Prestudy on System Level Impacts of Automation, Electrification and Digitalization for Long-term Transport Analysis and Planning

Erik Stenemo, Integrated Transport Research Lab, KTH Royal Institute of Technology Sweden

Zeinab Raoofi, Integrated Transport Research Lab, KTH Royal Institute of Technology Sweden

Albin Engholm, Integrated Transport Research Lab, KTH Royal Institute of Technology Sweden

Anna Pernestål, Integrated Transport Research Lab, KTH Royal Institute of Technology Sweden

Summary

The aim of this prestudy is to investigate how developments within automation, electrification and digitalization (AED) may affect the demand for passenger and freight transport in Sweden in terms of transport activity (ton-kilometers TKM and passenger-kilometers PKM), traffic activity (vehicle kilometers traveled VKT), modal distribution and other characteristics of the transport system, in order to assess whether the current base forecasts for 2040 that are developed and used by Trafikverket are still robust when accounting for developments and impacts of AED. Both freight and passenger transports are considered, as well as several transport modes. These include road (passenger cars, light and heavy trucks), rail (long and short distance), marine (ships and ferries) and air (planes). In addition, support infrastructure such as charging stations and goods terminals are considered. Automation technologies include automated vehicles and goods handling. Electrification refers to the replacement of conventional fuels with electric energy, as well as charging infrastructure. Digitalization is the broadest of the technological fields, and includes both digital services and digital infrastructure. The latter is furthermore an enabler for first and foremost automation, but also for electrification to some extent.

The theoretical perspective of the study is that transport demand is derived from the need to transport goods and people. Several drivers of transport demand (such as mode characteristics and economic structure) are presented and included in a general framework for assessing transport demand. The framework further incorporates a variety of previously constructed models and consists of three layers (activities & material flows, transport services and infrastructure) which connect in two markets (the transport and traffic market). The effects on transport demand are assessed from a set of demand parameters, including TKM, PKM and VKT. Finally, six mechanisms through which AED could affect transport demand are presented and integrated into the general framework.

Through literature reviews and workshops, a set of general trends within AED were identified. Since there is a considerable uncertainty regarding how these trends could develop until 2040, an explorative scenario-based approach was employed. In order to structure this approach, a morphological analysis was conducted where the identified trends were formulated as parameters and their stages of development as attributes. Combined, these parameters and attributes formed a morphological box which could be used to illustrate different scenarios. In this study, four scenarios were then mapped in the morphological box: a base scenario intended to mimic explicit and implicit assumptions in the base forecast and three alternative scenarios (Partnership Society, Social Engineering 2.0 and Swimming in Data) intended to

contrast the base scenario by illustrating alternative societal and technological development paths.

These scenarios and their respective morphological box mappings were then analyzed based on the general framework. The first step in this impact analysis consisted of investigating possible separate impacts of the parameters on each layer and market in the general framework. The mechanisms of which each parameter would affect the system were also identified. Examples of effects include changes in generalized costs and service levels. In the second step, the impacts from combined AED development were studied based on the scenario mappings in the morphological box. This highlights possible synergies between the technologies. Finally, the combined effects were compared with the base scenario in order to reach the study's aim.

The results of the analysis show that automation, electrification and digitalization technologies separately could lead to changes in transport efficiency as well costs. Furthermore, synergetic effects leading to even stronger impacts on factors such as these could arise when they are combined. Through the general framework and the demand impact mechanisms, it was shown that factors such as these could lead to changes in the transport demand, modal distribution and transport system characteristics. Since the scenario mapping shows that the base forecasts do not consider development in automation and digitalization to a significant extent, the base forecasts would probably not be robust if these technologies see a continued development and implementation in the transport system.

Sammanfattning

Syftet med denna förstudie är att undersöka hur teknologisk utveckling inom automatisering, elektrifiering och digitalisering (AED) kan påverka efterfrågan på person- och godstransporter i Sverige med hänsyn till transportarbete (tonkilometer TKM och personkilometer PKM), trafikarbete (fordonskilometer VKT), trafikslagsfördelning och andra egenskaper i transportsystemet, för att undersöka huruvida de nuvarande basprogonoserna för 2040 som tas fram och används av Trafikverket skulle vara robusta gentemot teknologisk utveckling inom AED. Både gods- och persontransporter inkluderas i studien, likaså ett flertal trafikslag. Dessa inkluderar vägtrafik (personbilar, lätta och tunga lastbilar), järnvägstrafik (kort- och långväga), sjöfart (båtar och färjor) samt luftfart (flygplan). Dessutom inkluderar studien infrastruktur som laddstationer och lastterminaler. Automatiseringsteknologier inkluderar automatisering av fordon och godshantering. Elektrifiering innebär ersättandet av konventionella bränslen med elektrisk energi samt laddinfrastruktur. Digitalisering är den bredaste av de tre fälten och inkluderar både digitala tjänster och digital infrastruktur. Det sistnämnda är dessutom en möjliggörare för framförallt automatisering, men även till viss del elektrifiering.

Den teoretiska utgångspunkten för studien är att transportefterfrågan kan härledas från behovet att transportera människor och gods. Ett flertal drivkrafter för denna efterfrågan presenteras (exempelvis samhällets ekonomiska struktur) och inkluderas i ett generellt ramverk för att undersöka effekter på transportefterfrågan. Ramverket inkorporerar dessutom ett antal tidigare modeller och består av tre lager (aktivitets- och godsflöden, transporttjänster och infrastruktur) som möter varandra i två marknader (transport- och trafikmarknaderna). Effekter på transportefterfrågan utvärderas utifrån en samling efterfrågeparametrar som inkluderar TKM, PKM och VKT. Slutligen inkluderas sex mekanismer genom vilka AED kan påverka transportefterfrågan.

Genom litteraturstudier och workshops identifierades ett antal generella trender inom AED. Då det finns en stor osäkerhet kring hur dessa kan utvecklas till 2040, användes ett explorativt och scenariobaserat tillvägagångssätt. För att strukturera detta ytterligare utfördes en morfologisk analys inom vilken de identifierade trenderna formulerades som parametrar. Stegvis utveckling inom varje parameter formulerades som tre till fyra attribut. Tillsammans utgör dessa parametrar och attribut en morfologisk box som kunde användas för att illustrera olika scenarier. I den här studien kartlades fyra sådana i den morfologiska boxen: ett basscenario med syftet att spegla explicita och implicita antaganden i basprognoserna, samt tre scenarier (Partnership Society, Social Engineering 2.0 och Swimming in Data) med syftet

att utgöra kontraster till basscenariet genom att illustrera alternativa samhälleliga och teknologiska utvecklingsvägar.

Scenarierna med deras respektive kartläggningar i den morfologiska boxen analyserades sedan med utgångspunkt i det teoretiska ramverket. Det första steget i denna effektanalys var att undersöka separata effekter för varje parameter på varje lager och marknad i ramverket. Exempel på dessa effekter inkluderar förändringar i generaliserad kostnad och servicenivåer. Även de mekanismer genom vilka varje parameter skulle påverka systemet identifierades. Det andra steget i analysen innefattade att undersöka kombinerade effekter av AED-utveckling, baserat på kartläggningarna i den morfologiska boxen. Detta synliggjorde potentiella synergier mellan teknologierna. Slutligen jämfördes de kombinerade effekterna för att uppnå studiens syfte.

Resultaten visar att automatisering-, elektrifiering och digitaliseringsteknologier separat skulle kunna leda till skillnader i bland annat transporteffektivitet och transportkostnad. Vidare skulle synergieffekter som uppkommer då teknologierna kombineras kunna leda till ännu större effekter på dessa faktorer. Enligt det teoretiska ramverket innebär det att transportefterfrågan, trafikslagsfördelningen och egenskaperna hos transportsystemet skulle kunna förändras. Slutligen, då scenariekartläggningen visar att basprognoserna inte beaktar automatisering eller digitalisering till en hög grad, skulle prognoserna antagligen inte vara robusta om utvecklingen och implementeringen av AED-teknologier fortskrider.

Table of Contents

Abbreviations and terminology

AED	Automation, Electrification, Digitalization
AV	Automated vehicle
Base forecast(s)	The official Swedish transport demand forecasts for 2040 by TrV for passenger transport (Sachse and Almkvist 2020) and freight transport (Wikström 2020) (Swedish: “Basprognos(er)”)
BEV	Battery electric vehicle
BF	Base forecast
ICEV	Internal combustion engine vehicle
PKM	Person-kilometers
TKM	Tonne-kilometers
Traffic activity	VKT (Swedish: “Trafikarbete”)
Transport activity	PKM/TKM (Swedish: “Transportarbete”)
Transport need	#trips, #tons, etc.
TrV	The Swedish Transport Administration (Swedish: “Trafikverket”)
VKT	Vehicle-kilometers traveled

1. Introduction

A recent estimate suggests that over $300 billion USD has been invested in emerging transport technologies within automation, electrification and digitalization (AED) since 2010 (Holland-Letz et al. 2021). During the coming decades, advancements within AED may lead to far reaching effects for the transport system and its services by a combination of a variety of multifaceted effects. AED will likely lead to several incremental improvements of current transport services and infrastructure (e.g. safer and more efficient vehicles, improved service quality, improved traffic management systems, etc.). The AED development may also enable the emergence of new transport services, changing the characteristics and cost structures for the different modes of transport, and affecting the organization and structure of transport services, markets and networks affecting transport patterns, business models and efficiency. Collectively this development will affect transport related decisions both within freight and passenger transport such as choice of origins and destinations, transport modes, routes which will affect transport activity and traffic volumes both in terms of total volumes and their spatio-temporal distribution. In parallel, this technological development could lead to behavioral and structural changes within logistics systems and the daily lives of citizens affecting the need for transport. All in all, it is possible that transport demand could be substantially affected through this complex web of interrelated effects resulting from technological development within AED (Milakis, van Arem, and van Wee 2017; Pernestål et al. 2020).

Previous studies have suggested that the combination of electrified, automated and shared mobility (which is enabled through digital technologies) could result in a substantially more resource efficient transport system (Jaller et al. 2020; Fulton, Mason, and Meroux 2017), and narratives equating the AED development with a better and more sustainable are common in the political (Henriksson, Witzell, and Isaksson 2019) and industrial discourse (Paulsson and Sørensen 2020). On the other hand, claims have been made that AED could negatively affect transport-related sustainability through a substantial increase in transport demand that counteracts gains in transport and resource efficiency (Wadud, MacKenzie, and Leiby 2016), through reduced use of less carbon-intensive transport modes such as rail, public transport, walking and biking (Klimatpolitiska rådet 2019; Almlöf, Nybacka, and Pernestål 2020; Engholm, Kristoffersson, and Pernestål 2021) and possibly by reinforcing cultural and behavioral patterns of private mobility (Sovacool and Axsen 2018). However, the current understanding provided by the growing body of scientific literature examining the transport system impacts of AED is rather that the transport demand and sustainability effects of AED are highly uncertain and complex. This is since the development is dependent on uncertain factors such as the pace and dynamic of technological development, market introduction and diffusion of these technologies and services, but also due to that the prerequisites and effects of AED are highly determined and shaped by the societal, political, economic landscape and what policy instruments are in place. This means that there are numerous plausible futures for how AED can manifestate as changing transport systems and services and that the impacts on transport demand and sustainability indicators vary drastically between different future scenarios (Miskolczi et al. 2021).

This prestudy is motivated by the need for The Swedish Transport Administration - Trafikverket (TrV) to account for the potential impacts of AED in long-term transport demand analysis and planning. The current base forecast for the year 2040 (Wikström 2020; Sachse and Almkvist 2020) does only to a limited extent account for the effects of these technologies and may therefore not reflect important factors affecting transport demand. This prestudy is intended to provide guidance on what developments within AED that could be relevant to consider in future complementary analyses to the base forecast.

1.1 Aim

The aim of this prestudy is to investigate how developments within automation, electrification and digitalization (AED) may affect the demand for passenger and freight transport in Sweden in terms of transport activity (ton-kilometers TKM and passenger-kilometers PKM), traffic activity (vehicle kilometers traveled VKT), modal distribution and other characteristics of the transport system, in order to assess whether Trafikverket's current base forecasts for 2040 are still robust when accounting for developments and impacts of AED.

The following questions are addressed:

- What emerging AED related transport technologies and transport services may affect transport demand, modal distribution and transport system characteristics? Through what mechanisms?
- How can the combined effects of plausible combinations of developments within AED affect transport demand, modal distribution and transport system characteristics?
- Are the estimates regarding transport demand, the modal distribution and/or the transport system characteristics provided by the current base forecasts for 2040 robust when accounting for developments and impacts of AED?

1.2 Scope and simplifying assumptions

This scope of this prestudy is broad in several dimensions. It covers three technological megatrends, AED, which each one includes numerous technology areas and a multitude of present and possible products, services and applications based on these technologies. It covers both freight transport, passenger transport and the interactions between those. All transport modes are covered. Furthermore, the study considers the impacts of AED on transport demand both through changes at the societal level (e.g. localization effects, changes to the industrial structure and trade patterns and travel behavior and preferences) that affects the need for transport but also the numerous potential changes within the transport system that AED could lead to which can affect transport demand. All in all, this creates a large set of dimensions and factors to consider.

This broad scope is stipulated in the project assignment as defined by the project commissioners. The ambition to take a “holistic” approach to plausible technological development is regarded as a key merit of this study and the main motivation for it to be performed. However, the broad scope and the available resources for this prestudy restrain the possibility to perform in-depth analysis. Furthermore, it is possible that important aspects of the AED development have been omitted from the study. In the following paragraphs, a definition of AED is given along with additional clarification of the scope. Also, the simplifying assumptions that have been made are presented.

A key factor for scoping this prestudy is how the terms of automation, electrification and digitalization are defined and how these concepts are assumed to relate to each other.

- **Automation** can be defined as the application of machines to tasks once performed by human beings or to tasks that would otherwise be impossible (Encyclopedia Britannica 2021). In this prestudy, automation refers to the automation of physical transport or logistics related tasks such as driving, load handling, etc. Automation of non-physical digital processes (e.g. route planning, transport market transactions, etc.) are categorized as belonging to *digitalization*.
- **Electrification** can be defined as the process of making a machine or system operate using electricity when it did not before (Cambridge dictionary 2021). For the context of this prestudy, electrification refers to the electrification of vehicles and vessels as well as the infrastructure for providing electric energy to these vehicles and vessels (i.e. charging infrastructure).
- **Digitalization** is not a technology trend that can be separated from automation and electrification since digital technology is also foundational for these technology areas.

For instance, automated driving could be interpreted as “digitalizing the driving task” and digital technology is core to charging management. In this prestudy, the general principle is that digital technologies that enable, or are developed or used for the main purpose to support, electrification or automation (e.g. automated driving systems, charging management systems or vehicle remote operation systems) are treated as parts of electrification or automation respectively. The term digitalization does in this prestudy relate to two main areas. One is digital services and applications, i.e. the use of digital technologies to enable, deliver or enhance products or services (that are not used for the main purpose of automation or electrification). The other area is digital infrastructure, including connectivity infrastructure, that enable digital services and applications and general digital maturity in society and business that allows a broader set of, and more complex digital applications and services to be used.

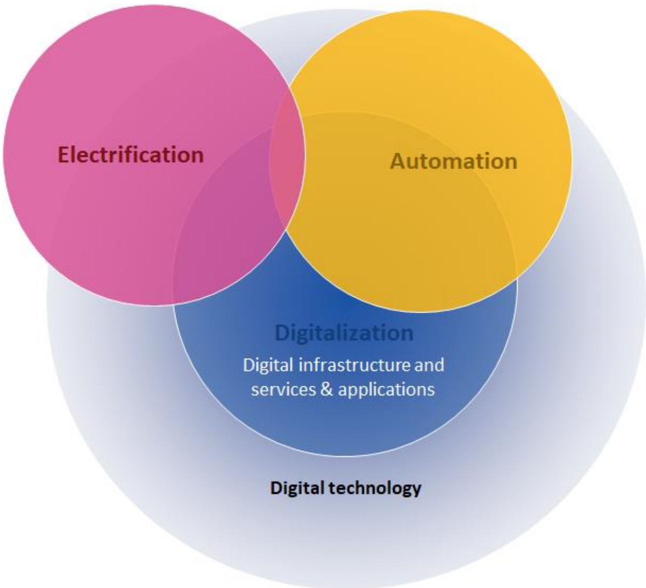

Figure 1.1. How AED concepts are assumed to relate to each other.

Other key scoping factors and assumptions are:

- Geographically, the project focus is on the Swedish transport system which refers to the infrastructure and transport operations performed on Swedish territory. However, transport and traffic activity within Swedish territory is not only generated by domestic transport (trips starting and ending in Sweden), but also from trips to, from and through Sweden. In particular, international transport is an important component of freight transport since trade patterns and supply chains to a large extent are international phenomena and Swedish freight transport is to a significant degree constituted by import, export and transit flows. Therefore, the study of the impacts of AED is not delimited only to developments within Sweden, but also international development that could have an impact on the Swedish transport system are in scope.

- The temporal scope is until the year 2040. This is therefore the year that the scenarios developed in this prestudy are intended to represent. The main reason for this is that 2040 is the main scenario year for the base forecast.
- As suggested by the aim, the focus in terms of what impacts of AED that are considered, are on factors that directly or indirectly may affect transport demand. Other areas affected by AED, including those directly affected by changes in transport demand such as climate and environmental impacts, social and labor market impacts, macroeconomic impacts, etc. are not studied (other than when they are considered to have an influence on transport demand).
- The analysis focuses on AED technology, innovations and related services that are currently deployed or emerging and that have been described in previous literature. In other words, the study does not aim to predict the emergence of completely novel AED related technology or solutions but rather focuses on how further development, deployment and use of “known” emerging AED innovations could play out.

1.3 Disposition

The study’s theoretical framework is presented in chapter 2. Sections 2.1 and 2.2 describe drivers on freight and passenger demand, and are followed by a general framework for assessing transport demand on a system level in section 2.3. In chapter 3, the project process and methodologies used are introduced. Section 3.1 presents the general morphological analysis, the method and structure of the impact analysis are discussed in section 3.2, and section 3.3 describes the workshops that were conducted throughout the course of the project. Chapter 4 contains a morphological analysis of the 2040 transport system, and sections 4.1, 4.2 and 4.3 present general and selected trends of the technological fields automation, electrification and digitalization respectively. In chapter 5, the four scenarios are presented. Section 5.1 introduces Trafikverket’s base forecasts for freight and passenger transports and the base scenario constructed from these, while section 5.2 presents the three alternative scenarios. The impact analysis based on the morphological analysis and the theoretical framework is described in chapter 6. In section 6.1, examples of individual impacts of each parameter are described. This is followed by examples of combined impacts for each scenario in section 6.2, and furthermore comparisons between them in section 6.3. Finally, the conclusions drawn from the study are presented in chapter 7.

2. Theoretical framework and research approach

Section 2.1 and 2.2 outline theoretical concepts for understanding transport demand and the factors driving it for freight and passenger transport respectively. Section 2.3 presents the theoretical framework that is used in the prestudy. Section 2.4 presents and motivates the research approach.

2.1 Drivers of freight transport demand

The theoretical perspective in this study is that the demand for freight transport is a demand derived from the trade, logistics and transportation activities required to move goods from production sites to consumption sites (L. A. Tavasszy, Ruijgrok, and Davydenko 2012). Freight transport demand results from the interplay between activities and decisions within a set of interrelated systems that can be conceptualized as a set of interdependent layers (Lorant Tavasszy 2008) as illustrated by Figure 2.1. The dependencies result in that changes within one layer may affect decisions and activities in the adjacent layers. For instance, changes to the cost, quality or availability of transportation services may influence decisions in the logistic system. Therefore, understanding the impacts on transport demand of AED developments affecting any of these layers, requires that also the indirect effects resulting from changes in adjacent layers are accounted for.

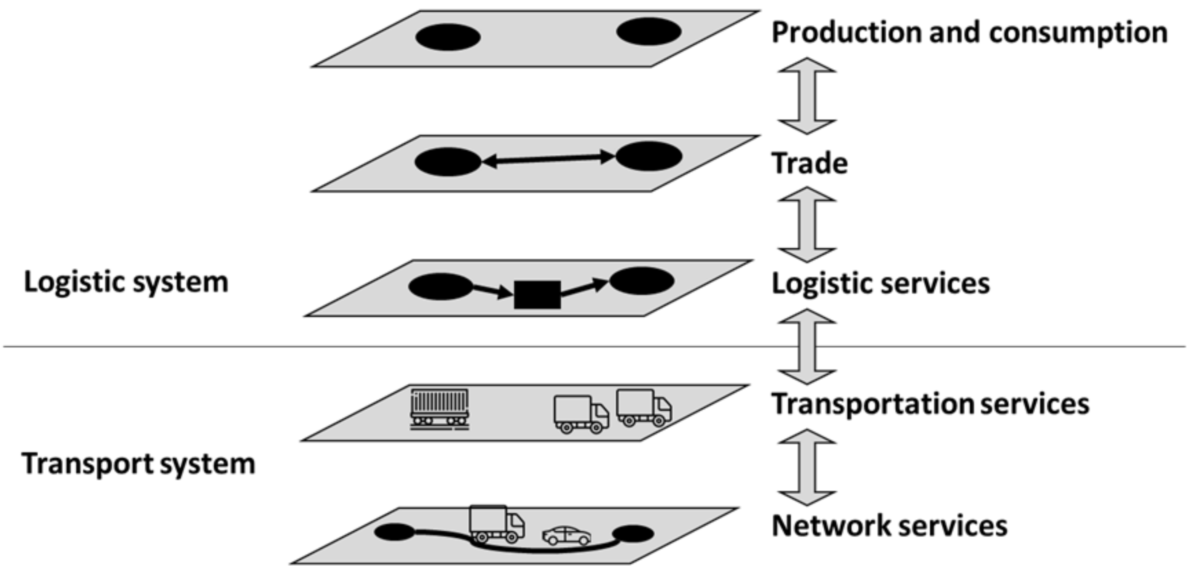

Figure 2.1. System layers in the logistic and freight transport system. Adapted by the authors based on Tavasszy (2008).

Freight transport can be understood as one function within a supply chain. As illustrated by Figure 2.2, the supply chain for a given product typically consists of multiple logistic chains (here loosely defined as the organization of material flows within one company) which may consist of one or several transport chains (see Section 2.3.2). In some situations it is relevant to analyze freight transport on the transport chain level, but it is important to acknowledge and understand the implications of transport chains as an integral part of a logistics chain and an overarching supply chain. Reis and Macário (2019) highlights that supply chains tend to be complex and there are interdependencies among the adjacent steps meaning that changes to one activity (e.g. one transport chain) will have effects upstream and downstream in the supply chain. Furthermore, in many supply chains, transport decisions tend to have a marginal focus and often, transport decisions are implicitly determined by product and market related decisions and requirements taken elsewhere in the supply chain (ibid).

