogeneous and likely, the economic benefits of driverless trucks differ substantially between different fleet owners depending on what type of transport services they are providing. Such research could for instance target specific industrial sectors or commodity types, the transport network of specific transport operators or logistics service providers, or specific transport flows. Such studies should also consider widening the system boundaries to not only focus on the cost impacts on transport activities but also study changes and adaptations in upstream and downstream logistical processes and what the associated cost and benefits may be. Key factors to analyze are to what extent non-driving related tasks such as goods handling still will require human labor and the costs for various forms of remote support.

Studying the dynamics of the driverless truck market formation and the impacts of new business models on freight transport markets
As highlighted in Paper 3, driverless trucks may challenge existing business models and result in changes to the value chain of road freight transport. It is not certain that the current owners and operators of manually driven trucks will be the type of companies that will own and/or operate driverless trucks. This could have substantial effects on the dynamics of the market uptake and how transport markets are functioning which in turn are critical factors for forecasting the impacts of driverless trucks. A future contribution to this area could be a follow-up to the study in Paper 3 with a more pronounced focus on the market formation function and collecting a larger empirical material related to transport buyers in their role as “end-users” of driverless truck transport services. Another interesting area is how the Swedish driverless truck TIS is embedded in global efforts to develop driverless trucks. The need for this is highlighted by the developments during the last year (after the study in Paper 3 was performed) where strategic collaborations between Swedish truck OEMs and international automated driving system technology companies have been announced by both Scania (Traton group, 2020) and Volvo (AB Volvo, 2021). This could potentially influence both the timeline for market introduction, what type of driverless truck operating models will be taken to market, and the dynamics of the innovation system in Sweden.

Improving the model representation and analysis of the hub-to-hub model
There are several potential improvements of the representation of the hub-to-hub operating model in Samgods that was done in Paper 2. A straightforward extension of the analysis in Paper 2 would be to run scenarios in which also a 60-ton driverless truck type is available in Sweden in addition to the 40-ton driverless truck type. Another possibility is to evaluate the impacts of a new terminal
Concluding remarks

Infrastructure that is dedicated to facilitating transfers between manually driven trucks and driverless trucks instead of using the current terminal infrastructure which has been developed primarily for consolidation and transshipment purposes. Other improvements would require modification of the model structure. For instance, if the number of available truck types would be increased, then more than one type of driverless truck can be used in parallel within the hub-to-hub network. This would allow a more nuanced representation of the hub-to-hub concept and better analysis of how manually driven trucks and driverless trucks would complement each other.

Another improvement would be to being able to specify transfer cost per vehicle pair which would allow “trailer swaps” between manually driven trucks and driverless trucks to be represented without biasing the costs for regular vehicle transfers. In addition to work that can be done by using the Samgods model, there are also multiple operational aspects of the hub-to-hub operating model related to vehicle and terminal scheduling, fleet optimization, transfer terminal placement and operations, etc. that are open research areas. Another question to dig deeper into is whether the hub-to-hub operating model would lead to a fundamental change of business models and the relationships between actors as argued by Monios and Berquist (2020).

Assessing the sustainability impacts & societal costs and benefits of driverless trucks in a broader set of future scenarios

As shown by this thesis, the introduction of driverless trucks may substantially increase the demand for road freight transport. The externalities and societal costs resulting from this require further research and analysis. One key research effort would be to combine findings from research on potential vehicle level effects (e.g. more energy-efficient driving, reduced headways, and reduced risk for accidents) with potential changes in road transport demand to estimate the emerging net impacts on system-level (e.g. impacts on total CO2 emissions, congestion and the total number of traffic accidents and injuries). Societal costs and benefits of driverless trucks need to be analyzed in various future scenarios that represent combinations of plausible technological, economic, and social developments. Also, there is a need to study the impacts during the “transition period” at which driverless trucks are introduced, since the penetration rate is an important factor for the magnitude of impacts of driverless vehicles (Elvik et al., 2019) and to capture any dynamic effects occurring during the transition. Given the deep uncertainty surrounding these topics, there is a need for a broader and more open-ended analysis of the impacts of driverless trucks than what traditional freight transport model frameworks are designed for. One potential approach may be to use so-called exploratory modeling and analysis (Kwakkel and Pruyt, 2013; Milkovits et al., 2019) which allows a wide range of scenarios and policy alternatives to be simulated and evaluated, albeit on a less detailed level than what state-of-the-art freight transport models (e.g. Samgods) allow. This type of analysis would require the development of a faster and more aggregate freight transport model. Such a model was proposed to be developed for the Swedish freight transport system in the form of a system dynamics model already in the early years of this millennium (de Jong et al., 2002) but was never realized. Re-visiting this idea might be a fruitful way forward to gain further knowledge on how the future transport system with driverless trucks could look like.
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