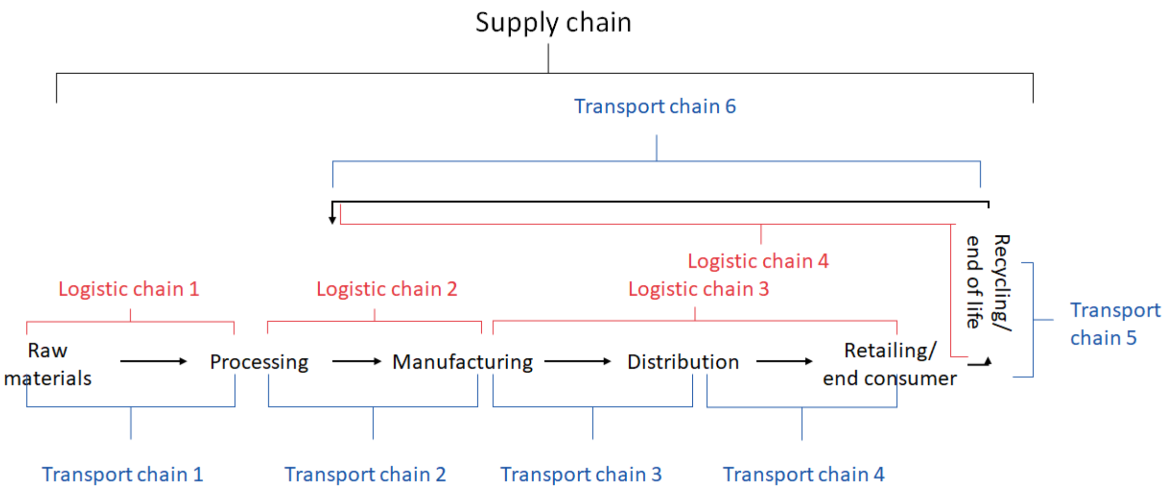

Figure 2.2. A generic supply chain containing multiple transport chains and logistic chains. Adapted from Reis and Macário (2019) with authors' modifications.

These systemic dependencies between the various system layers result in numerous mechanisms for how changes in freight transport demand may occur. van de Riet, et al. (2007) provide a framework of factors influencing freight transport demand and identify the following main drivers of freight demand.

1. GDP and consumer demand. Historically there has been a strong correlation between changes in GDP and TKM. In other words, GDP has been a strong predictor of freight transport demand. However, since the economic crisis in 2009, the relationship between GDP and TKM in Sweden has not been as strong as previously and, as Kågeson (2019) highlights, when the economy is developing towards a larger share of services rather than physical products, GDP and TKM can be expected to be further decoupled. The link between GDP and transport demand is primarily that GDP is an indicator of the consumer demand for products which is what actually drives the need

for freight transport. Three important aspects of consumer demand that affect transport demand are i) the consumed volume of consumption of different types of goods, ii) the variety of goods consumed, iii) the spatial distribution of consumption (e.g. population density) which influences transport distances.

2. Economic structure. The sectoral structure of the economy is an important determinant of freight demand and its constitution highly influences the relationship between GDP and freight volumes. Similarly, trade patterns, which is where different types of resources or goods are delivered to/sourced from, determine the spatial characteristics of freight flows. Similarly, the time routines of businesses and consumers, set temporal requirements on freight flows. Also, changes in communication technology and patterns (e.g. e-commerce) can have a substantial effect on freight demand by affecting purchasing and sourcing behaviour (for both companies and consumers), geographically enlarging markets and generating new requirements for traffic, e.g. by increasing the number of delivery trips.
3. Logistics system. The spatial organization of supply is one factor that influences transport distances. The location of some types of facilities are fixed (e.g. some types of raw material sites) while the location of other facilities in the supply chain is sensitive to economic pressures, although such decisions have significant inertia and tend to be made for relatively long time-horizons. Transport demand and freight transport requirements is furthermore affected by inventory management strategies and structures which influence decisions on shipment size and transport frequencies (Combes 2014). Also the characteristics of the broader supply chain strategy (e.g. demand driven production, the use of hub-spoke systems, etc.) are highly important, see e.g. Tavasszy et al. (2020).
4. Mode characteristics. The supply of freight transport in terms of infrastructure capacity, availability of modes, service quality, vehicle capacity, transport costs and transport times, are important factors primarily for the choice of transport mode. Also, freight transport demand is sensitive to generalized costs through a number of mechanisms, for instance through changing transport distance by affecting sourcing decisions or changing the demand for the product (although this effect is likely most often small) (G. de Jong et al. 2010).

The decisions determining freight transport demand are complex in the sense that they consist of many interrelated decisions taken by multiple decision makers that have different objectives, logics and time-horizons. Tavasszy and de Jong (2014) distinguish three types of freight-related decisions based on what market they are performed for and their time horizon. Decisions concerning decisions on production, consumption and trade of goods are typically made on long time horizons. These decisions concern plant locations, products, supplier choice, shipment sizes, etc.. Decisions for the inventory market which relates to the structure and organization of the inventory network such as warehouse and distribution center locations, inventory volumes, etc. are typically taken on medium term. Decisions for the transport market relating to transport organizations such as the selection of transport service, which determine transport mode, vehicle choice, scheduling, routing, etc. are decisions taken on short term.

A common way to conceptualize how the different system layers are interrelated is based on the notion of markets connecting the adjacent layers' supply and demand sides. For this study, a framework originally proposed by Wandel et al. (1992) is used as a starting point for the framework developed for this prestudy. In short, the framework by Wandel et al. (1992) separates three system layers: material flow (the movement of goods in the logistic system), transport flow (the movement of load units and vehicles in the transport system) and the infrastructure, with the transport market linking material flows with transport flow and the traffic market linking traffic flows with the infrastructure capacity, see Figure 2.3.

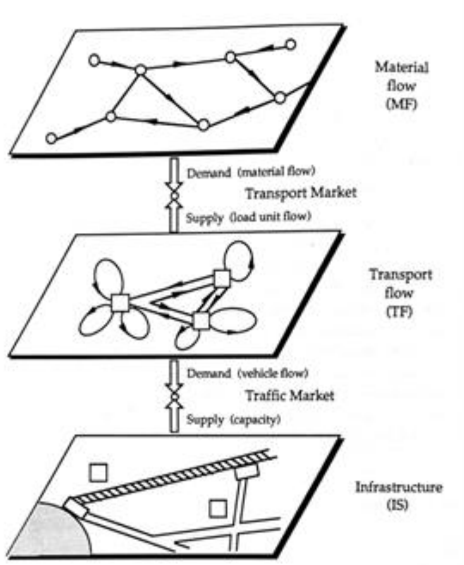

Figure 2.3. Three Layers Model of Freight Transport by Wandel et al. (1992).

2.2 Drivers of passenger transport demand

Passenger transport demand differs from that of freight as it is driven by another logic. A common approach to modelling it is using the Four Step Model, which is illustrated in Figure 2.4 and was adapted from (McNally 2008). The model is generally used by inserting data and calculating traffic flows in a specific area. Even though no such calculations were conducted in this project, the way it structures passenger transport demand generation and its outcome was deemed useful for the purpose of this study.

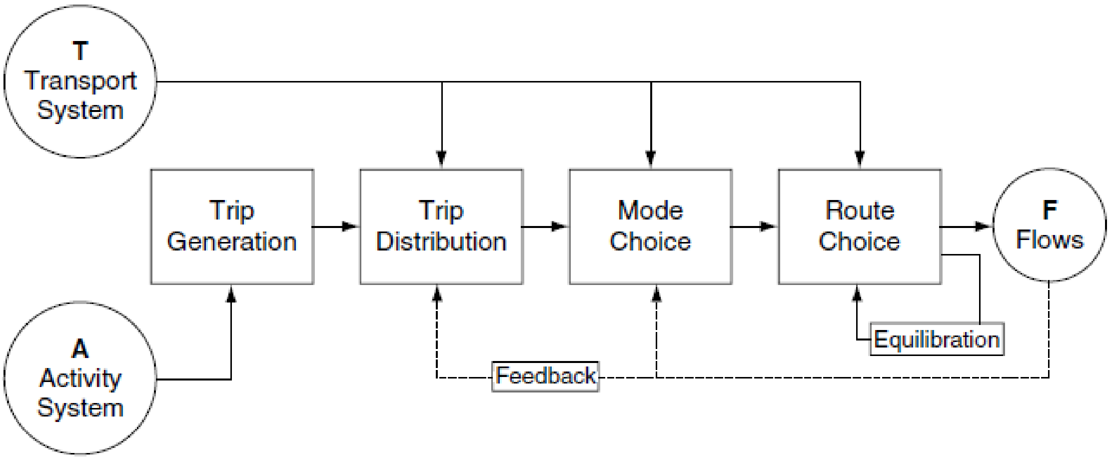

Figure 2.4. The Four Step Model, adapted from McNally (2008).

The transportation system (T) includes infrastructure and transport services, whereas the activity system (A) refers to spatial factors as well as demographic and economic activities. The beginning and end of a passenger trip is generally the household, and the household's needs and activities are what generates trips with a certain frequency. The trips are distributed based on a variety of factors such as generalized cost and time, leading to a certain modal distribution. The final step, route choice, represents which route that is selected to perform the generated trip, resulting in traffic flows (McNally 2008).

The drivers of passenger transport demand can be structured in a similar fashion as those for freight transport demand (G. C. de Jong and van de Riet 2008). Four metrics, in the form of choices, are used to evaluate how the drivers will affect transport demand. These include car ownership, activities and destinations, mode as well as time-of-day and routes. The drivers of demand are presented below.

1. Population characteristics. Demographic factors such as population size, age distribution and gender roles affect the transport demand. However, the foremost driver is identified as households' socioeconomic status. Socioeconomic status also directly affects other drivers, as well as car ownership and mode choice. Examples of other demographic drivers include education levels, labor participation and household sizes.
2. Spatial structure. Population density, location of activities and transport network integration are drivers included in this category. The density of the population affects average trip lengths as well as the location of activities and general integration with the

transport network. A higher density tends to lead to less private car ownership and more efficient public transport. Regarding the modal distribution, more densely populated areas see less car PKMs in favor of public transport or walking. The location of activities impact destination and mode choices, which in turn affect PKM and PKM per mode. Transport network integration primarily affects mode choice.

3. Economic structure. As with freight transport demand, passenger transport demand could be affected by new communication patterns such as the use of remote working, e-commerce services or other online activities. Time routines, which are causes of congestion, have experienced change as economies are becoming more service-oriented. The economic structure also is expected to impact time-of-day and route choices.
4. Mode characteristics. This category includes the availability of private and public modes, service characteristics, vehicle and infrastructure capacity and service characteristics, as well as travel costs and time. Car ownership, i.e. the availability of private modes, primarily influences mode choice but also affects the amount and length of trips.

2.3 A general framework for assessing transport demand

For this prestudy, a conceptual model that links the relationships between the activity & logistics system, transport system, transport market, infrastructure and traffic market and how these affect various transport demand parameters is used as a framework for the analysis, see Figure 2.5. The framework is created by combining elements from the existing frameworks by Wandel et al. (1992), van de Riet, et al. (2007) and de Jong and van de Riet (2008). The purpose of the framework is to enable a systematic discussion on how various AED developments may impact various system layers and to facilitate discussions on the direct and indirect effects of AED on different transport demand parameters for both passenger and freight transport. Focus is on the two first layers representing the activity & logistics system and the transport service layer as well as the interaction between those on the transport market since these determine transport volumes and modal distribution.

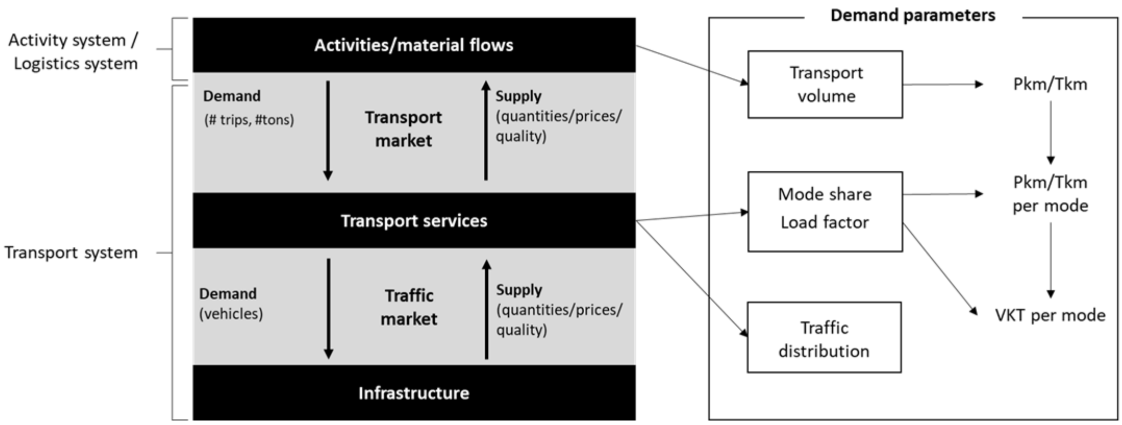

Figure 2.5. Conceptual model of the research framework adapted from Wandel et al. (1992), van de Riet, et al. (2007) and de Jong and van de Riet (2008)

2.3.1 Activities and material flows

The framework's top layer represents the need for people to perform activities or for companies to move materials and thus generate demand for transportation. In that sense, the demand for transportation is a derived demand resulting from these needs. For passenger transport, this demand arises from peoples' needs and desires to participate in activities which creates a demand for trips with associated temporal and spatial requirements (i.e. move from location a to b within a given time-window). Freight transport demand arises due to the need for companies to move materials in time and space between various facilities in the supply chain which conversely generate a demand for moving goods, as discussed in Section 2.1. The demand for activities and material flows is to a large extent driven by factors external to the transport system such as the technological and spatial structure of the economy and industry, trade patterns, land use systems, cultural and behavioral aspects, etc.. However, transport demand is sensitive to changes in transport supply since transport volumes, through several mechanisms, are sensitive to transport costs (see e.g. Litman (2019) and de Jong et al. (2010)). This means that AED can affect transport volumes both by directly affecting the activity and/or logistic systems (e.g. increasing the share of e-commerce) or indirectly by altering the transport supply (e.g. through changing generalized cost of transport).

2.3.2 Transport services

The transport services layer represents the different types of transport alternatives and constitutes the supply side of the transport market. For passenger transport, this includes both service provided by a transport provider (e.g. taxi, public transport, mobility services) and transport by privately owned means of transport such as private car, walking, biking, etc..

Freight transport

Freight transport can be categorized into four main transport modes, air, road rail and sea, which each has numerous sub-categories. A simple high-level categorization of modes and subcategories is provided in Figure 2.6 in which sub-categories primarily are separated based on shipment sizes or load units. There are important differences between transport modes related to geographical coverage (which is related to infrastructure availability), transport times, capacity, transport times, etc..

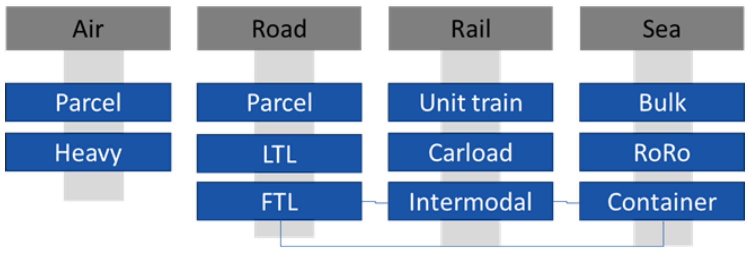

Figure 2.6. Overview of freight transport modes. Adapted from Rodrigue (2020).

The different transport modes tend to have different cost structures, as illustrated by Figure 2.7. Two basic cost components can be distinguished: fixed costs, which are independent of transport distance (e.g. loading/unloading of vehicles or vessels, terminal handling, etc., the intercept in Figure 2.7) and distance dependent costs (the slope in Figure 2.7). Typically, road transport has low fixed costs but high distance dependent costs while rail has higher fixed costs but lower distance dependent costs compared to road, and sea transport has the highest fixed costs but lowest distance dependent cost. This results in that different modes tend to be most competitive for certain transport distances, although it should be noted that this exercise is a crude simplification of real transport cost structures. Also, the same relationship between the modes is generally speaking present when it comes to volumes.

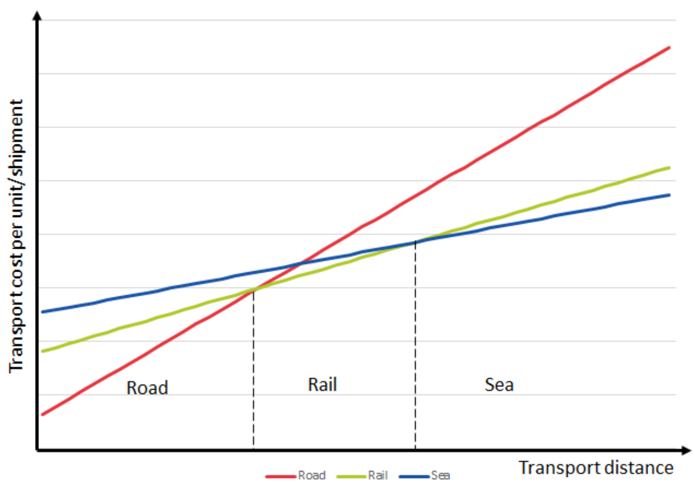

Figure 2.7. Schematic illustration of transport cost structures with respect to transport distance. Adapted from Rodrigue (2020).

Often, several transport modes, or different vehicles of the same mode, are combined for transporting a shipment from its origin (shipper) to its destination (receiver). Such a combination is called a transport chain. In the example provided by Figure 2.8, four stylized alternative transport options and their respective transport chains are illustrated.

- (1) Direct road (FTL=Full TruckLoad) is when a shipment is transported directly from its origin to its destination and the shipment size is rather well-matched with the vehicle capacity.
- (2) Road (LTL=Less than TruckLoad) is when several smaller shipments from similar origin locations to similar destination locations are transported collectively by a single truck. This is done to achieve cost reductions by having multiple transport buyers sharing capacity and costs. The shipments are picked up in sequence in the origin region and then delivered in sequence in the destination region, which adds costs and time compared to a direct road transport chain.
- (3) Consolidation-Distribution (parcel) is when many smaller shipments (parcels) are transported by utilizing a network of terminals that facilitates consolidation in the origin region and distribution within the destination region. Between the terminals, line-haul transport with large trucks is performed while the first- and last mile tours typically are performed by smaller vehicles.
- (4) Intermodal is when rail or sea is used to perform the main haul and road transport is used as a complement for the first and last mile between the origin/destination and the terminal which provides access to rail or sea transport.

Some origins/destinations also have direct access to the rail or sea networks (i.e. access to rail terminals or ports without the need for intermediate road transport) which is not illustrated here. In all the above examples, the truck driver may fulfil several important roles in addition to driving the truck (Flämig 2016). At the origin location, this could for example include performing or supervising loading, securing the load and managing shipping documents. During the transport the driver may need to perform vehicle inspections, customs formalities, etc.. At a terminal or destination location the driver may supervise or perform unloading, load returns, handle delivery confirmations, etc.. For (2), the non-driving tasks of the driver is typically of particular importance since many origins and destinations are served at the same trip, often under volatile conditions (e.g. stops being added or removed, time slots changed, etc.) and the shippers and receivers may not have available staff or equipment for performing these tasks.

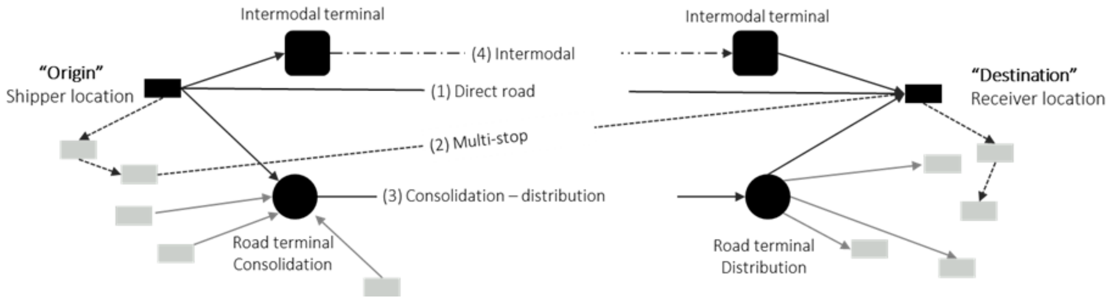

Figure 2.8. Schematic illustration of different transport options and transport chains, adapted from Engholm (2021)

As previously mentioned, adding transfers (between vehicle types as in (3) or between modes as in (4) in Figure 2.8) adds transport costs and transport time which is shown by Figure 2.9. Therefore, there is a tradeoff between adding costs and time for transfers and the reduced distance costs (also, see Figure 2.7). However, transport cost is just one out of several factors determining transport chain choice, which is further discussed in Section 2.3.3.

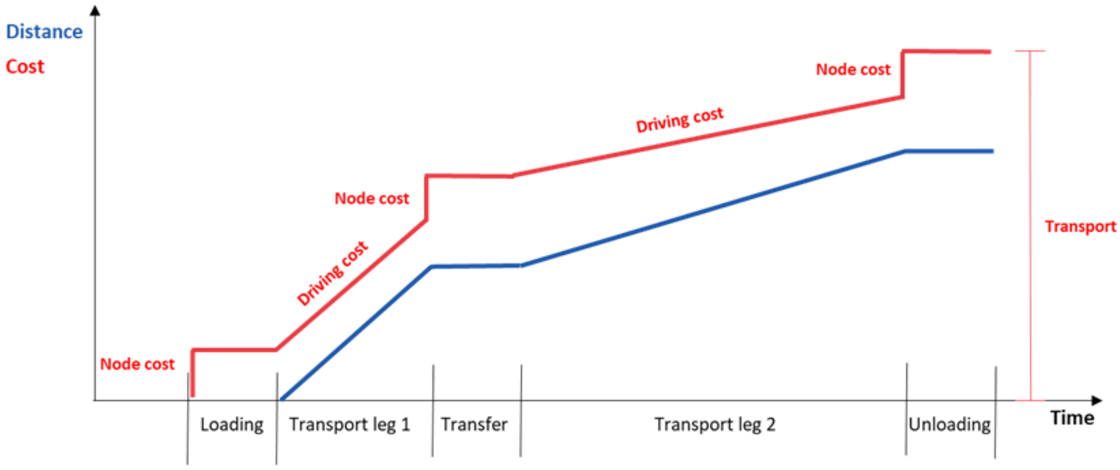

Figure 2.9. Example of transport costs and distance over time for a transport chain with two legs. Node costs refers to costs for loading, unloading and transfers (which for a given shipment are fixed with respect to transport distance). Adapted from G. de Jong and Baak (2020)

Passenger transport

A passenger looking to transport themselves between two locations can do so by 1) paying for an actual service such as public transport or taxi or 2) Using a privately owned vehicle such as a car or bike, or walking. While alternative 1) does not necessarily could be defined as a service, both options are considered in the *transport services* layer in this framework. The modes for passenger transport can be categorized in the same manner as those for freight, as illustrated in Figure 2.10. One significant difference is that while freight transport can concern many types of goods, passenger transport modes exclusively transport people.

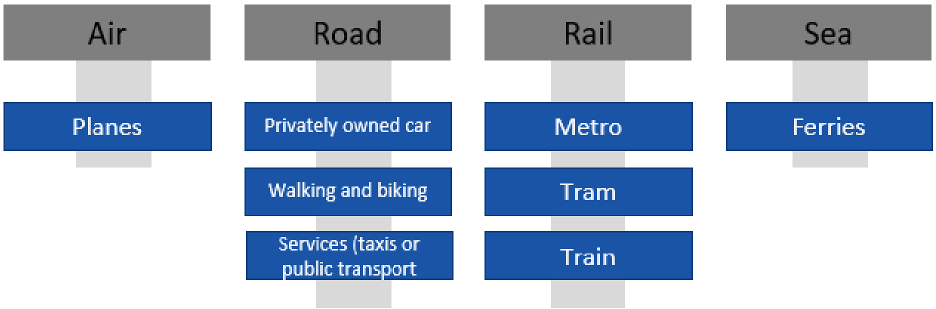

Figure 2.10. Overview of passenger transport modes considered in this study.

There are however different types of trips, which can be categorized based on a framework provided by Nelldal and Svalgård (2013) and illustrated in Table 2.1.

Table 2.1. Trip categorization framework adapted from (Nelldal and Svalgård 2013).

Type of trip	Frequency	Distance	Dominant private mode	Dominant public mode
Local	Daily	<10 km	Car, walking, biking	Bus, metro
Regional	Daily	<10 km	Car	Bus, train
Inter-regional	Non-daily	>10km	Car	Train

Firstly, trips can be of either a daily or non-daily frequency. For daily trips, time and budget are the main restrictions. Secondly, trips can be defined spatially as local, regional or inter-regional. Local trips are less than 10 km long, generally daily and mostly performed by car, public transport, walking and biking. Regional trips also tend to be daily and less than 10 kilometers long. Car is the most common private mode, while the most common public mode is bus or train. Finally, inter-regional trips are non-daily and longer than 10 kilometers. Car is the most common mode, and the most common public mode is train. The majority of the transport work in Sweden is done on a regional level (Nelldal and Svalgård 2013).

2.3.3 Transport market

As previously mentioned, the types of decisions, involved actors and decision mechanisms at the transport market differ substantially between passenger and freight transport.

Freight transport

Transport buyers select and purchase transport services at the transport market. In other words, the transport market is where the demand for transportation interacts with the supply of transport services. Even though the concept of “the (freight) transport market” is used in this prestudy, it should be noted that this does not imply that the transport market is a single, coherent marketplace. Rather, it is composed of several heterogeneous, partly overlapping, sub-markets serving different types of transport needs, commodity types, geographies, etc. The discussion in the following paragraphs is intended to introduce important general concepts and principles that are relevant for an overall understanding of decisions affecting transport demand and how AED may affect these decisions.

The transport buyer represents the demand side of the market and specifies the requirements for the transport service given its specific logistical context. The transport buyer can be either the company sending the goods (outbound transport) or receiving the goods (inbound transport) (Lammgård, Andersson, and Styrhe 2013). If, and to what degree transport and logistic services are outsourced and how complex those services are (i.e. whether various logistic functions are included) vary among transport buyers, sectors and industries (Hartmann, Birkel, and Kopyto 2021). The interactions between transport buyers and transport service providers on the freight transport market influences several transport and logistic decisions. One important decision is the selection of transport mode(s) which previously often has been understood as taken at the discretion of the transport buyer (De Jong 2008). Experimental economic research on the interaction between transport buyers and transport service providers suggests that mode and shipment size choices can be understood as a cooperative process meaning that it does not matter whom of these actors that actually make these decisions as the transport buyer will choose the bid best serving its interests (Jose Holguín-Veras et al. 2011).

The selection of transport mode (transport chain) is often the focus of transport policy interventions but, however, this decision is often times taken without much consideration (Lóránt Tavasszy and de Jong 2014) or it may not be much of a choice since there is only one mode being a feasible alternative (Sundin 2017). The process behind this decision, or lack thereof, can be understood by applying the framework provided by (Landborn, Nordberg, and Nelldal 1981) as it is summarized by (Lundberg 2006), which describes this decision process as being determined by restrictions, choice and inertia.

- **Restrictions** are physical (e.g. access to harbors or the rail network) or other forms of dimensioning customer requirements such as transport lead times or shipment sizes which may exclude certain transport options. The restrictions thus determine what options are feasible for the specific freight flow.

- **Choice** is when the transport buyer chooses between several feasible transport options which offer different levels of cost, quality, transport times, etc. This decision involves considering several trade offs, which are discussed in a later paragraph. However, many times the restrictions leave only one feasible option and it is important to consider that competition between transport modes only occurs when there is an overlap in availability, service quality and geographical coverage.
- **Inertia** are various forms of biases or lock-ins that lead to non-optimal transport decisions or delaying the choice of the optimal solution. In other words, inertia are the factors that explain why the theoretically best transport option is not chosen. For transport buyers, these these factors can be i) administrative - lock-ins to contracts that delays a different choice of transport service, ii) physical - lock-ins due to the physical properties of the logistics system, for instance, warehouses and inventory structures may be adjusted to a specific transport mode or iii) mental - lack of information, status quo bias or other mental lock-ins that prevents or delay changes. Note that inertia is not necessarily irrational, for instance, physical factors can mean that choosing a transport service that may not be optimal from a purely transport perspective may be more beneficial when also considering investments and operational aspects of upstream activities. Inertia can also be present for transport service providers, e.g. by not developing their service or adopting new technology. The likelihood for the presence of such inertia can be expected to be higher in sub-markets where there is a lack of competitive pressure.

There is a sizable empirical literature on the factors that influence decisions on the transport market, and in particular the choice of transport service and transport mode. A review of empirical studies examining European freight transport buyers' selection of transport services by Flodén et al. (2017) concludes that cost is the primary factor considered. However, this consideration is done only after it is ensured that the service meets requirements on transport quality (i.e. non-physical restrictions). Thereafter, price primarily determines the selection. A recent empirical study of the U.S. identifies transport price and reliability as the two most important factors determining mode choice (José Holguín-Veras et al. 2021). This study also highlights that, often, the selection of transport mode is determined by the receiver requesting a specific mode. Also, the receiver often specifies the shipment size which could impose restrictions on the mode choice.

Another important topic is how the decisions on the transport market for a given (hypothetical) situation can be predicted by using models. These models can be either aggregated (e.g. modeling the mode split within a complete region or nation as a continuous function of transport mode characteristics) or at a disaggregated level for a single transport buyer or a single freight flow. See Holguín Veras et al. (2021) for an overview of the literature on various types of models. A common approach for modeling the behaviour of individual transport buyers is to assume that they operate based on principles of inventory theory and to use the total logistic cost framework (Combes 2014; José Holguín-Veras et al. 2021). The principle is then that transport buyers seek to minimize total logistic costs through decisions on shipment size, the use of consolidation centres and terminals, transport chain choice (mode choice) and vehicle choice (G. de Jong and Ben-Akiva 2007). However, it should be noted that in reality, all firms do not necessarily make explicit tradeoffs between total logistic cost elements using an explicit cost model (Reis and Macário 2019). Nevertheless, this approach is useful for this prestudy as it provides a framework for discussing how changes in transport service supply due to AED can affect various components of the total logistic costs and in turn affect transport decisions and thus demand (assuming this model being a sufficient approximation of reality). Total logistic costs can be specified in numerous ways, but for the purpose of this prestudy, a simplified version of the formulation provided by Ben-Akiva and de Jong (2013) is sufficient, see Eq. 1.

$$G=O+T+D+Y+I+K+Z \quad \text{(Eq.1)}$$

G is the total logistic cost for a given transport flow (and a specific transport solution). O is order costs, T is transport costs (including both driving costs and node costs, i.e. costs for loading, unloading, transferring goods to/from/between vehicles or vessels, see Figure 2.9), D is cost for deterioration and damage of the goods during transit, Y is capital costs of goods during transit, I is inventory storage costs, K is capital costs of inventory and Z is stockout costs.

The various components of G are not independent, and the minimization of total logistic costs is therefore a tradeoff between these various cost components. This means that decisions on the freight transport market not only determine transport decisions (e.g. transport chain choice) but also logistic decisions (e.g. shipment size). One important trade off occurs when selecting shipment size, which indirectly determines frequency and is interrelated with mode and vehicle choice. Typically, transport costs, T, tend to decrease with increasing shipment size (due to economy of scale benefits with increasing vehicle sizes or being able to select a different transport mode with lower unit costs, e.g. rail instead of road). However, several other cost components, e.g. Y, I, K, and Z tend to increase with increasing shipment sizes and reduced frequency, partially due to that transport times tend to increase due to the use of slower transport modes and/or longer transport times due to transfers and terminal handling. The optimal shipment size is then the shipment size yielding the minimum of the sum of transport costs and other (relevant) logistic cost components , as illustrated by Figure 2.11. This means that if the transport cost curve is shifted downwards (at least for shipment sizes smaller than the current optimum), the optimal shipment size would decrease.

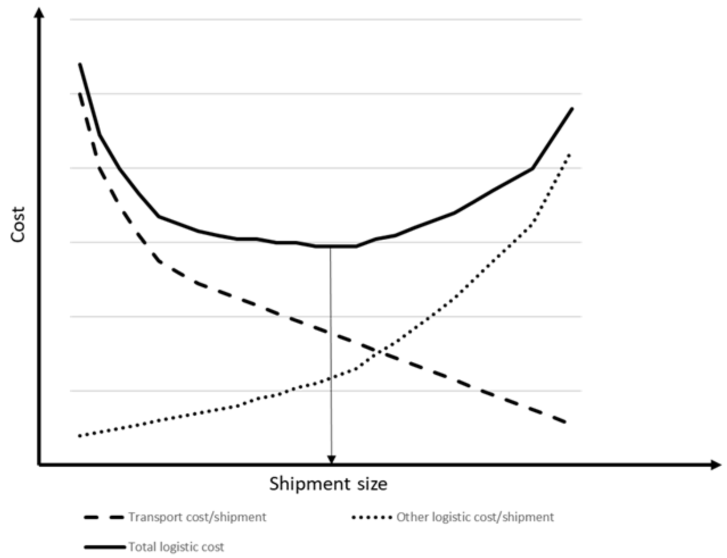

Figure 2.11. Schematic illustration of the relationship between transport cost, other logistic cost and shipment size selection.

A related trade-off is related to transport time, for which the concept of value of time is useful. Value of time is the marginal rate of substitution between money and transport time (G. de Jong 2021). This can be broken down into two components, one which is related to transport costs (longer travel times requires access to vehicles and drivers for a longer time) and one that is related to the cargo, which includes costs such as interest costs on capital during the time of transport, time-dependent value reduction of perishable goods and logistics related costs. The cargo related value of time is highly contextual for the characteristics of the particular goods, freight flow and supply chain, but typically, cargo value of time is positively correlated with high cargo value. The cargo value of time affects the choice of transport chain since minimizing total logistic costs G, requires the trade-off between a more costly but fast transport chain (i.e. increase T) and reductions in other cost components (e.g. Y, I, K which are time-dependent) to be considered. The higher the cargo value of time component is, the more valuable reductions in transport time is which favours transport chains with short transport times.

Passenger transport

Depending on availability, time constraints and budget, passengers can choose from and combine a variety of different transport services. As presented in Section 2.2, main decisions include choices of mode, what route to take and when, which activities and destinations that are feasible, as well as whether or not to own a private car (McNally 2008). While freight related transport decisions tend to be market-based, passenger transport decisions are commonly explained using psychological concepts and theories. One example is the theory of planned behavior (Klöckner and Friedrichsmeier 2011; Bamberg, Hunecke, and Blöbaum 2007; Rezvani, Jansson, and Bodin 2015), in which it is assumed that decisions are made based on intention, i.e. the combined advantages and disadvantages of performing an action. This intention is a result of three factors: attitudes, social norms and perceived behavioral control (Bamberg, Hunecke, and Blöbaum 2007). For the general framework used in this study, behavioral theories such as these will not be utilized, and passengers' transport decisions will first and foremost be regarded as an outcome of generalized cost minimization. Generalized cost for passenger transport can be defined as the total transport cost which is constituted by time and monetary costs, as well as factors relating to trip comfort (Trafikverket 2020a). An equation to describe the average generalized transport cost per kilometer was adapted from Koopmans et al. (2013):

$$C_{it}=PC_{it}+TT_{it}(VOT_{it}+VOR_{it}+DC_{it}) \text{ (Eq. 2)}$$

where C_{it} is the average generalized transport cost, PC_{it} is the direct cost per kilometer, TT_{ir} is the travel time in hours per kilometer, VOT_{it} is the value of time per hour, VOR_{it} is the value of unreliability per hour and DC_{it} is the inconvenience cost per hour.

In addition to costs, mode choice is also affected by geographical factors. On a local level, walking and biking is the most prevalent mode for smaller cities. The larger the city, the larger the utilization rate of public transport. However, the need to travel longer distances also leads to an increase in car use, with the exception of major cities since congestion and parking lead to more utilization of public transport. For trips on a regional level, the modal distribution is affected by the availability of transport services as well as the general quality of public transport. On an inter-regional level, trains or flights are predominant due to longer distances. The variations are also affected by availability, cost, quality and service. There are no significant regional differences in what type of activities that are performed. The majority of all transport work is done in leisure trips, followed by work-related trips (Nelldal and Svalgård 2013).

Finally, modes can either complement or compete with others. Complementing passenger transport modes tend to have different geographical markets and service levels. Where there is an overlap of these factors, competition could arise. In such competitions, cost relative to the service provided is the main determining factor for the modal distribution. When one mode becomes more beneficial than others in performing the same service, a modal shift could occur (Rodrigue 2020).

2.3.4 Infrastructure

The infrastructure layer represents the physical (e.g. road, rail, ports, terminals, charging stations etc.) and digital infrastructure (e.g. connectivity, data platforms, etc.) that enables the provision of transport services (e.g. by enabling the movement of vehicles and vessels). For this prestudy, the role of the infrastructure layer in relation to AED is primarily understood as a barrier or enabler for implementation of AED (see Tongur and Engwall (2017)). For instance, a rapid expansion of public charging stations may accelerate the uptake of electric vehicles while an insufficient supply can be a barrier for adoption. The available (or proposed) infrastructure could also be influential on what specific AED technologies and services that become developed and implemented and act as a technology shaping force. For instance, the electrification of heavy trucks may take different paths depending on whether large-scale investments in electric road systems along the public road network are done or not. Similarly, it can be assumed that the development of digital road infrastructure and connectivity can be influential on the capabilities, and design of automated driving systems as well as the service design of driverless vehicle services (Engholm et al. 2020). Also, the characteristics of the available digital infrastructure are important for what forms of cooperative driving systems and other connected vehicle solutions are feasible (Shladover 2018).

2.3.5 Traffic market

In the traffic market, infrastructure supply and the demand for traffic activity is matched. The traffic market consists of several markets, typically separated by mode (and with sub-markets within the modes) and the logics between the different markets vary substantially. In the AED context, the concept of a market between the infrastructure and transport service layer should also be extended to markets for connectivity capacity, data, access to charging infrastructure, etc. which can be expected to be of growing importance.

2.3.6 Demand parameters

For this prestudy, transport demand is assessed from a set of interrelated demand parameters (see Figure 2.5). Transport volume is the demand for transport activity which can be measured in (total) TKM for freight transport or PKM for passenger transport. This demand is derived from the activity and logistic systems but can be indirectly affected due to changed transport supply. The decisions on the transport market and the organization of transport services determine the mode share and load factors which results in transport- and traffic activity per mode which is measured in TKM/PKM and VKT per mode. The decisions on the traffic market in combination with the organization of transport services determine the traffic distribution on the networks in time and space.

2.3.7 Demand impact mechanisms

Based on the conceptual framework, a set of generic mechanisms through which AED may affect transport demand can be outlined. These are named Demand Impact Mechanisms (DIM) 1 through 6.

- **DIM1** AED directly affects behaviors and patterns in the logistics or activity system and thereby affects transport volume.
- **DIM2** affects the supply of transport services e.g. through changed (generalized) cost structures of existing transport alternatives (e.g. EVs vs. ICEs) or by enabling new services that may compete with or complement the existing alternatives (e.g. MaaS vs. public transport). This could change the transport market decisions for some agents and thereby result in new transport patterns (e.g. mode choice, vehicle choice, route choice, etc.).
- **DIM3** indirectly affects behaviors or patterns in the logistics or activity system resulting from (2) by reducing generalized transport costs. This could lead to e.g. changed localization decisions, changed inventory networks, origin choices or supply chain strategies and thereby effects on transport volume.
- **DIM4** affects the performance and/or logic of the transport market, e.g. by reducing transaction costs and enabling a better matching of supply/demand based on more accurate and up-to-date market information. This can be interpreted as a reduction of inertia (see Section 2.3.3).
- **DIM5** affects the traffic market by enabling more efficient and dynamic forms of matching of supply and demand for infrastructure capacity (e.g. more dynamic train planning, dynamic congestion charges, etc.). This could result in better utilization of infrastructure and increase the supply of infrastructure (or reduce the need for infrastructure investments) and indirectly affect transport services and thus transport demand.
- **DIM6** can affect the performance, or utilization of infrastructure, e.g. by cooperative driving, predictive maintenance, etc.. This could affect the supply of infrastructure and indirectly affect transport services and thus transport demand.

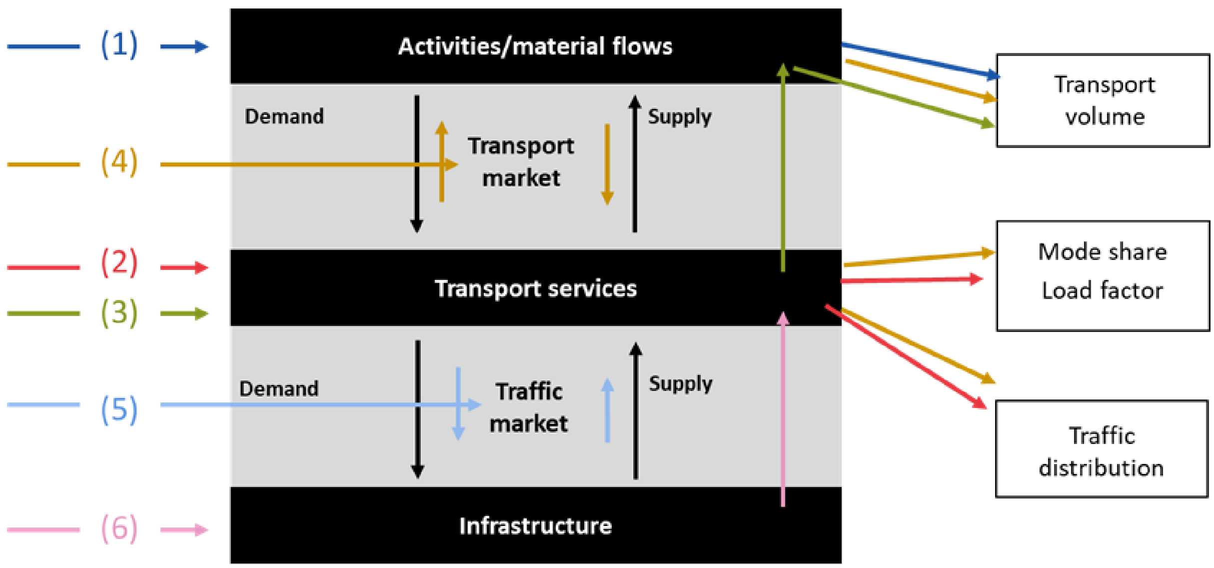

Figure 2.12. Overview of generic demand impact mechanisms for AED.

3. Process and methodology

In this section, the project process and the methodologies used are described. In order to capture system impacts from automation, electrification, and digitalization on the 2040 transport system, several methods were combined, as illustrated by Figure 3.1. The first stage in the project was to identify relevant trends and technologies, as well formulating the problem definition. This was done through a literature review and the first workshop. The findings were then integrated into a general morphological analysis (GMA), in which a morphological box with several parameters and attributes was designed. The selection of these parameters and attributes delimited the scope of the analysis further than what is stated in the scope of the study (see Section 1.2). The second workshop was held in this stage to validate the morphological box. As the next step in the process, a scenario mapping was conducted. Four scenarios, of which three were based on Pernestål et al. (2021) and one on the base forecasts for freight and passenger transport (Wikström 2020; Sachse and Almkvist 2020), were mapped into the morphological box. Finally, an impact analysis was conducted based on the theoretical framework and the morphological analysis. The analysis included the assessment of potential separate impacts for each trend or technology, combined impacts in the different scenarios, and a comparison of demand impacts between scenarios. The remainder of this section presents the full methodology.

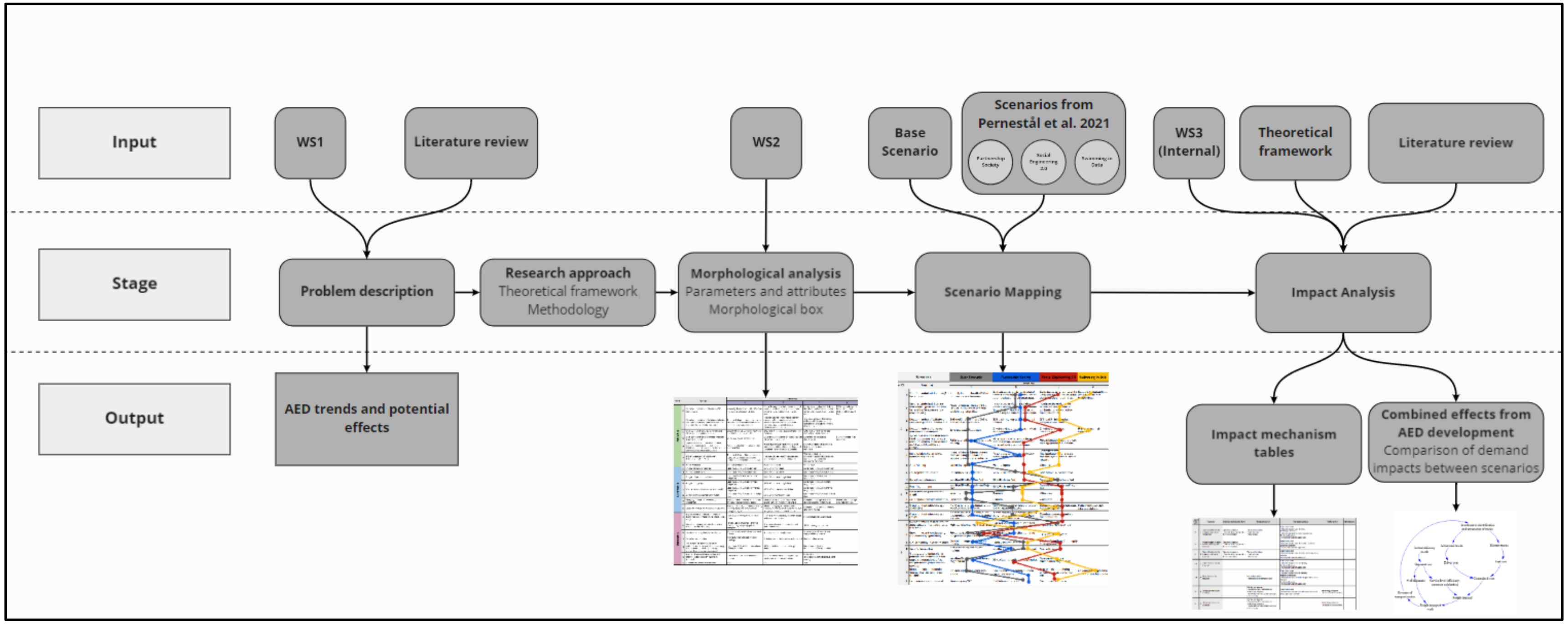

Figure 3.1. Illustration of project process.

3.1 General morphological analysis

One possible method for approaching sociotechnical uncertainties in a structured manner while maintaining a holistic perspective is through a general morphological analysis (GMA), an iterative method developed by astrophysicist Fritz Zwicky in the 1940s (Álvarez and Ritchey 2015). In this study, relevant knowledge and experience was found in the scientific literature and through performing a workshop with experts from the Swedish Transport Administration. The remainder of this section will describe how the GMA was conducted.

3.1.1 Morphological box

In a morphological box, relevant aspects are represented as parameters that are assigned attributes (Álvarez and Ritchey 2015). An example of a morphological box is provided in Figure 3.2. A given parameter could have any number of attributes. However, the attributes need to be mutually exclusive.

Parameter A	Attribute A1	Attribute A2	Attribute A3	...	Attribute An
Parameter B	Attribute B1	Attribute B2			
Parameter C	Attribute C1	Attribute C2	Attribute C3	...	Attribute Cn

Figure 3.2. Structure of a morphological box.

3.1.2 Scenario mapping

Technological forecasting and investigating future scenarios are common applications for GMAs (Álvarez and Ritchey 2015). To represent scenarios in the morphological box, relevant attributes are marked and combined. They illustrate the condition of the studied system at a certain time. As mentioned previously, all attributes are mutually exclusive, which means that only one attribute in each parameter can be marked for a given scenario. Figure 3.3 provides an example of how a scenario mapping is represented in a morphological box.

Parameter A	Attribute A1	Attribute A2	Attribute A3	...	Attribute An
Parameter B	Attribute B1	Attribute B2			
Parameter C	Attribute C1	Attribute C2	Attribute C3	...	Attribute Cn

Figure 3.3. Example of a scenario represented by attributes A3, B1 and C3 in the morphological box.

3.2 Impact analysis

The aim of the impact analysis was to answer the study's research questions based on the theoretical framework and identified AED trends. It was structured in three stages, where the first was to map the impacts from each individual parameter of the morphological box in an impact mechanism table. This was done through the project's second literature review, as well as drawing conclusions based on the theoretical framework. Impacts were categorized according to the general framework presented in section 2.3. The second step involved identifying and investigating the combined effects of AED parameters for all the scenarios and assessing how the combined impacts could affect drivers of freight and passenger transport demand. Some examples are utilized here to clarify the impacts and causal relationships, which are presented in the form of causal loop diagrams (CLDs). Finally, the last step was to compare demand impacts between different scenarios.

3.3 Workshops

Three workshops were conducted during the course of the project. The aim of the first workshop was to facilitate trends found in the initial literature review, and the participants included experts from the Swedish Transport Administration. The results from the workshop were then analyzed by the authors and integrated into the morphological box along with parameters and attributes. The morphological box was presented to the Transport Administration expert group during the second workshop session. The output was analyzed to improve the morphological box parameters and attributes. The third workshop was held internally in the project group, with the purpose of investigating how system impacts could be represented in the conceptual CLD. The workshops are summarized in Table 3.1.

Table 3.1. Summary of workshops.

	# Participants	Organization	Purpose of workshop
Workshop 1	13	Trafikverket-ITRL	Problem formulation
Workshop 2	13	Trafikverket-ITRL	Validation of the morphological box
Workshop 3	7	Trafikverket-ITRL	Mapping the conceptual CLD with the morphological box parameters in different scenarios

4. Morphological analysis of the 2040 transportation system

A GMA was used to investigate the 2040 transportation system in Sweden, as it provides a structured method of describing the many uncertainties and possible outcomes of development and implementation of AED technologies.

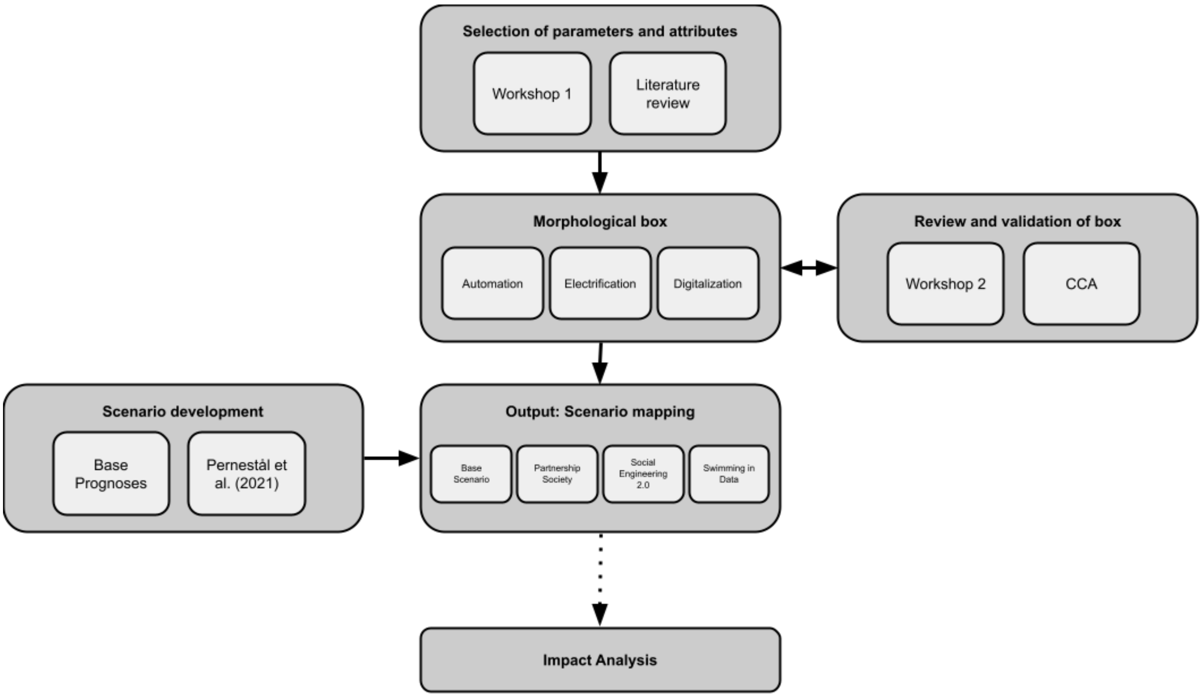

Figure 4.1. Overview of the GMA process.

The parameters and attributes included in the morphological box were selected through a literature review as well as workshops with expert groups from the Swedish Transport Administration. In order to decrease the number of parameters, they were limited to technical aspects as well as general trends that were deemed to have a direct impact on AED development. Attributes were also chosen based on previous research and workshops. When possible, results or assumptions from the base forecasts were used to formulate the attributes. The remainder of this chapter will present the parameters and attributes that constitute the morphological box. In order to structure the system, the morphological box was categorized in the three technological fields: automation, electrification and digitalization. In cases where a parameter related to more than one of the fields, it was placed in the most relevant category. A holistic analysis is performed in chapter 6.

4.1 Automation

Within automation, the following four areas are considered.

1. Automated road vehicles for freight transport (heavy trucks and light freight vehicles) and passenger transport (cars, buses and public transport vehicles)
2. Automated train operations
3. Automated marine transport
4. Automation within various types of “nodes” in the transport system (e.g. terminals and ports)

The following subsections give an overview of these areas and motivate the selection and specification of parameters and attributes for the morphological analysis.

4.1.1 Automated road vehicles

There have been ongoing development efforts for automated road vehicles (AVs) since the 1950s (Shladover 2018) although both progress and investments have increased rapidly during the last decade (Chan 2017). There is a wide range of AV applications and operating concepts which differ both in terms of when they can be expected to be mature and available on the market and the impacts they may have on the transport system (Shladover 2018). The organization SAE International categorizes automated driving systems in six levels, ranging from level 0 (no automation) to 5 (full driving automation) (SAE International 2018). This categorization will be used in the remainder of this report to separate AVs with different capabilities.

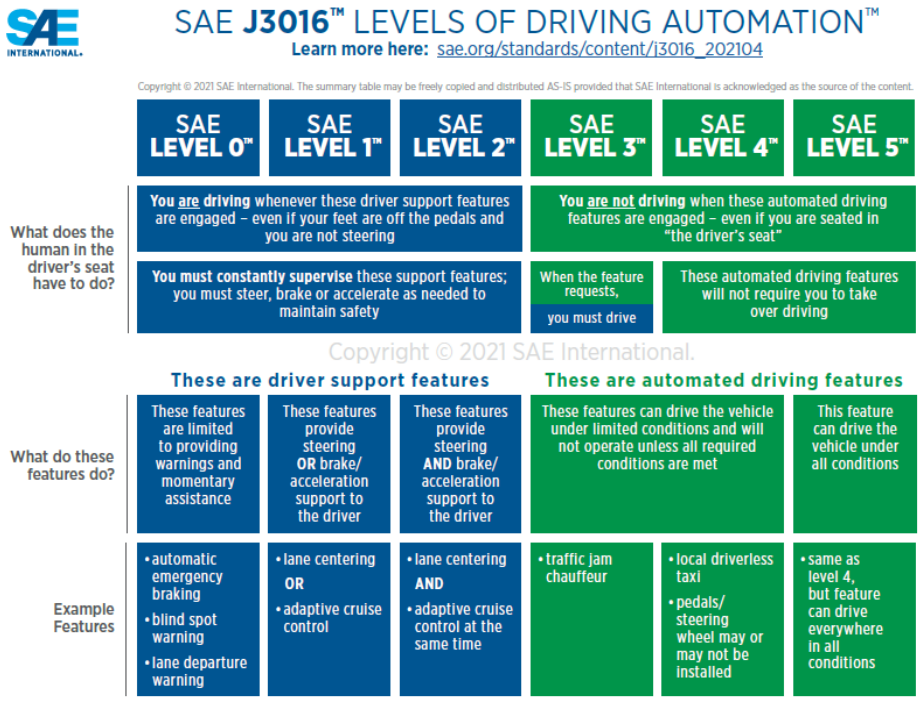

Figure 4.2. SAE levels of driving automation (SAE International 2021).

Based on the SAE framework, an overarching terminology for automated road vehicles for separating three broad classes of vehicles is outlined and used throughout the remainder of this report.

- Automated vehicle (AV) is a vehicle equipped with an automated driving system at SAE level 3-5.
- Self driving vehicle (SDV) is a vehicle equipped with an automated driving system at SAE level 3-4 which in some situations is capable of handling the full driving task but that occasionally requires a human driver to perform the driving task, either when outside the operational design domain (SAE level 3 and 4), or as a fall back to the automated driving system (SAE level 3).
- A driverless vehicle is a vehicle equipped with an automated driving system at SAE level 4-5 which is designed to be operated without any human driver in the vehicle. This means that a driverless vehicle at SAE level 4 is only operated within its operating design domain.

Automated vehicle systems have been used for logistics and freight transport since at least the 1950s, primarily in the form of vehicles relying on infrastructure guidance within terminals, harbors and warehouses (Flämig 2016). During the last years, significant progress for developing automated road freight vehicles operating without such guidance on public roads have been made (Chan 2017; Daduna 2020) and increasing attention has been given to the freight sector as a promising area for deployment and value creation of automated vehicles

(Ackerman 2021; Zarif et al. 2021). For the morphological analysis, the area of automated road freight vehicles is broken down into two segments, heavy trucks (>3.5 tonnes) and light trucks (<3.5 tonnes) as these typically are associated with different transport tasks and markets with highly different logics. Automation of heavy trucks is covered by Parameter A and light trucks by Parameter B.

Regarding heavy trucks, the focus in the morphological analysis is primarily on describing the plausible development for vehicles equipped with automated driving systems at SAE-levels 4 to 5 (i.e. SDVs and driverless vehicles) since these are expected to have a potential for substantial effects on the transport system compared to vehicles at lower automation levels (Shladover 2018; Müller and Voigtländer 2019). However, it should be noted that automation functions at lower SAE levels can provide many benefits, for instance by reducing accident rates (Teoh 2021). Several publications suggests that self-driving and driverless trucks could bring several benefits for actors in the transport industry such as reduced ownership and operating costs (Wadud 2017; Ghandriz et al. 2020; Engholm, Pernestål, and Kristoffersson 2020), alleviate driver shortage (Kristoffersson and Pernestål Brenden 2018; Müller and Voigtländer 2019), reduce lead times (Sindi and Woodman 2021; Chen and Lu 2020) and increase vehicle utilization rates (Chottani et al. 2018) which could provide competitive advantages. On the other hand there are several challenges and barriers for an introduction such as technological challenges, investment costs, need for regulatory alignment, public acceptance, need for infrastructure modification, labor union resistance etc. (Kristoffersson and Pernestål Brenden 2018; Sindi and Woodman 2021; ITF 2017; Engholm et al. 2020).

During recent years, many pilot projects with self-driving and driverless trucks have been announced and performed around the world (Zarif et al. 2021), some of which are in Sweden (see Table 4.1). In 2019, Scania announced a driverless mining truck (Scania 2019) and the year after a partnership with the U.S. based automated driving system company TUSimple was announced (Traton group 2020). Volvo launched a concept vehicle in the form of a driverless, battery-electric tractor trailer truck in 2018 (AB Volvo 2019) and offer driverless mining and quarry trucks (AB Volvo 2020). Since 2021, Volvo has been in a partnership with the American automated driving system company Aurora stating to primarily target the US market (AB Volvo 2021). The Swedish company Einride, founded in 2016, has launched a cabless, battery electric rigid truck (Einride 2020) and has been running several pilot projects.

Table 4.1. Examples of pilot projects with self-driving or driverless trucks in Sweden. The table may not be exhaustive.

Company	Project	Status	Source
Volvo	Short distance hub-hub with cabless, battery-electric tractor trailer in Gothenburg	Announced, not started	(AB Volvo 2019)
Scania	Highway driving between Södertälje and Jönköping with Scania truck equipped with TUSimple automated driving system.	Announced, to start in 2021	(Scania 2021)
Einride	Several projects with driverless battery-electric trucks, partly operating on public road. Supported by remote driving.	Ongoing	(Einride 2018; 2021)

Internationally, there are, in addition to many incumbent truck OEMs, several companies working towards achieving self-driving or driverless trucks such as Aurora[1], Embark[2], Gatik[3], Kodiak[4], Locomotion[5], Plus[6], TUSimple[7], Waymo[8]. Several of these have partnered with incumbent OEMs (Bishop 2020).

It is challenging to provide forecasts on when various types of self-driving or driverless trucks will be available and how fast the market adoption within different use cases will be. However, most certainly, driverless trucks will will be restricted to certain types of use cases (i.e. <SAE L.5), at least during the coming decade. Also, the market uptake of driverless trucks, once available on the market, could take several decades (Simpson et al. 2019). The roadmaps by Ertrac (2019) provide an indication on what automated driving features could be expected within different application domains during the coming decade (see Figure 4.3). The roadmap suggests that SDVs and/or driverless trucks will first be available for operations within confined areas (e.g. ports, terminals, fenced off industrial sites), then for short-distance hub-hub applications (repetitive transport flows in peripheral areas, for instance between factories and ports), and then on open roads (e.g. highways and rural roads) and for certain routes in urban areas. In the open roads segment, particularly long-distance highway driving is by many players in the AV industry seen as the most feasible and attractive initial application and this is the current focus of many AV companies (Engström et al. 2019). Note that driverless trucks at SAE level 5 are not expected to become available during the time-horizon of the roadmap, i.e. 2030.

1 https://aurora.tech/
2 https://embarktrucks.com/
3 https://gatik.ai/
4 https://kodiak.ai/
5 https://locomation.ai/
6 https://plus.ai/
7 https://www.tusimple.com/
8 https://waymo.com/waymo-via/

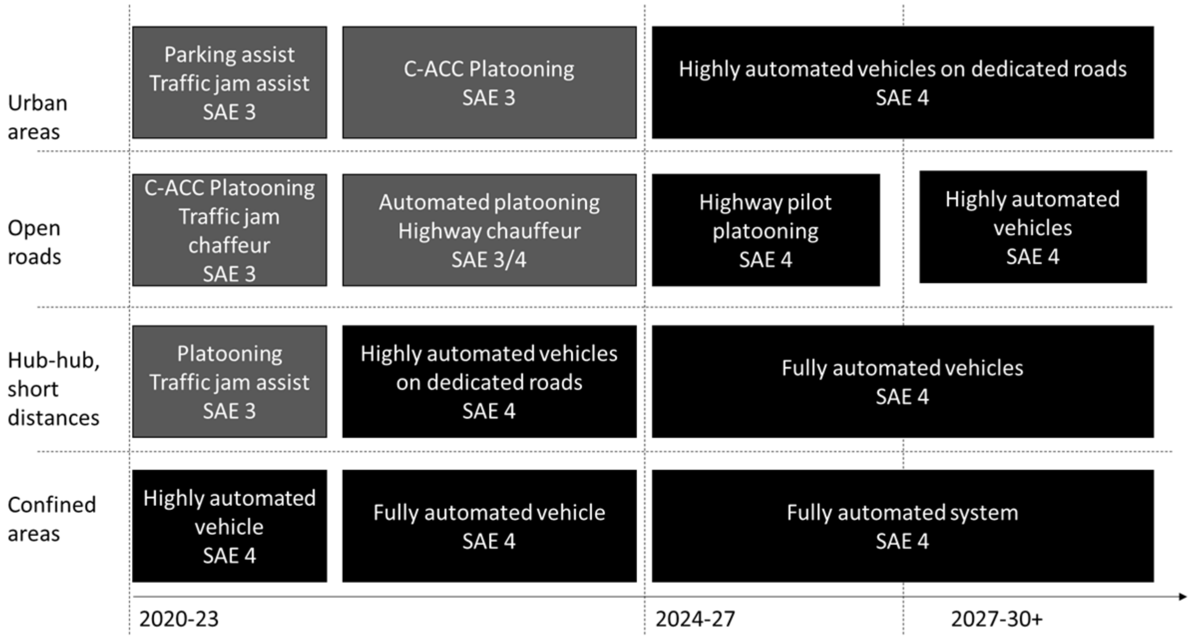

Figure 4.3. Summary of the roadmaps by Ertrac (2019) for automated vehicle deployment in different transport segments. Authors' own figure edits and interpretation of SAE levels.

As previously suggested, it is expected that the development and introduction of driverless trucks will be a gradual process as automated driving system capabilities (i.e. their operating design domain) improve over time meaning that these trucks can be used for a growing set of transport use cases. This means that self-driving and driverless trucks will, at least initially, be a complement to manually driven trucks (and other modes) rather than a direct substitute to manually driven trucks (which could be the case for driverless trucks at SAE level 5) (Engholm 2021; Monios and Bergqvist 2019). Another highly important aspect of driverless truck operations and services is the lack of a driver to perform the non-driving related tasks truck drivers often perform which are essential and/or value adding for road transport services (e.g. loading/unloading, document handling, load securing and surveillance) (Flämig 2016). Therefore, it can be expected that the costs for alternative solutions for managing these tasks (e.g. other personnel taking over tasks, automation, digitalization, etc.) is an important determinant for what use cases are feasible. Given the current developments in the market and what has been discussed in the literature, some examples on initial use cases for driverless trucks operating on public roads can be outlined. This is not a comprehensive mapping of all plausible use cases and covers far from all current (or future) types of road freight transport applications. Also, the descriptions of the use cases and the associated logistics and transport processes are highly simplified. In Figure 4.4, an overview of some of the discussed use cases is provided.

Short distance dedicated flows. A use case that may be feasible in the short to mid-term is for short distance (up to a few kilometers), fixed routes between two facilities within an existing supply, see Figure 4.4a. Typically, these routes are within industrial areas in the urban periphery and are characterized by a repetitive transport assignment between two fixed locations and standardized processes for loading, unloading, and goods handling. Thereby, any adjustments in these processes due to that no driver is present to assist can be tailored for the specific case. One example is to transport goods between two closely located warehouses or industrial facilities. Another example is a short distance pre- or post-haulage leg in a multimodal transport chain, for instance between a factory or logistics terminal to/from a harbor or rail terminal.

Another type of use case is driverless trucks operating long-distance transport flows between fixed hubs where the majority of the route is driven on major roads, for instance, highways at which the ODD allows for automated driving to be performed. This type of use case could include both dedicated routes (i.e. between two specific hubs) and networks of multiple hubs. Four specific use cases of this type are outlined below, and they differ either based on the type of transport flow or how the first and last sections of the transport flow (i.e. to and from the major road) are dealt with.

The dedicated flows use case is for transport flows between two fixed facilities (with proximity to the highway road network (see Viscelli 2018) and where the driverless trucks are capable of automated driving along the whole route. This could for instance be within an industrial supply chain with large volumes of raw materials being delivered from an extraction site to a production facility in a repetitive fashion. In these cases, often the first and last stretch to the highway network is within industrial areas with rather controlled traffic environments. Thereby, it is conceivable that DL-trucks could be developed with an operational design domain tailored for the specific route. Another option is to use remote operations for parts of the route. This use case can be seen as a long-distance version of the short distance dedicated flow use case.

Middle mile in hub & spoke networks is when DL-trucks are used for the line-haul within logistics networks of hub-and-spoke character, for instance, within parcel networks, see Figure 4.4b. In such networks, shipments from multiple senders are sorted and consolidated at a logistics terminal (a hub) and then transported in larger trucks to the receiving terminals in the network. Then de-consolidation is performed, and distribution is performed by other (smaller) trucks. In this use case, DL-trucks replace the consolidated “middle-mile” line-haul transport between the terminals while still the feeder and distribution transport to and from these hubs are performed by smaller MD-trucks.

Hub-hub with truck transfer is when DL-trucks with an operating design domain that enables highway driving are used to tow trailers in a network of transfer hubs located close to highways on-/off ramps, see Figure 4.4c. MD-truck tows the trailer from the good's origin/destination to/from the transfer terminal where the trailer is transferred between the MD-truck and DL-truck. This use case could apply to both FTL and LTL shipments. Since the trailer swap process would not be needed for direct MD-truck transport, this use case generates additional costs for trailer transfers that must be compensated for by cost savings during the DL-truck transport leg. Therefore, the cost competitiveness of this operating model compared to a direct MD-truck transport chain hinges on whether the cost savings achieved during the DL-truck leg are greater than the additional costs for the required transfers. Important factors favoring the cost competitiveness include e.g. transfer terminals located near the origin and destination for the goods (Monios and Bergqvist 2019), a "long-enough" DL-truck leg to compensate for the additional transfer, and a cost-effective transfer process.

Middle-mile with remote operations is a variant of the above use case when the first and last part of the trip that is outside of the DL-truck ODD is performed by using remote operations (Zhao, Darwish, and Pernestål 2020), see Figure 4.4d. This eliminates the need for the trailer transfer process but relies on access to high-performance connectivity and is associated with technology and labor costs. Also, this use case is less feasible for LTL transport.

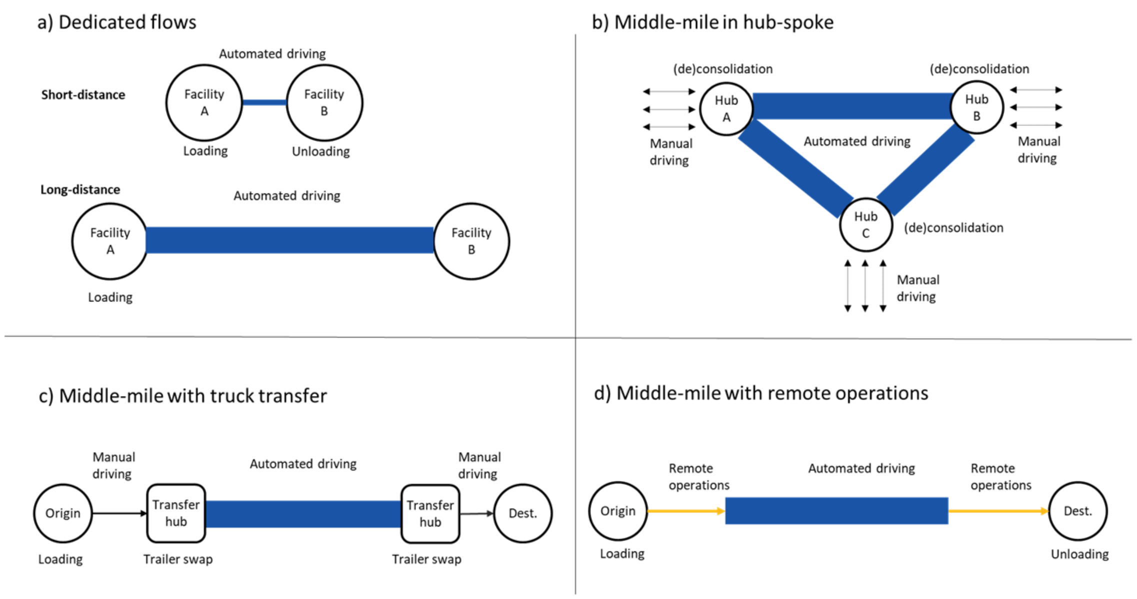

Figure 4.4. Schematic overview of examples of driverless truck use cases for SAE level 4 trucks. The wide lines represent major roads or highways and the thin lines access roads or urban roads. Blue color indicates the part of the route within the ODD, yellow lines where remote operations are required, and black lines where manual driving is required.

The attributes for this parameter are on whether driverless trucks have been implemented at scale, and if so, what type of driverless truck operating model is most common. One is denoted as the hub-to-hub model, which corresponds to the use cases a, b and c in Figure 4.4, which will likely be one of the first practically feasible operating models for early generations of driverless trucks that are capable of operating between terminals located nearby larger roads, i.e. SAE level 4 (Viscelli 2018). This operating model is represented by attribute A2 (only on highways) and A3 (hub-to-hub trucks can operate on all roads, but only between hubs/terminals). This is in stark contrast to attribute A4 in which driverless trucks are assumed to be able to operate the full road network unrestricted (i.e. SAE level 5).

Light trucks and urban distribution

There is a wide range of proposed automated vehicle concepts for light trucks and other types of vehicles for last-mile distribution in urban and suburban settings. Many of these concepts are targeting the growing demand for e-commerce, package deliveries and other deliveries to end consumers (Toy et al. 2020). Two primary categories can be separated, automated light trucks or vans operating on the roadway and sidewalk robots which are not operating on the roadway. In the former category, one example is the U.S. company Nuro[9] that has developed a driverless vehicle for end consumer deliveries, in which the delivery process is fully automated and the end customer picks up the goods from the vehicle by using a digital customer interface (Ferguson 2020). It has also been significant development in the latter category of sidewalk robots with companies such as Starship[10], Robby[11], KiwiBot[12] aiming to commercialize the technology. There may be various operating concepts for sidewalk delivery robots. For instance, they could be used for last-mile deliveries from a distribution center, to deliver food from restaurants, or to perform package deliveries within a campus area. One concept for package deliveries that has gained attention is to operate a fleet of sidewalk robots from a “mothership” van (Jennings and Figliozzi 2019). The van is loaded with sidewalk robots and a set of parcels at a distribution center and is then driven to an area where the sidewalk robots are unloaded from the van and perform the parcel deliveries.

Passenger vehicles

Based on recent development in the vehicle industry, (Doll et al. 2020) discuss development of passenger AVs in the near future. Around 2020, vehicles with SAE level 3 or 4 features had been announced by a multitude of actors. According to these, level 3 vehicles are expected to have been deployed by 2025 and before 2030 the first level 4 vehicles are expected to be on the roads. There are however barriers to passenger AV implementation. These include high

[9] https://www.nuro.ai/
[10] https://www.starship.xyz/
[11] https://robby.io/
[12] https://www.kiwibot.com/

investment costs and consumers' willingness to adopt the technology. Finally, there is also a considerable skepticism among consumers towards adopting fully driverless vehicles (Doll et al. 2020). The implementation of AVs with higher SAE levels (e.g. 4 or 5) could both replace or complement current transport services and lead to new organizational structures in the mobility industry (Soteropoulos, Berger, and Ciari 2019). Potential positive effects include a more efficient land use which contributes to more livable cities (e.g. through improved conditions for biking and walking), new mobility options for certain groups such as youths and the elderly, as well as a reduction in the road vehicle fleet. However, there are possible negative rebound effects as a consequence of the decreased value of time, generalized and marginal costs. These potentially include increases in GHG emissions, pollution and congestion. In order to combat these negative effects, policy measures are needed (Pernestål et al. 2020).

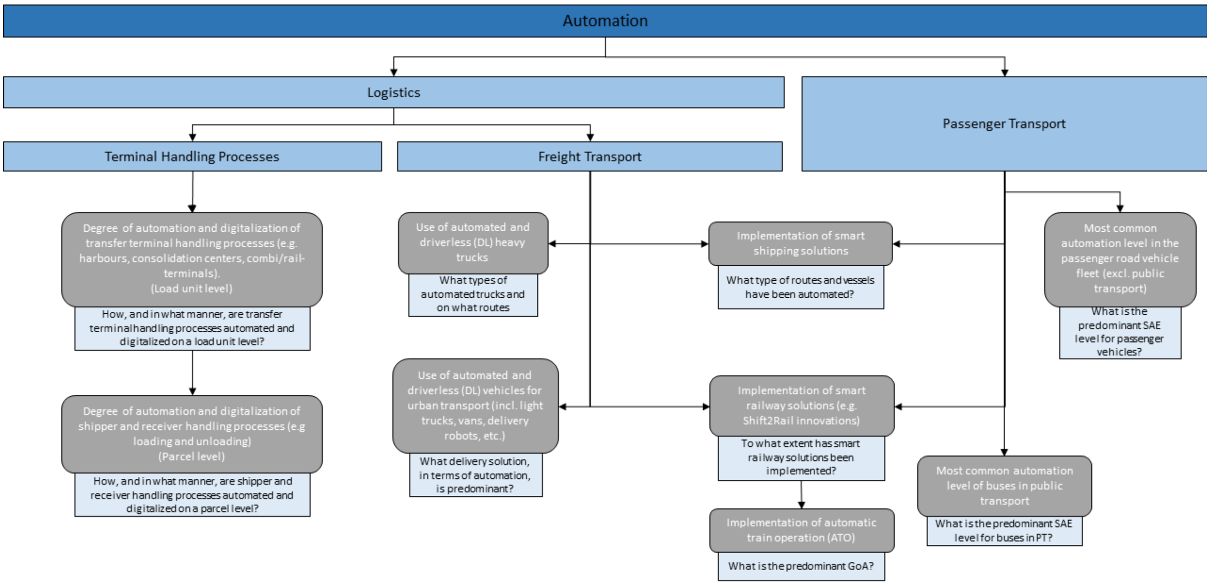

Figure 4.5. Main themes and parameters regarding automation considered in the GMA.

4.2.2 Automation in rail, marine and terminal processes

While high-level automation still is a novelty in road transportation, automated systems are well integrated in other modes. Automatic train operation (ATO) could contribute to a more punctual, effective and robust rail network (Jansson 2020). Similarly to SAE levels, rail automation is measured by grades of automation (GoA) from GoA 1 (no automation) to GoA 4 (full automation) (Shift2Rail.org 2019). Even though higher GoAs are uncommon for long-distance rail transports, many of the world's metro systems are already fully automated. (Jansson 2020). Air transport relies on automation technology for deployment of civil and military unmanned aerial vehicles (UAVs) such as drones, and for autopilot systems in airplanes (Flämig 2016). In the marine sector, smart shipping connects ports and ships to enhance the decision-making process for different stakeholders to reduce costs, improve efficiency with fewer ecological footprints. Smart waterways, smart ports, smart ships, and maritime intelligence could be considered as the four primary domains of the smart shipping system (Xiao, Chen, and McNeil 2021).

In the freight sector, automation is not only relevant for the vehicles performing goods transport. It can also contribute to increased efficiency in logistic chain nodes such as terminals, warehouses and harbors. It was in this area that automated vehicles were first introduced, in the shape of automated guided transport (AGT) and automated guided vehicles (AGVs) (Flämig 2016). Bell (2021) summarizes the current development and future prospects of automation within container ports. Although several container ports around the world have invested significant capital in the automated cranes, AGVs and other automation technology, the adoption of automation has so far been rather slow. However, going forward, it is expected that investments in container port automation will increase and currently, technology solutions are emerging in which crane operations, horizontal movement of containers as well as planning and optimization of storage and retrieval are automated along with automated document handling and communication with upstream and downstream activities. Furthermore, Bell (2021) highlights that container port automation is strongly synergistic with both digitalization and electrification.

The parameters and attributes related to automation technology are presented in Figure 4.5. They could be regarded as belonging to two fields, passenger transport and logistics. The latter category contains parameters concerning terminal handling processes as well as freight transportation. In addition, Table 4.2 demonstrates the selected parameters, attributes as well motivations for each.

Table 4.2. Parameters and attributes concerning automation in the morphological box, along with motivations for why they were included.

<table>
<tr><th colspan="2">Automation parameters</th></tr>
<tr><th colspan="2">Parameter A: Use of automated and driverless (DL) heavy trucks</th></tr>
<tr><td>A1: Manually driven trucks with ADAS on highways and in urban areas.</td><td rowspan="4">Automated driving is highly attractive for road freight transport due to economic reasons and there are several use cases which are technologically feasible in a short and mid-term perspective. The development and pace of AV introduction may differ significantly between various types of transport areas. The attributes are intended to describe a set of development stages: A1) Driverless trucks have not reached any substantial market penetration, although lower levels of automation are widely deployed. A2) Driverless trucks are used for hub-to-hub applications (see Figure 4.4b and 4.4c) in a limited set of transport corridors complemented with manual truck transport for other parts of the network. There is an initial deployment of driverless trucks also for urban traffic. A3) Same as A2 but driverless trucks are capable of operating the whole non-urban road network between hubs. A4) driverless trucks at SAE level 5 are available and have had a substantial penetration across the whole truck fleet and all transport markets.</td></tr>
<tr><td>A2: DL trucks operating hub-hub on a set of corridors on the highway network, and on certain distribution tours in urban areas.</td></tr>
<tr><td>A3: DL trucks operating hub-hub on the whole road network, and on certain distribution tours in urban areas.</td></tr>
<tr><td>A4: DL trucks widespread in the whole truck fleet for all transport types.</td></tr>
<tr><th colspan="2">Parameter B: Use of automated and driverless (DL) vehicles for urban transport (incl. light trucks, vans, delivery robots, etc.)</th></tr>
<tr><td>B1: To a small degree - manually driven vehicles (in combination with other solutions, e.g. cargo bikes)</td><td rowspan="3">Urban B2C delivery operations present completely different operational challenges and development dynamics compared to other forms of road transport and are therefore treated separately to heavy trucks. There is a large array of different innovations of automated and driverless vehicles in this space (incl. light trucks, vans and sidewalk delivery robots) and large uncertainties in how fast the development can go and what solutions will be in use. The parameters are intended to reflect the market penetration of automated or driverless light vehicles.</td></tr>
<tr><td>B2: To some degree - Automated delivery vehicles with human service staff onboard (in combination with other solutions, e.g. cargo bikes) is a commonly used solution</td></tr>
<tr><td>B3:To a large degree - driverless delivery vehicles dominate with a highly automated delivery service</td></tr>
<tr><th colspan="2">Parameter C: Most common automation level in the passenger road vehicle fleet (excl. public transport)</th></tr>
<tr><td>C1: SAE level <3</td><td>The technological development of automated driving for private cars could well follow a linear trajectory from</td></tr>
</table>

C2: SAE level 3 (conditional automation)	ADAS, to automated vehicles to driverless vehicles (i.e. without a steering wheel). There are significant uncertainties in when various development stages will become available, what the technology costs will be and what the willingness to pay for this technology will be for different groups. The attributes for the parameter were set as the most common SAE level in the passenger road vehicle fleet.
C3: SAE level 4 (highway autopilot cars)	
C4: SAE level 5 (fully DL everywhere)	
Parameter D: Most common automation level of buses in public transport	
D1: SAE level <3 (driverless buses not common)	The uncertainties surrounding automated buses in public transport resemble those for private vehicles. The attributes for the parameter were therefore set as the most common SAE level of deployed buses.
D2: SAE level 3 (Conditional automation with a driver on board that can take over if necessary)	
D3: SAE level 4 (DL on dedicated infrastructure)	
D4: SAE level 5 (Fully DL in all conditions)	
Parameter E: Implementation of smart railway solutions excluding ATO (e.g. Shift2Rail innovations)	
E1: To a small degree	There are large efforts to introduce technical innovations to improve rail transportation. One example is the Shift2Rail program administered by the EU, which promotes rail related innovation (Shift2Rail.org 2021). The performance of the rail freight system is highly related to the efficiency of terminal handling and similar processes, and needs to be understood from a multimodal perspective. Due to the broad nature of smart railway technologies, the attributes were set as their implementation grade. A larger implementation grade implies a more attractive and competitive rail sector.
E2: To some degree	
E3: To a large degree	
Parameter F: Implementation of automatic train operation (ATO)	
F1: GoA 1 most common	Automated train operations (ATO) is an example of a smart railway technology. The introduction of ATO in the rail network could lead to increased punctuality, effectiveness and robustness as well as cost reductions (Jansson 2020). Grades of Automation (GoA) are used to measure train automation, ranging from GoA 1 (no
F2: GoA 2 most common	

F3: GoA 3 most common	automation) to GoA 4 (full automation) (Shift2Rail.org 2019). In the morphological box, the attributes were set as the most common GoA level of deployed trains.
F4: GoA 4 most common	
Parameter G: Implementation of smart shipping solutions	
G1: To a small degree	Smart shipping encompasses all technology-based autonomous operations of ships and vessels, ranging from onboard technologies to ports and waterways design. A ship can operate autonomously based on accurate and real-time data, and the crew can make better decisions. It could improve the competitiveness, security and sustainability of the maritime industry (Government of Netherlands 2019).
G2: To some degree	
G3: To a large degree	
Parameter H: Degree of automation and digitalization of intermodal terminal handling processes. (Load unit level)	
H1: Partly automated and digitalized	There are two system levels of terminal handling processes which have been considered in this parameter and the following one. First, intermodal terminal handling processes, e.g., harbours, consolidation centers, combi/rail-terminals, international modals, containers, road-rail, and second, shipper and receiver handling processes (parcel itself), e.g., loading/unloading, last-mile delivery. Intermodal terminals, as the fundamental component of intermodal transports, could decrease cost, energy consumption, and environmental pollution and improve the quality of services (Krstić et al. 2019)
H2: Fully automated and digitalized in larger terminals. Load and container handling partly automated.	
H3: Fully automated and digitalized	
Parameter I: Degree of automation and digitalization of shipper and receiver handling processes (e.g loading and unloading), including warehouses, cross-docking and distribution centers (Parcel level)	
I1: Partly automated and digitalized	In this system level, shipper and receiver handling processes including warehouse operations, cross-docking, and distribution centers have been evaluated. Intelligent automated systems, such as intelligent hardware, robots, and 3D visual perception, enhance the automation level of the whole logistical procedure. Besides, Loading and unloading is a critical component that determines the efficiency of the system (Shen et al. 2019)
I2: Highly automated and digitalized processes at a set of shipping and receiving facilities	
I3: Highly automated and digitalized processes at a majority of shipping and receiving facilities	

4.2 Electrification

Electrification of the transportation system would lead to less dependence on fossil fuels and provide benefits in other areas such as public health (Khalili et al. 2019). There are different types of electric vehicles (EVs). Battery electric vehicles (BEVs) are typically powered by lithium-ion batteries whereas plug-in hybrid electric vehicles (PHEVs) can be driven both by electricity and conventional fuels. In this study, only BEVs are considered as it is assumed that all internal combustion engine vehicles (ICEVs) and conventional fuels will have been phased out by 2040. BEVs can be charged in a variety of ways. E-roads provide charging while vehicles are moving and are expected to contribute significantly to the electrification of heavy duty road vehicles. Charging stations require vehicles to be stationary while charging, but their implementation is more flexible and less costly (Trafikverket 2021). From a transport system perspective, only the coverage of charging infrastructure was deemed relevant and not what type of charging that is supplied. An often mentioned alternative to BEVs is biofuel, which could contribute to a fast decarbonization of the vehicle fleet. However, dependency of biofuels could have direct negative impacts such as food shortages and deforestation as a result of large-scale biomass production (Zhang and Fujimori 2020). Therefore, biofuel is in this study considered as a first step on the road to a fossil-free and electric vehicle fleet.

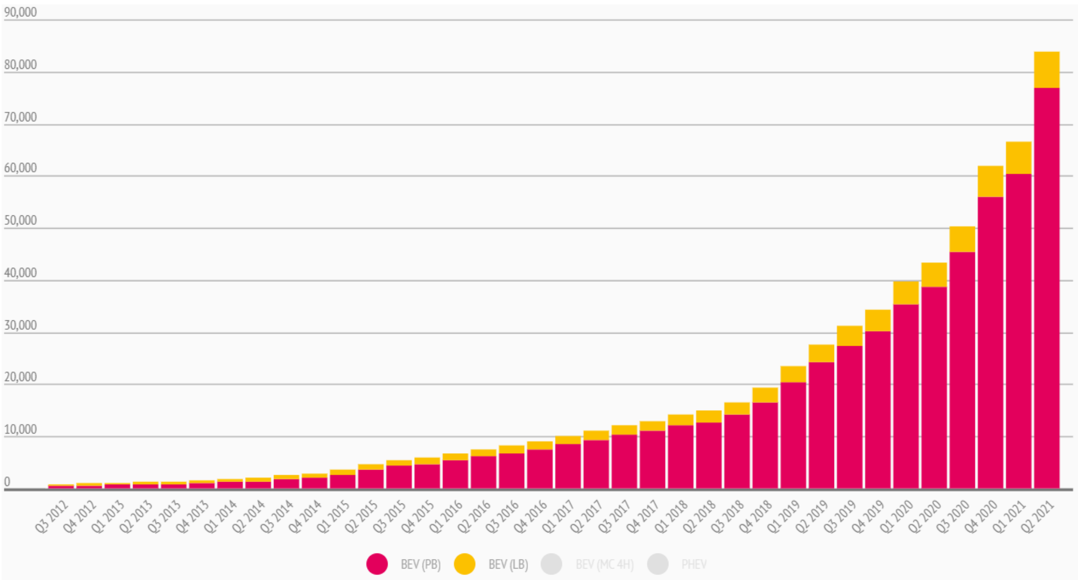

Figure 4.6. Adoption of battery electric passenger cars (red) and light trucks (yellow) in Sweden during the time period 2012 and 2021 (Power Circle 2021b).

As seen in Figure 4.6, EV adoption has been gaining momentum since the early 2010s. In 2020, 70,000 BEV passenger cars were in use (Power Circle 2021a). While there were around 10,000 public charging stations in Sweden, about 90,000 are required in 2030 if the forecasted

2.5 million passenger EVs (Andersson and Kulin 2019) are to be accomodated (Power Circle 2021c). Regarding road freight transport, mostly light duty vehicles (LDVs) have been electrified. However, several electric heavy trucks have been launched or announced (Volvo Trucks 2021; Scania Group 2020). The adoption barriers are similar to those for passenger cars, but as trucks are larger and heavier more energy is needed and larger batteries are subsequently required (Nicolaides, Cebon, and Miles 2018). Swedish railways are electrified to a large extent (80%) (Trafikverket 2019). However, in marine transport mostly short distance passenger ferries are fully electrified, whereas ships used for longer routes and freight transportation tend to rely on hybrid or diesel electric energy (Borgh et al. 2018). Finally, fully electric airplanes are currently able to operate short routes with a small amount of passengers, as seen in Norway (Reimers 2018).

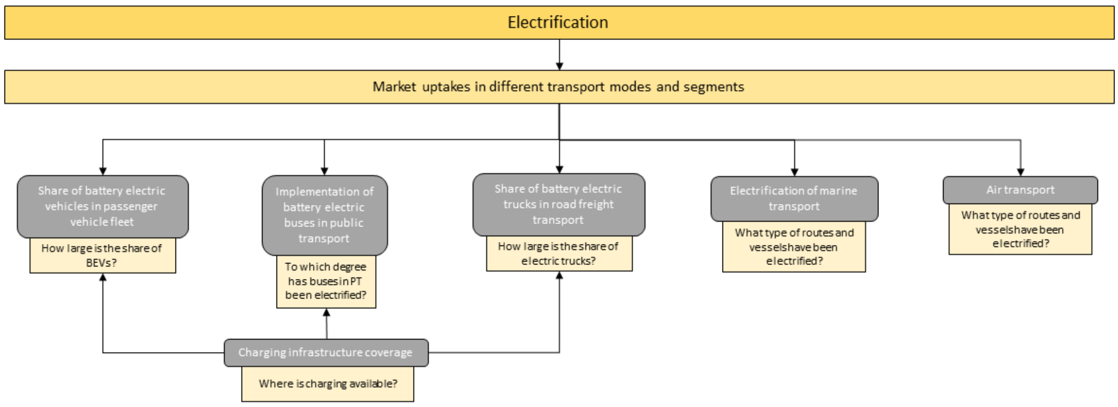

Figure 4.7. Main theme and parameters regarding electrification considered in the GMA.

There are a variety of possible system impacts as a result of electrification. The investment cost, i.e. the purchasing price, of BEVs have historically been higher than that of ICEVs. The operating cost is however lower (Rezvani, Jansson, and Bodin 2015), which could create incentives for private, corporate and public actors to adopt the technology. There are also attitudinal factors to consider, as those who are environmentally conscientious could prefer electrified mobility or transport services (Rezvani, Jansson, and Bodin 2015). This could in turn lead to changes in mobility preferences and the modal distribution. In addition to the high investment cost there are several other barriers for BEV adoption. A large portion of investments in electrification are focused on the development of lithium-ion batteries (Holland-Letz et al. 2021). While batteries have experienced a rapid improvement during the recent decade (Emilsson and Dahllöf 2019), “range anxiety” is still a common concern among adopters (Egbue and Long 2012). Furthermore, production of BEVs and lithium-ion batteries is energy intensive (Emilsson and Dahllöf 2019). For distribution road vehicles, the GHG emissions during the production phase are almost double those for ICEVs. However, the life cycle emissions of BEVs are lower than ICEVs (Burul and Algesten, n.d.).

As discussed previously, the electrification technologies considered in this report include BEVs in all modes as well as charging infrastructure. Figure 4.7. presented the main theme and parameters related to the electrification category. Besides, in Table 4.3 the parameters are presented along with their respective attributes, most of which concerns the market uptake and implementation grade of the considered electrification technologies.

Table 4.3. Parameters and attributes concerning electrification in the morphological box, along with motivations for why they were included.

Electrification parameters	
Parameter J: Share of battery electric vehicles in passenger vehicle fleet	
J1: Less than 40 %	Since the system effects of BEVs largely depend on the total amount in the system, the attributes were decided as the share of the car fleet that is battery electric, based on an assumption in the most recent base forecast that 38 % of all private vehicles will be electric by 2040 (Trafikverket 2020b).
J2: Around 40 %	
J3: Around 70 %	
J4: More than 70 %	
Parameter K: Implementation of battery electric buses in public transport	
K1: To a small degree	In the base forecast, one assumption is that all city buses and 20 % of long distance buses will be fully electric by 2040 (Trafikverket 2020b). However, as the parameter covers all buses, the parameters were set as degrees of implementation ranging from small to large.
K2: To some degree	
K3: To a large degree	
Parameter L: Share of battery electric trucks in road freight transport	
L1: Less than 10 %	This parameter encompasses trucks used for both urban and long-distance road freight transports, even though the challenges and opportunities vary for the two sectors. The attributes were decided in accordance with the base forecast, where it is assumed that around 10 % of all trucks will be electrified by 2040 (Scenarioverktyg).
L2: Around 10 %	
L3: Around 30 %	
L4: More than 30 %	
Parameter M: Electrification of marine transport	

M1: To a small degree: short distance ropax ferries (e.g. Swe-Den) electrified	Marine and air transportation are currently only electrified to a small extent. The attributes of these parameters were set as the degree of electrification ranging from small to large, including some use cases as examples.
M2: To some degree	
M3: To a large degree	
Parameter N: Electrification of air transport	
N1: To a small degree	Marine and air transportation are currently only electrified to a small extent. The attributes of these parameters were set as the degree of electrification ranging from small to large, including some use cases as examples.
N2: To some degree: a non-negligible share of domestic, regional traffic fully electrified	
N3: To a large degree: a substantial share of domestic, regional traffic fully electrified and a non-negligible share of medium distance traffic is electrified	
Parameter O: Charging infrastructure coverage for passenger vehicles	
O1: Mainly at home (private houses) and on select places in urban areas	Charging infrastructure is crucial for both passenger and freight BEV implementation. For passenger vehicles, the parameter's attributes range from private and some public charging stations, to full nation-wide coverage similar to the gas stations of today. As charging infrastructure for freight vehicles is expected to be organized differently, a separate parameter with more appropriate attributes was added.
O2: Most urban areas (incl. "apartment areas") and on important highways	
O3: Complete coverage in urban areas and along larger roads	
O4: Nation-wide coverage (like gas stations)	
Parameter P: Charging infrastructure coverage for freight transport	
P1: Mainly at "home", at terminals, during loading/unloading of the vehicle, during the night	Charging infrastructure is crucial for both passenger and freight BEV implementation. For passenger vehicles, the parameter's attributes range from private and some public charging stations, to full nation-wide coverage

P2: "Home" charging + common with charging along some routes during the day using a public/open infrastructure	similar to the gas stations of today. As charging infrastructure for freight vehicles is expected to be organized differently, a separate parameter with more appropriate attributes was added.
P3: Complete coverage at terminals and along routes	

4.3 Digitalization

Digitalization can be defined as “an integration of digital technologies into everyday life by the digitization of everything that can be digitized” (Encyclopedia of Information Science and Technology, Fourth Edition). Using the term "digitalization" instead of "digital" suggests that the transition is continuous with no apparent beginning or end (Hagberg, Sundstrom, and Egels-Zandén 2016). In the transport sector, digitalization can enhance the connectivity, efficiency, reliability, and sustainability of the entire system. Digital technologies can, therefore, profoundly affect the movement of people and goods (Noussan and Tagliapietra 2020) and thus have the potential to affect individuals, communities and entire nations (Leviäkangas 2016).

There are several important characteristics of digitalization trends that should be considered. First of all, connectivity is a fundamental prerequisite for all digitalization technologies, particularly for AV applications (Shladover 2018). Digitalization through connectivity enables vertical (supplier to customer) and horizontal (between competitors and partners) integration along the supply chain (Kayikci 2018). Besides, collecting accurate, reliable and timely data, and access to information are essential for transport decision-making and planning (Moschovou, Vlahogianni, and Rentziou 2019). Additionally, the combination of connectivity and access to information creates a great potential to improve shared mobility. Shared mobility refers to trip alternatives rather than vehicle ownership in order to maximize utilization rate, efficiency and competitiveness of mobility resources (Machado et al. 2018) and with some rebound effects of increased VKT and unequal access to public transport (Dijck, Poell, and Waal 2018).

Use of online activities including teleworking, online education, online shopping, etc. became another widespread trend with new advancements in digitalization. The Covid-19 pandemic accelerated the expansion rate of these flexible models of activities tangibly and rapidly (Sheveleva and Rogov 2021). The shift from physical to online activities has several effects on the transport system. Specifically, in Sweden, a large segment of the population (42 %) started working from home using digital communication technologies (Statistiska centralbyråns bibliotek 2021), which led to a reduced mobility demand and consequently a reduction in energy used for transportation (Hook et al. 2020). Some of these changes might result in long-term changes in transport structures such as geographical preferences (location choice) and mobility behavior (Bin et al. 2021; Toger et al. 2021).

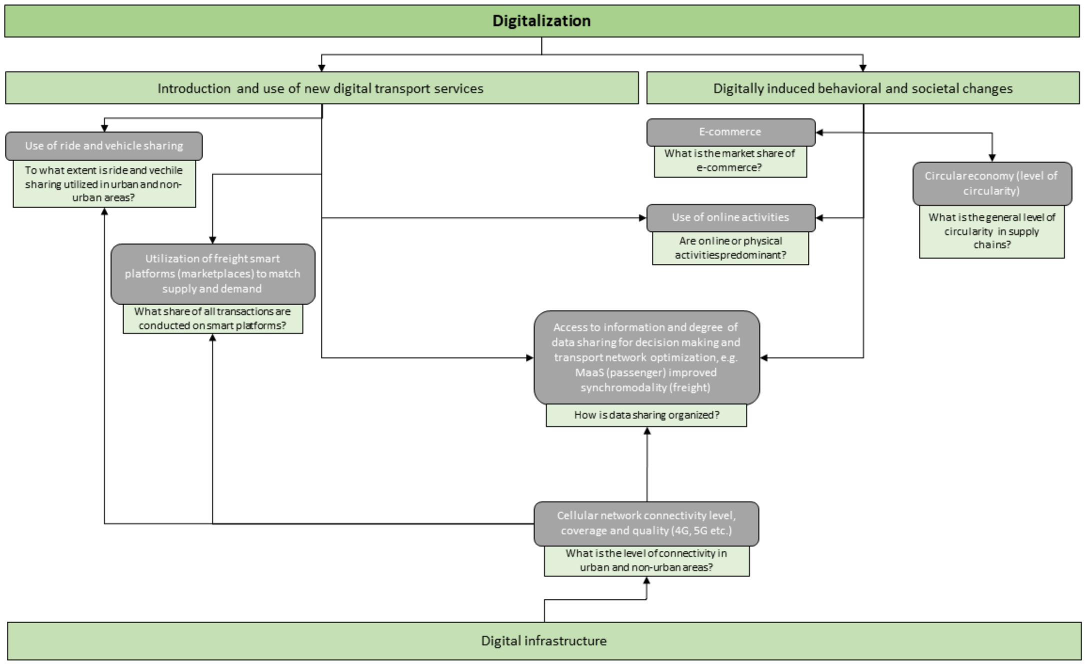

Figure 4.8. Main theme and parameters regarding digitalization considered in the GMA.

As discussed partially in the previous paragraph about the growth rate of online shopping, on the other side of this coin, e-commerce and smart platforms play a significant role in creating a turning point in the future of freight transportation. The e-commerce share of total retail grew from 11 to 14 % during 2020, which was a drastic growth due to the Covid-19 pandemic (PostNord 2021). Even if the e-commerce share of total trade could decrease after the pandemic, it has been established in a broader segment of the population (PostNord 2021), and online shopping is a habit that is likely to be kept (Bin et al. 2021). However, increased e-commerce demand could lead to negative rebound effects. One example is that growth in e-commerce demand does not necessarily lead to less personal trips (Rotem-Mindali and Weltevreden 2013). Besides, smart platforms facilitate supply and demand matches to satisfy the growing need for transparent, accurate, rapid and flexible freight services (Chung et al. 2016). These platforms enable logistic systems to reduce costs and improve service level (Buchman 2021).

Digitalization provides different opportunities and challenges for the transportation sector, however, it so far seems to have been a source of profitability and productivity from a business/economical perspective (Leviäkangas 2016). Previous studies have identified the potential benefits and barriers of digitalization for transportation, including holistic impacts (Leviäkangas 2016; Liu et al. 2019; Melander et al. 2019; Pernestål et al. 2021), impacts on sustainability and environment (Bieser and Hilty 2018; Kayikci 2018; Creutzig et al. 2019) and impact on intermodal transport (Bontekoning and Priemus 2004; Harris, Wang, and Wang

2015; Altuntaş Vural et al. 2020). In Table 4.4, the digitalization parameters and attributes included in the morphological box are presented. Table 4.5 illustrates the morphological box in its entirety.

Table 4.4. Parameters and attributes concerning digitalization in the morphological box, along with motivations for why they were included.

Digitalization parameters	
Parameter Q: Cellular network connectivity level, coverage and quality (4G, 5G etc.)	
Q1: High level of connectivity in urban areas	Connectivity between vehicles, infrastructure and pedestrians is fundamental to many AV applications and can be utilized to reach a variety of goals such as traffic safety and transport efficiency (Shladover 2018). To enable different types of connectivity, there is a need for infrastructure. The attributes have been set to levels of connectivity in different geographical areas.
Q2: High level of connectivity in urban areas and some rural areas	
Q3: High level of connectivity everywhere	
Parameter R: Use of emerging ride and vehicle sharing services	
R1: Private vehicle ownership (and rides) is preferred	Shared mobility refers to trip alternatives rather than vehicle ownership in order to maximize utilization rate, efficiency and competitiveness of mobility resources (Machado et al. 2018).The attributes have been chosen as utilization modes of ride and vehicle sharing, ranging from preference of private vehicle ownership to 100 % sharing everywhere.
R2: Urban areas: Vehicle sharing services with private rides dominant Non-urban areas: private vehicles dominant	
R3: Urban areas: Vehicle and ride sharing is dominant Non-urban areas: private vehicles dominant	
R4: 100% sharing of vehicles and rides everywhere - no private vehicles	
Parameter S: Level of circularity of supply chains	
S1: Conventional, linear supply chain approach	Due to achieving sustainable development goals, the supply chains generally experience a shift from a linear system (in which virgin materials are employed as inputs) to closed-loop models (in which waste is utilized as raw materials). In a circular economy, principles such as reuse, reconditioning, remanufacturing, and recycling become the ‘new normal’ practices (Nasir et al. 2017). The attribute represents the level of this shift, ranging from linear supply chain to partially circular supply chain and then to a circular, closed-loop, green supply chain.
S2: Partially circular supply chain (e.g. most supply chains are partially circular or some supply chains are fully circular while others are not)	
S3: Circular, Closed-loop, Green supply chain approach	
Parameter T: Use of online activities	

<table>
<tr><td>T1: Most activities require physical meetings</td><td rowspan="3">Use of online activities including teleworking, online education, online shopping, etc. become another widespread trend with new advancements in digitalization. The Covid-19 pandemic accelerated the expansion rate of these flexible models of activities tangibly and rapidly (Sheveleva and Rogov 2021). The shift from physical to online activities has several effects on the transport system. Specifically, in Sweden, a large segment of the population (42%) started working from home using digital communication technologies (Statistiska centralbyråns bibliotek 2021), which led to a reduced mobility demand (Hook et al. 2020). In this morphological analysis, the attributes represent whether online or physical activities are dominant.
Also, online shopping is investigated in a separate parameter (e-commerce).</td></tr>
<tr><td>T2: Activities are partially online and physical</td></tr>
<tr><td>T3: Most activities online</td></tr>
<tr><td colspan="2">Parameter U: Utilization of freight smart platforms (marketplaces) to match supply and demand</td></tr>
<tr><td>U1: Small share of total transactions in freight market</td><td rowspan="3">Smart platforms facilitate supply and demand matches to satisfy the growing need for transparent, accurate, rapid and flexible freight services (Chung et al. 2016). These platforms enable logistic systems to reduce costs and improve service levels by managing and utilizing capacity fluctuation, multiple actors' involvement, support capabilities, automating procurement, etc. (Buchman 2021). The attributes have been set to the share of all transactions that are performed on the smart platforms.</td></tr>
<tr><td>U2: Some share of total transactions in freight market</td></tr>
<tr><td>U3: Large share of total transactions in freight market</td></tr>
<tr><td colspan="2">Parameter V: Access to information and degree of data sharing for decision making and transport network optimization, e.g. MaaS (passenger) improved synchromodality (freight)</td></tr>
<tr><td>V1: Industrial organization-limited data sharing</td><td rowspan="4">Collecting accurate, reliable and timely data, and access to information are essential for transport decision-making and planning (Moschovou, Vlahogianni, and Rentziou 2019). Digitalization enhances information availability anywhere, anytime, within any context and by any user (Kayikci 2018). In addition, data sharing makes the transportation sector more efficient and optimized, especially in the use of shared vehicles. The attributes have been chosen as the level of openness of data sharing.</td></tr>
<tr><td>V2: Semi-extensive data sharing in vertical, trusted relationships</td></tr>
<tr><td>V3: Semi-extensive data sharing through centralized platforms or brokers</td></tr>
<tr><td>V4: Network-based organization-comprehensive data sharing</td></tr>
<tr><td colspan="2">Parameter W: E-commerce</td></tr>
<tr><td>W1: Small share of total retail</td><td rowspan="2">The e-commerce share of total retail grew from 11 to 14 % during 2020 due to the Covid-19 pandemic (PostNord 2021). However, increased e-commerce demand could lead to negative rebound effects. One example is that growth in e-commerce demand does not necessarily lead to less personal trips (Rotem-Mindali and Weltevreden 2013). In the morphological box, the attributes have been set to the degree of share of e-commerce to total retail.</td></tr>
<tr><td>W2: Some share of total retail</td></tr>
</table>

W3: Large share of total retail	

Table 4.5. The research morphological box.

A/E/D	Freight Passenger		Parameter	Attributes 1	2	3	4
A	F	A	Use of automated and driverless (DL) heavy trucks	Manually driven trucks with ADAS on highways and in urban areas.	DL trucks operating hub-hub on a set of corridors on the highway network, and on certain distribution tours in urban areas.	DL trucks operating hub-hub on the whole road network, and on certain distribution tours in urban areas.	DL trucks widespread in the whole truck fleet for all transport types.
	F	B	Use of automated and driverless (DL) vehicles for urban transport (incl. light trucks, vans, delivery robots, etc.)	To a small degree - manually driven vehicles (in combination with other solutions, e.g. cargo bikes)	To some degree - Automated delivery vehicles with human service staff onboard (in combination with other solutions, e.g. cargo bikes) is a commonly used solution	To a large degree - DL delivery vehicles dominate with a highly automated delivery service	
	P	C	Most common automation level in the passenger road vehicle fleet (excl. public transport)	SAE level <3	SAE level 3 (conditional automation)	SAE level 4 (highway autopilot cars)	SAE level 5 (fully DL everywhere)
	P	D	Most common automation level of buses in public transport	SAE level <3 (driverless buses not common)	SAE level 3 (Conditional automation with a driver on board that can take over if necessary)	SAE level 4 (DL on dedicated infrastructure)	SAE level 5 (Fully DL in all conditions)
	P+F	E	Implementation of smart railway solutions excluding ATO (e.g. Shift2Rail innovations)	To a small degree	To some degree	To a large degree	
	P+F	F	Implementation of automatic train operation (ATO)	GoA 1 most common	GoA 2 most common	GoA 3 most common	GoA 4 most common
	P+F	G	Implementation of smart shipping solutions	To a small degree	To some degree	To a large degree	
	F	H	Degree of automation and digitalization of intermodal terminal handling processes. (Load unit level)	Partly automated and digitalized	Fully automated and digitalized in larger terminals. Load and container handling partly automated.	Fully automated and digitalized	
	F	I	Degree of automation and digitalization of shipper and receiver handling processes (e.g loading and unloading), including warehouses, cross-docking and distribution centers (Parcel level)	Partly automated and digitalized	Highly automated and digitalized processes at a set of shipping and receiving facilities	Highly automated and digitalized processes at a majority of shipping and receiving facilities	
E	P	J	Share of battery electric vehicles in passenger vehicle fleet	Less than 40 %	Around 40 %	Around 70 %	More than 70 %
	P	K	Implementation of battery electric buses in public transport	To a small degree	To some degree	To a large degree	
	F	L	Share of battery electric trucks in road freight transport	Less than 10 %	Around 10 %	Around 30 %	More than 30 %
	P+F	M	Marine transport	To a small degree: short distance ropax ferries (e.g. Swe-Den) electrified	To some degree	To a large degree	

	P+F	N	Air transport	To a small degree	To some degree: a non-negligible share of domestic, regional traffic fully electrified	To a large degree: a substantial share of domestic, regional traffic fully electrified and a non-negligible share of medium distance traffic is electrified	
	P	O	Charging infrastructure coverage	Mainly at home (private houses) and on select places in urban areas	Most urban areas (incl. "apartment areas") and on important highways	Complete coverage in urban areas and along larger roads	Nation-wide coverage (like gas stations)
	F	P	Charging infrastructure coverage	Mainly at "home", at terminals, during loading/unloading of the vehicle, during the night	"Home" charging + common with charging along some routes during the day using a public/open infrastructure	Complete coverage at terminals and along routes	
D	P+F	Q	Cellular network connectivity level, coverage and quality (4G, 5G etc.)	High level of connectivity in urban areas	High level of connectivity in urban areas and some rural areas	High level of connectivity everywhere	
D	P+F	R	Use of emerging ride and vehicle sharing services	Private vehicle ownership (and rides) is preferred	Urban areas: Vehicle sharing services with private rides dominant Non-urban areas: private vehicles dominant	Urban areas: Vehicle and ride sharing is dominant Non-urban areas: private vehicles dominant	100% sharing of vehicles and rides everywhere - no private vehicles
D	P+F	S	Level of circularity of supply chains	Conventional, linear supply chain approach	Partially circular supply chain (e.g. most supply chains are partially circular or some supply chains are fully circular while others are not)	Circular, Closed-loop, Green supply chain approach	
D	P	T	Use of online activities	Most activities require physical meetings	Activities are partially online and physical	Most activities online	
D	F	U	Utilization of freight smart platforms (marketplaces) to match supply and demand	Small share of total transactions in freight market	Some share of total transactions in freight market	Large share of total transactions in freight market	
D	P+F	V	Access to information and degree of data sharing for decision making and transport network optimization, e.g. MaaS (passenger) improved synchromodality (freight)	Industrial organization-limited data sharing	Semi-extensive data sharing in vertical, trusted relationships	Semi-extensive data sharing through centralized platforms or brokers	Network-based organization-comprehensive data sharing
D	P+F	W	E-commerce	Small share of total retail	Some share of total retail	Large share of total retail	

5. Scenario mapping

Four scenarios were used in the study, of which one was based on the Swedish Transport Administration's base forecasts for freight and passenger transport. In addition, three alternative scenarios were adapted from (Pernestål et al. 2021). This chapter will firstly, in section 5.1, introduce the base forecasts for freight and passenger transports and the base scenario constructed based on those. In section 5.2, the alternative scenarios will be presented. Finally, a comparative mapping of the scenarios is illustrated in section 5.3.

5.1 Base forecasts and the base scenario

The Swedish Transport Administration provides forecasts used in national infrastructure planning that illustrate the most reasonable scenarios for future freight and passenger transport, based on several factors. Both forecasts consider decided or announced policies and investments, and are to a large extent based on other forecasts. The aim of the forecasts is to describe future modal distributions and amount of transport work. The results are then used in national infrastructure planning (Sachse and Almkvist 2020). While AED could significantly affect many of the factors that are foundational for the forecasts, e.g. through changed driving costs, no technological development with the exception of electrification is explicitly described in the forecasts or their sensitivity analyses.

5.1.1 Base forecast for passenger transportation

In the base forecast, modes included are cars, planes, trains, buses, metro, trams, biking and walking. Only domestic transportation is considered, with the exception of short-distance regional traffic flows between Sweden and Denmark in the Öresund region. Important factors for the results of the forecasts are changes in income, driving costs (SEK/km), population, employment level and cars per capita. Infrastructure is included in the model based on the government's national infrastructure plan. These factors are processed in the modelling system Sampers, and the results include domestic transport work per year and mode. In 2040, the total transport work is expected to have increased as shown in Figure 5.1.

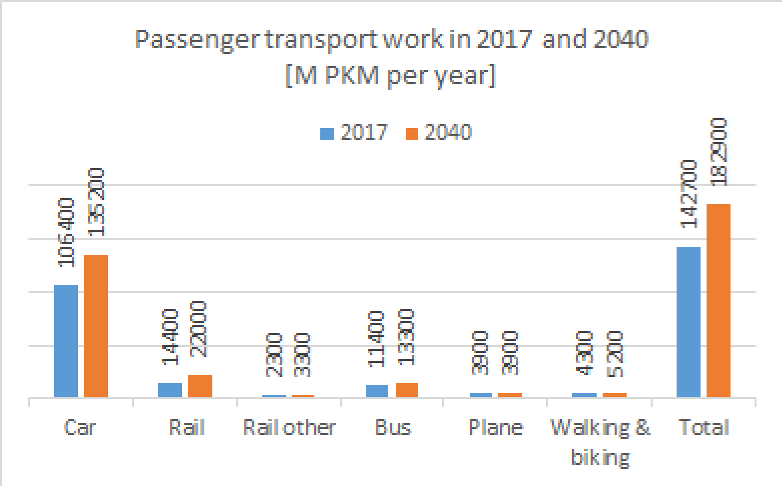

Figure 5.1. Passenger transport work in 2040 (Sachse and Almkvist 2020).

Regarding the modal distribution, the transport work from passenger cars will have seen a yearly growth of 1 %, while transport work on rail will have increased by 1.9 % per year. In terms of total transport work, that for passenger cars will have increased by 27 % and rail transport by 53 %. Bus transport is expected to increase by 17 %, and biking and walking by 21 %. Car continues to be the dominant mode, as the modal distribution is not expected to change significantly (Sachse and Almkvist 2020).

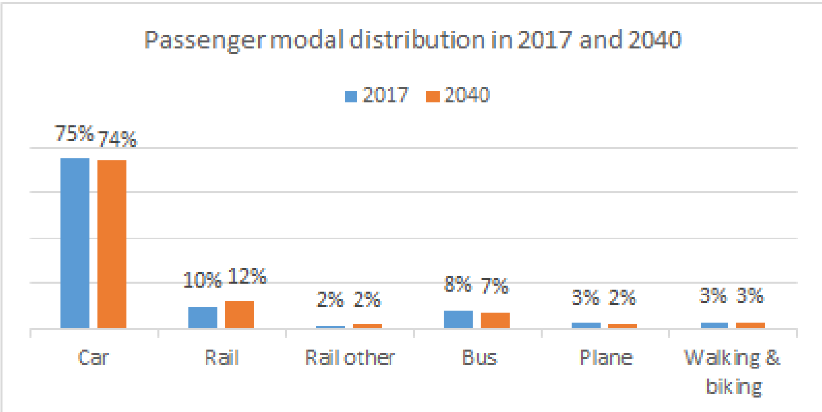

Figure 5.2. Passenger modal distribution in 2017 and 2040 (Sachse and Almkvist 2020).

In the forecast report published in 2020, the forecast's sensitivity was evaluated through three additional scenarios: no change in income between 2017 and 2040, doubled driving costs in 2040 and a 50 % driving cost reduction (Sachse and Almkvist 2020).

5.1.2 Base forecast for freight transportation

The base forecast for freight transportation (Wikström 2020) is a result of calculations made in the national freight model Samgods, in which possible logistic chains and shipment sizes are calculated. Similarly to the forecast for passenger transport, the results are used in national infrastructure planning. Foundational for the base forecast for freight transportation is another forecast: REF18 by the National Institute of Economic Research (NIER). REF18 provides a long-term overview of the national economic development and includes factors such as GDP, private and public consumption, investments, export and import and productivity. It is among other things based on technological development, demographics and consumer behavior. REF18 also includes cost increases for energy and CO_2 emissions.

Several other forecasts are used in Samgods to estimate the future transport work and modal distribution, including those for population, employment, value of goods, international trade and transit. Costs for the 2017-2040 time period are fundamental to the Samgods model, and are based on further assumptions and conditions. One is that the climate and environmental targets for transportation are reached through an increase in energy efficiency and the use of alternative fuels such as electricity or biofuel. In addition, it is also assumed that the price for diesel increases due to tax increases and an energy shortage. The energy shortage is also assumed to affect the electricity price, leading to cost increases for both road and marine transports, especially since a larger portion of the vehicle fleet is expected to be electrified. Rail transport is also expected to be affected by the increased electricity price, as well as higher track fees. The total transport demand is projected to increase by 1.8 % every year, leading to a 51 % increase in 2040. Marine transport is expected to see the largest growth (2.16 % per year), while rail is expected to see the least (1.55 % per year).

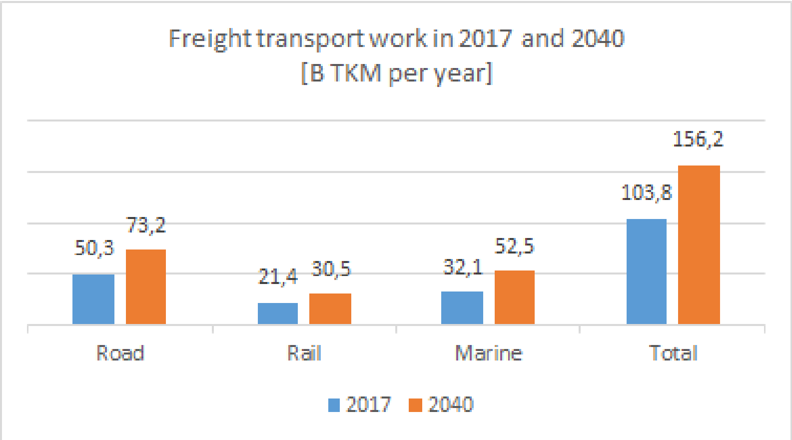

Figure 5.3. Freight transport work in 2017 and 2040, in terms of billion TKM per year (Wikström 2020).

Although road transports will increase the most in total numbers, the yearly change is lower than that for marine (1.65 %). This deviates from historical trends, where road transportation generally has experienced the largest growth. The expected modal distribution is shown in Figure 5.4.

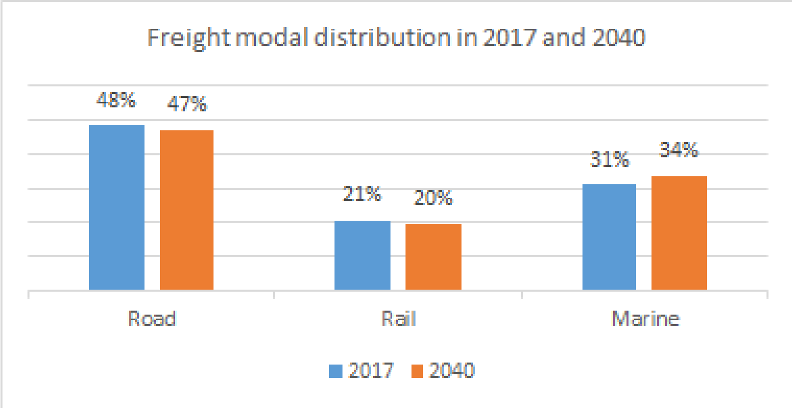

Figure 5.4. Freight transport modal distribution in 2040 (Wikström 2020).

A few alternative scenarios are presented in addition to the main scenario: a lower GDP growth than in REF18, an increase in the use of HGV74 trucks and a scenario where the planned long trains are not introduced.

5.1.3 Base scenario

The base scenario is intended to reflect a development in line with Trafikverket's base forecasts for passenger and freight transport in 2040 (Wikström 2020; Sachse and Almkvist 2020). These are built on legislation and policies that have been either announced or decided as of the time of the forecasts' publication. For the base scenario used in this study, it is therefore assumed that public and political attitudes toward data sharing and sustainable development remain the same as in 2020, e.g. long-term political goals such as the 2030 Agenda are highly prioritized. It is further assumed that technological development within automation and digitalization has continued on a similar trajectory as in the early 2020s. However, electrification is expected to have become widespread as it is emphasized as an important strategy in the base prognoses. Finally, the prognoses project a continued urbanization and concentration of job opportunities in larger cities (Wikström 2020; Sachse and Almkvist 2020). General trends for the base scenario include:

- Environmental, social and economic dimensions of sustainability are equally prioritized.
- Population and job opportunities are concentrated in southern Sweden, particularly in large and medium sized cities.
- Strong focus on electrification of the road vehicle fleet, in order to reach the national climate targets.
- An energy shortage has led to increased electricity prices
- Transport demand has increased

5.2 Alternative scenarios

Pernestål et al. (2021) develop explorative scenarios for the impacts of digitalization on the Swedish road freight transport system in 2040 through workshops involving 54 experts from the freight transport landscape. The study identified two key uncertainties which may have a large impact on the development, as illustrated in Figure 5.5. One uncertainty is to what extent digitalization has changed the business logic in freight transport towards a network-based structure with extensive data sharing or whether it remains in the current linear organizational structure with limited data sharing among actors. The second uncertainty is whether climate issues are prioritized over other societal and sustainability issues. The scenarios indicate that the freight transport system could look highly different in the respective scenarios.

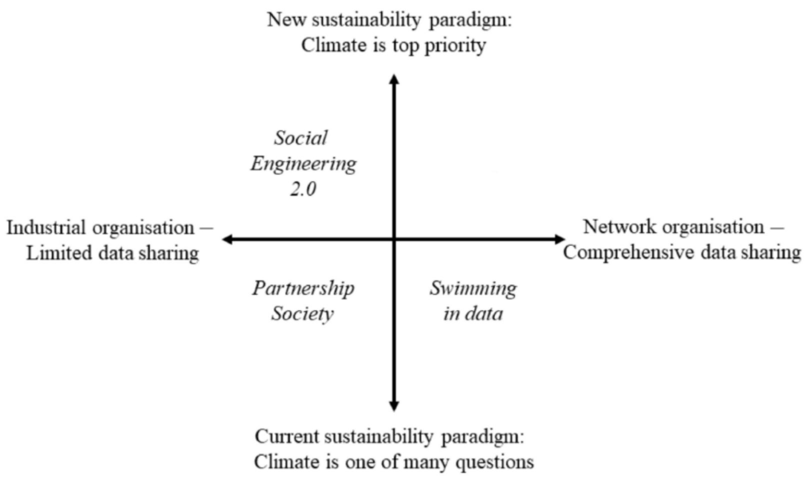

Figure 5.5. Pernestål et al. (2021) scenarios obtained by crossing two strategic uncertainties.

Of the four scenarios presented by Pernestål et al. (2021), three were adapted for this study. As they originally concerned freight transportation, they were modified to consider passenger transports. The selection includes the scenarios *Partnership Society*, *Social Engineering 2.0* and *Swimming in Data*. The three scenarios are presented in Table 5.1, while their respective mappings in the morphological box can be seen in Figure 5.6.

Table 5.1. Descriptions of alternative scenarios adapted from Pernestål et al. (2021).

Social engineering 2.0 ● A policy driven society fighting to avoid devastating climate change. Climate impact is part of companies' accounts. ● Bio-materials and circular solutions are used to maintain a lifestyle similar to 2021. ● Massive amounts of data are available, but data sharing is very restrictive and primarily due to legislation or within alliances of large actors. ● A unified political landscape has speeded up electrification, it is uncommon with vehicles driven by fossil fuels. ● The digitalization trend that took a leap during Covid has continued, and people primarily use e-commerce and remote work. ● The digitalization trend has started a trend that people move away from the larger cities, to smaller towns or the countryside. ● Common efforts around digital infrastructure have enabled automation on highways.	
Partnership society ● Environmental sustainability is considered as only one out of several sustainability goals. Focus is also on trade, welfare, and immigration. ● Same companies and market structures, new businesses are based on data and partnerships. ● Risk awareness limits data sharing, but partnerships enable data sharing and improved solutions. ● Decreased GHG per km, but increased transport demand caused by economic growth. ● Fragmented political landscape with shortsighted political decisions gives changing prerequisites, and forces companies to be flexible. Lack of long-term decisions. ● Digitalization continues, and more and more things are connected. ● The post-covid society reminds to a large extent of the pre-covid society: people work at the office most days, and both e-commerce and physical stores are used	**Swimming in data** ● A strong societal trend towards network-based organizations and data sharing. This enables many new convenient services for both goods and people transport. ● Environmental sustainability is second to resource efficiency, convenience and social sustainability. ● Convenience enabled by data sharing, automation in warehouses and in deliveries. ● A continued growth in e-commerce. ● Focus is on cities - it is in the cities there is commercial ground for the new sharing-based and circular services. ● AI-powered solutions are a key to enable new concepts ● IT and social media giants with customer insight provide cloud based logistic building blocks that are used to deliver opportunistic niche services

In order to assess and compare the scenarios, they were mapped in the morphological box in accordance with the method presented in subsection 3.1.2. The following section will present the mapping (see Figure 5.6) and provide brief motivations for why the chosen attributes were selected for each scenario.

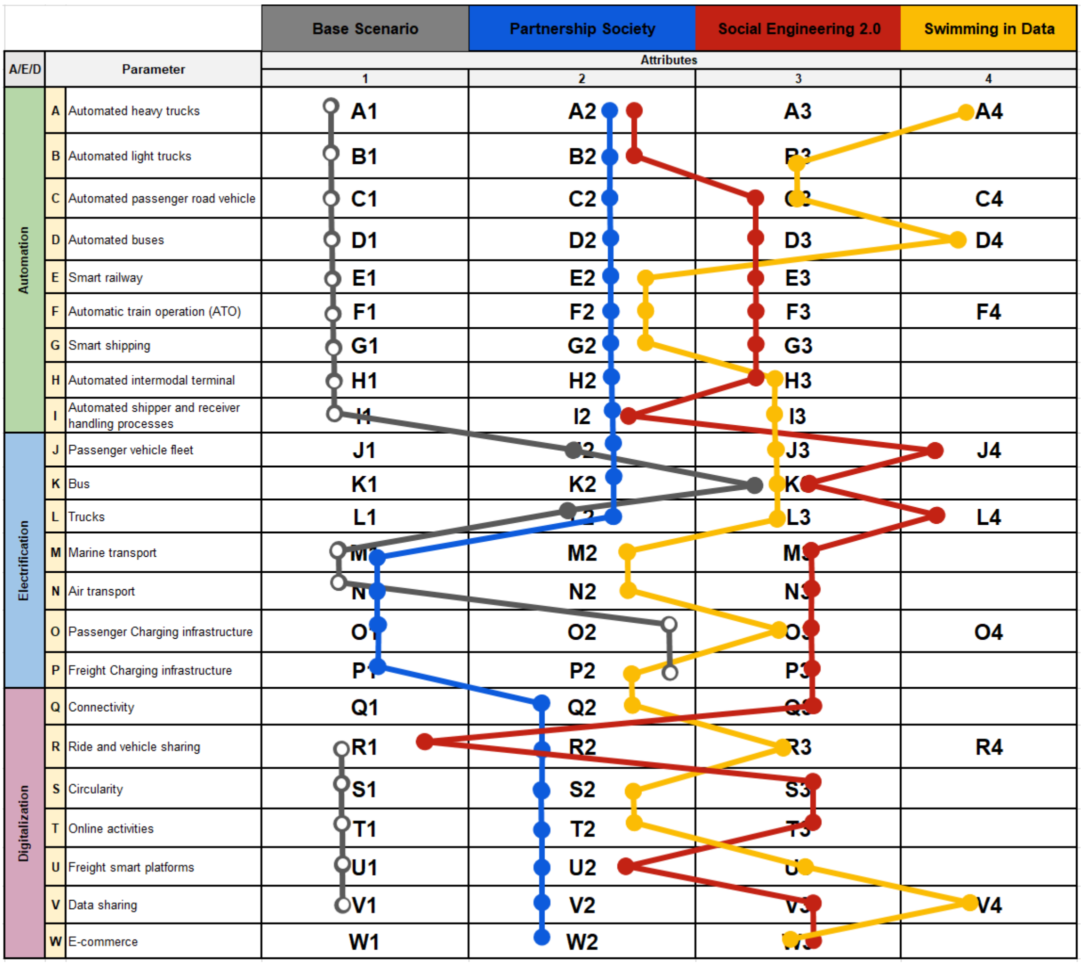

Figure 5.6. Illustration of scenario mapping comparison.

5.2.1 Base Scenario

In the base scenario, there is no explicit information given regarding the majority of the parameters. In these cases, the attribute was chosen through implicit assumptions and illustrated using an empty circle. In cases where the parameter is either out of scope or not considered at all, no mapping was made.

5.2.2 Partnership Society

As a result of the fragmented political landscape and low emphasis on environmental sustainability present in Partnership Society, electrification technologies have seen less development than in the base scenario. So has technologies that rely on investments that are too large for individual actors, such as those in the rail and marine sectors. However, automation and digitalization have advanced on the same trajectory as in the early 2020s and have thus developed further than in the base scenario.

5.2.3 Social Engineering 2.0

As decision-making in Social Engineering 2.0 is centralized through strong governmental institutions, rail and marine transport has seen large technological development. Electrification has been a major priority. This development has been in line with society's ambitious climate policies and at the same time enabled convenient transport services to the decentralized population. This decentralization has been enabled by a continued digitalization in the form of remote working and other services, which in turn is a result of a widespread access to connectivity. However, restrictive data sharing has led to somewhat less efficient road transports, particularly in the freight sector. This is represented by a lack of ride and vehicle sharing services as well as freight smart platforms.

5.2.4 Swimming in Data

In contrast with Social Engineering 2.0, the scenario Swimming in Data represents a future with a centralized population but decentralized decision making. Actors are largely driven by the vast amount of data that has been made available, which among other things is shown in the development and increased use of ride and vehicle sharing services. Both the physical and digital infrastructure has been modified to accommodate the new services, but primarily in cities. No large efforts have been made to implement charging stations and connectivity in non-urban areas that are not located along major roads. As governmental institutions are not as strong as in other scenarios, marine and rail technologies have not developed to the same extent.

6. Impact analysis

This chapter presents the findings from the conducted impact analysis. The results from the first step, where the impacts of each parameter from the morphological analysis in isolation were assessed, are presented in section 6.1. This is followed by a qualitative discussion about the combined effects from all attributes on the drivers of demand for passenger and freight transport in each scenario in section 6.2. Finally, in section 6.3, the impacts on the drivers of transport demand and the modal distribution for each scenario are compared with the base scenario.

6.1 Impact mechanism analysis

The first step of the impact analysis was an assessment of the possible effects on transport demand of each parameter in the morphological box. This analysis was based on previous literature, and insights from the conducted workshop. At this step of the analysis, the parameters were assessed without consideration to other parameters. The impacts were categorized according to the system layers and market as in the theoretical framework (see section 2.3).

6.1.1 Automation impact mechanisms

Parameter A: Use of automated and driverless (DL) heavy trucks

The introduction of automated driving systems in heavy trucks can affect the supply of road transport in various ways depending on the maturity of automated driving systems, operating model and how the transport services that they are used within are designed. An elaborate analysis for this parameter is provided in Appendix A, with the following paragraphs providing a short summary of the analysis.

Several studies have suggested that heavy trucks with automated driving capabilities would, assuming that the technology is mature and that driverless operations are legal, substantially reduce costs for truck ownership and operations (Wadud 2017; Engholm, Pernestål, and Kristoffersson 2020; Ghandriz et al. 2020). The extent of achievable cost savings vary based on assumptions on technology costs, efficiency gains, remaining need for human labor, etc. but are typically in the range of 20%-40% compared to manually driven trucks of a similar configuration. The cost savings are primarily driven by reductions in labor costs (Ghandriz et al. 2020) and the savings are robust for fairly large increases in truck acquisition costs due to automated driving technology costs (Engholm, Pernestål, and Kristoffersson 2020; Wadud 2017)[13]. Since driver costs are more or less unrelated to truck size, this means that the relative cost reduction (e.g. per TKM) is more substantial for smaller trucks than for larger trucks.

However, driverless trucks would not eliminate all labor costs. The introduction of automated driving systems only automates the driving task, which is only one of many tasks that truck drivers typically perform (Flämig 2016). Also, driverless trucks at SAE level 4 may require temporary driving assistance when operated outside their operating design domain. Solving the non-driving tasks that truck drivers typically perform, and supporting the automated driving system, will incur costs for driverless trucks that offset the cost reduction obtained by eliminating driver costs. However, the exact extent of this cost offset is uncertain and will vary for different transport applications. The need for, and costs of, driverless truck operations support may act as a *restriction* (see Section 2.3) affecting the feasibility for driverless truck transport services. As previously suggested, the extent of this restriction will most likely vary substantially for different transport flows. For instance, this could be a severe restriction for using driverless trucks for less-than-truckload services operating pick-up tours and distribution tours with multiple stops for which the truck driver currently is responsible for loading and

[13] As an example, to offset the cost reduction, truck acquisition costs would need to increase by 230% for the 40t truck in the intermediate scenario in the study by (Engholm et al. 2020)

unloading. For other applications, such as line-haul between distribution terminals, this may be much less of a restriction.

For long-distance transport, driverless trucks may shorten transport lead times since the currently mandated hour of service restrictions that apply to manually driven trucks would reasonably not apply for driverless trucks (Short and Murray 2016). Thereby, the average speed could increase. Conversely, this means that truck utilization could also be increased.

Driverless trucks with limited operating design domains may for some transport assignments require that an alternative transport chain is used compared to a manually driven truck, which would affect transport costs, for instance since transfers of goods or trailers between manually driven and driverless trucks may be required. A large-scale use of the hub-to-hub model (attributes A2 and A3), may have considerable effect on the organization and geography of road transport, possibly in the form of a segmentation where driverless trucks performing long-haulage between transfer terminals, and manually driven electrified trucks performing the pre- and post-haulage (Monios and Bergqvist 2019).

If driverless trucks would be introduced on a large scale, there may be significant effects on the demand of road transport. A modeling study by Engholm et al. (2021) suggests that if driverless trucks would be able to fully substitute manually driven trucks for Swedish freight transport flows, road TKM on Swedish territory increases by over 20% as a result of modal shifts from rail (for which TKM is reduced by around 30%) and sea transport (-~20%). There is a relatively larger increase in road VKT which is due to that a larger share of smaller truck types are used compared to the baseline scenario. The system cost (i.e. the sum of total logistics costs for all Swedish freight flows) would increase in the range of 1 billion Euro per year. A study of the impacts of driverless trucks on freight flows and trade patterns in the U.S by Huang and Kockelman (2020) finds that road TKM increases by 11%, if transport costs are assumed to be 25% lower for driverless trucks compared to manually driven trucks. This effect is a combination of modal shifts from rail to road and due to an increase in total TKM (+4% for domestic, +2% for export) due to changed origin choices.

Parameter B: Use of automated and driverless vehicles for urban transport (incl. light trucks, vans, delivery robots, etc.)

The operational logic and service requirements are highly different for urban road transport and long-haulage and interurban road transport. While the basic mechanisms for potential cost reductions due to reduced labor costs are in principle similar, the role of the driver to perform non-driving tasks (e.g. for performing home deliveries) is in many cases critical for the service provision in urban road freight applications. This could mean that, for some applications and customer segments, it would not make sense to operate without a human person onboard (although naturally the driving task could still be automated). Also, there is typically little modal competition for this type of road transport. For deliveries using vans assisted by sidewalk robots, it has been suggested that van VKT required to serve a given demand could be reduced in the range of 10%-30% (Jennings and Figliozzi 2019). On the other hand, if delivery services utilizing e.g. sidewalk delivery robots become highly cost efficient and popular, this could lead to an increase in the use of direct home-deliveries of products such as e-commerce parcels and food which could both generate additional urban traffic with possible upstream effects on supply chains but also potential substitution effects for passenger trips. However, the scarce literature evaluating deliveries supported by sidewalk robots can not yet provide clear answers to whether efficiency and/or service quality gains of such orders are achievable (Jennings and Figliozzi 2019; Simoni, Kutanoglu, and Claudel 2020). If a widespread use of different types of driverless delivery vehicles, including sidewalk robots materializes, there could be new types of transactions taking place in the traffic market, such as market-based use of curb space usage, although this would likely only apply to highly congested dense urban areas.

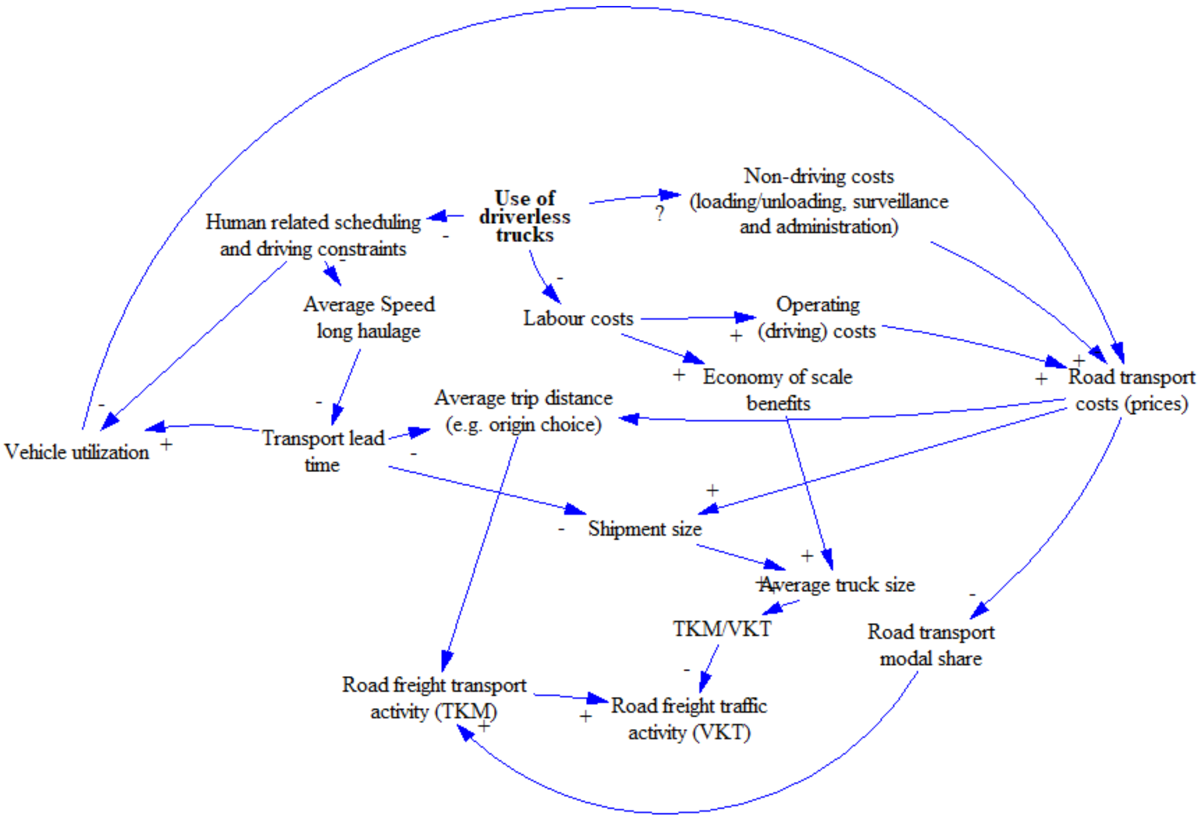

Figure 6.1. Examples of possible effects on transport demand from driverless trucks (Parameter A).

Parameter C: Most common automation level in the passenger road vehicle fleet (excl. public transport)

Automated passenger road vehicles (i.e. cars) could lead to structural changes in the transport market, as they could complement or replace currently available services. This is mainly a result of a reduction in the marginal cost of driving. This is due to a lower value of time, itself a result of the ability to use the time spent in the car for other things than driving (such as working or sleeping). As this previously has been an incentive to travel by train, especially on regional and inter-regional trips, there is a possibility that it could lead to a modal shift from rail to road transport. One barrier present in the transport services layer is an increased investment cost compared with manually driven cars, as DL cars are expected to be more expensive. The investment cost would however decrease over time. Other enablers and barriers are illustrated in the infrastructure layer and are the same as those for trucks.

The impacts on travel demand have been studied by Litman (2021). The introduction of AVs could lead to more travel demand in user groups that cannot afford or operate a car by themselves. A possible rebound effect is that AVs will need to perform empty VKTs, as the vehicles will need to reposition themselves in order to perform dedicated tasks. These increases in travel demand could however be balanced by decreases, for example through reduced private vehicle ownership levels.

Parameter D: Most common automation level of buses in public transport

Automation of buses in public transport would primarily affect the efficiency and service level, two factors in the transport services layer. More efficiency would be a consequence of increased utilization rates, as manually driven bus services (like trucks) need to be planned in consideration of human constraints. The impact on the perceived service level could be either positive or negative, depending on different user groups who could have varying attitudes towards driverless and digital technology. The enablers and barriers represented in the infrastructure layer largely resemble those for other automated road vehicles.

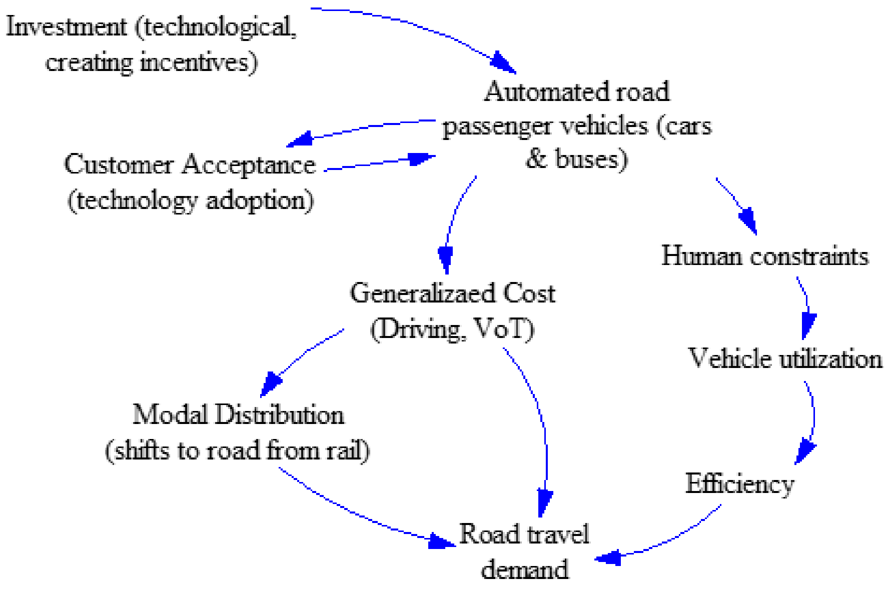

Figure 6.2. Causal relationships of automated road passenger vehicles (cars and buses).

Parameter E: Implementation of smart railway solutions excluding ATO (e.g. Shift2Rail innovations)

Shift2Rail adjacent innovations aim to create a more attractive rail sector and their implementation could contribute to more efficient rail transports, due to advancements in train technology and terminal handling processes. The services could also become more robust, leading to a higher service level. In the transport market, a more competitive rail transport system could result in a modal shift. Finally, the infrastructure itself could benefit from Shift2Rail innovations as it also could become more robust, efficient and offer a higher capacity. Rail infrastructure development is critical in creating better conditions for intermodal transportation.

Parameter F: Implementation of automatic train operation (ATO)

As ATO is included in Shift2Rail, many of the impacts discussed in the previous paragraph are relevant for this one as well. However, removing drivers from trains could lead to more flexible transport services and less standstills as scheduling would not have to consider human constraints. One barrier is that without a driver, there is no one onboard to handle system failures, e.g. if the train stops far away from a major terminal. In the infrastructure layer, the capacity could be increased due to a reduced variability in driving, which in turn leads to a possibility of scheduling trains with less time apart.

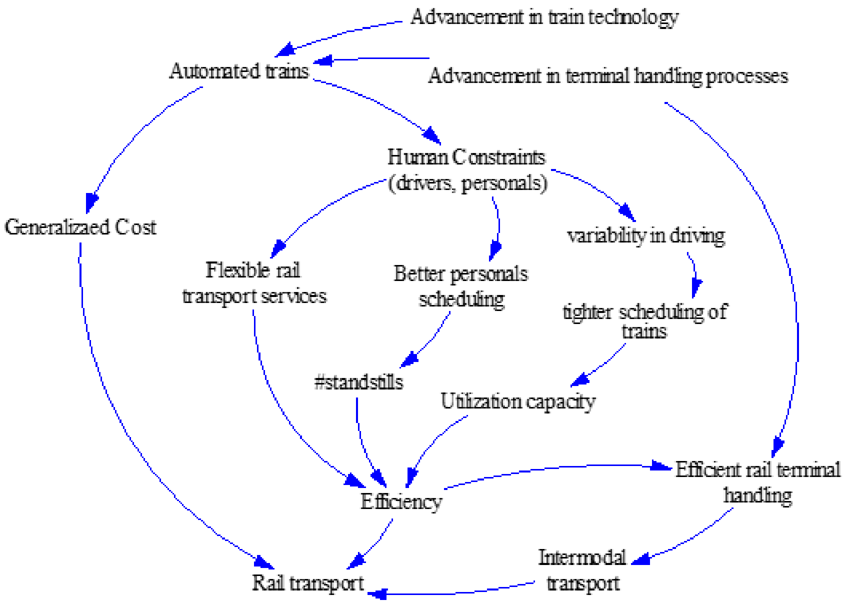

Figure 6.3. Causal relationships of automated trains.

Parameter G: Implementation of smart shipping solutions

The main impacts from smart shipping solutions come in the form of increased efficiency. In the transport service layer, it could increase as vehicles could be utilized more optimally. As a consequence, the fleet size could change. In the transport market, the generalized costs could be reduced. Further efficiency gains can be found in the infrastructure layer, due to improved communication between ships and ports, as well as better conditions for intermodality.

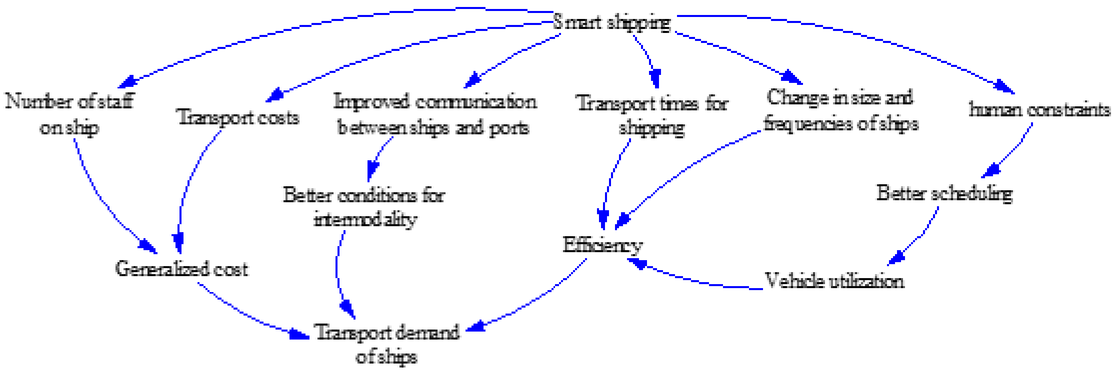

Figure 6.4. Causal relationships of smart shipping.

Parameter H: Degree of automation and digitalization of transfer terminal handling processes (e.g. harbors, consolidation centers, combi/rail-terminals). (Load unit level)

As discussed for previous parameters, the impacts from automated freight vehicles largely depend on how goods are handled. On a load unit level in the service layer, the generalized cost could decrease as node costs become lower. In other words, it could become cheaper to transfer between different modes and vehicles as there are less labor expenditures. One example of a service that could become more common is Digital Automatic Coupling (DAC) of freight trains which, in addition to reduced costs and time spent within nodes, could lead to larger and heavier trains and subsequently more efficient rail transports. Efficiency is also a key impact in the infrastructure layer, as the terminals themselves would be affected from more efficient handling, leading to increased throughputs and less space constraints. However, there are some barriers in regards to technology and infrastructure. In the traffic market, there would be further efficiency related impacts. One example is that bottlenecks for accessing terminals could be reduced.

Parameter I: Degree of automation and digitalization of shipper and receiver handling processes (e.g loading and unloading), including warehouses, cross-docking and distribution centers (Parcel level)

As for terminal handling processes on a load unit level, automation and digitalization for shipper and receiving handling processes (such as loading and unloading) could lead to a reduced generalized cost as a result of smaller node costs. In the transport services layer, the actual service level could also change. There could be better conditions for off-peak deliveries, as scheduling limitations would be removed with the absence of human drivers. Structural changes could occur in the infrastructure layer, as there would be a need for interoperability and standardization of digital and physical interfaces.

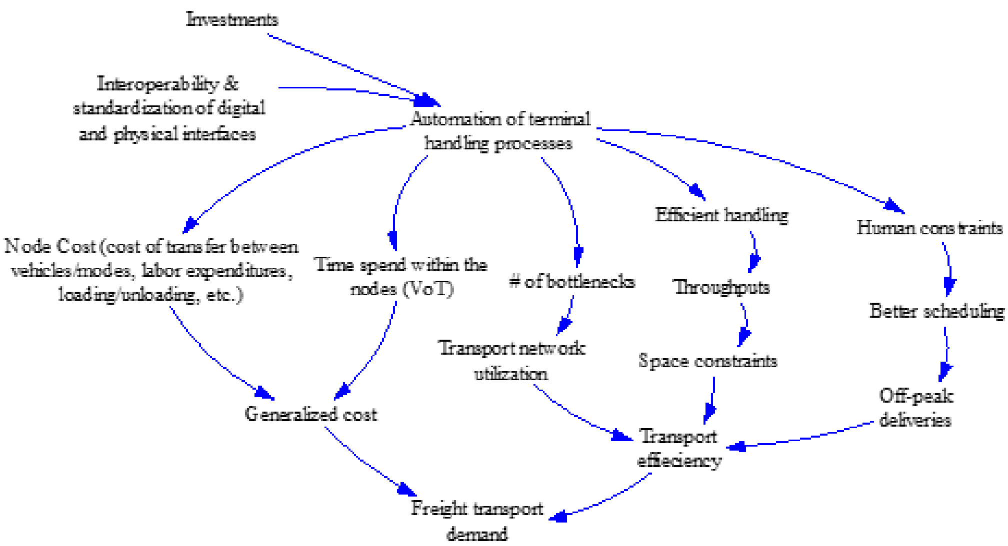

Figure 6.5. Causal relationships of automation of terminal handling processes.

Table 6.3. Impact mechanism table for each automation parameter included in the morphological analysis, illustrating direct and indirect effects, enablers & barriers and structural changes.

Freight Pass. Both	Parameter		Activities and material flows	Transport market	Transport services	Traffic market	Infrastructure
F	A	Use of automated and driverless (DL) heavy trucks		**Structural changes** - New business models and value chains	**Generalized cost** - Reduced labor costs during driving - Need to replace of the non-driving labor performed by driver **Efficiency** - Increased vehicle utilization (scheduling without human constraints) - No need to stop for resting leads to increased average speed and subsequently reduced transport lead times	**Structural changes** - Could enable a new logic for allocating infrastructure use	**Driving characteristics** - Changed driving characteristics **Enablers & barriers** - Need for remote services (control tower) - Need for connectivity - Physical support in the infrastructure - Changed rate and type of accidents - New types of incidents and risks
F	B	Use of automated and driverless (DL) vehicles for urban transport (incl. light trucks, vans, delivery robots, etc.)			**Generalized cost** - Reduced labor costs during driving **Efficiency** - No need for stops for resting leads to increased average speed and subsequently reduced transport lead times **Operational** - New process requirements since non-driving labor of driver needs to be replaced **Enablers & barriers** - Need to digitalize customer journey	**Structural changes** - Need to regulate usage of curb-space	**Enablers & barriers** - Need for remote services (control tower) - Need for connectivity - Need for physical support in the infrastructure - What infrastructure is it operating on?
P	C	Most common automation level in the passenger road vehicle fleet (excl. public transport)		**Structural changes** - Replacing or complementing current services	**Generalized cost** - Reduced marginal cost of driving (VoT) **Modal distribution** - Reduced demand for rail transport due to AVs? **Enablers & barriers** - Increased investment/capital cost (reduces over time)		**Enablers & barriers** - Need for remote services (control tower) - Need for connectivity - Need for physical support in the infrastructure
P	D	Most common automation level of buses in public transport			**Generalized cost** - Reduced VoT - Reduced production cost --> what will this lead to? Increased service, reduced ticket prices, increased margins? **Efficiency** - Increased vehicle utilization (scheduling without human constraints) **Service level** - Change in rider experience		**Enablers & barriers** - Need for remote services (control tower) - Need for connectivity - Need for physical support in the infrastructure
	E	Implementation of smart railway solutions excluding ATO (e.g. Shift2Rail innovations)		**Modal distribution** - Rail transport more attractive	**Efficiency** - More efficient terminal handling **Service level** - Increased service robustness		**Efficiency** - Terminal efficiency leads to better intermodal conditions **Service level** - Increased infrastructure robustness

P+F	**F**	Implementation of automatic train operation (ATO)		**Modal distribution** - Rail transport more attractive for freight and passengers	**Generalized cost** - Decreased costs due to more or flexible rail transports **Efficiency** - Decreased standstills due to personnel scheduling **Service level** - Increased service level **Enablers & barriers** - Methods of dealing with system breakdowns	**Efficiency** - Increased capacity and robustness	**Efficiency** - Reduced variability in driving enables tighter scheduling of trains and increased capacity **Enablers & barriers** - Radio communications - Safety systems - Traffic control centers (Swe: "Trafikledningscentraler") - Infrastructure (e.g. safety barriers)
P+F	**G**	Implementation of smart shipping solutions		**Generalized cost** - Reduced transport costs - Reduced number of staff on ship **Efficiency** - Reduced transport times for shipping - Change in size and frequencies of ships **Service level** - Changed service level	**Transport demand** - Increased demand due to cost reduction **Fleet size** - Change in ship fleet size (probably plenty of small ships) **Efficiency** - Increased vehicle utilization (scheduling without human constraints)		**Efficiency** - Increase due to improved communication between ships and ports - Better conditions for intermodality **Enablers & barriers** - Technology and infrastructure for smart shipping - Need for on-shore control centers - Connectivity - Changed accident rate (different types of accidents) - New types of incidents and risks (e.g. cyber security)
F	**H**	Degree of automation and digitalization of intermodal terminal handling processes. (Load unit level)			**Generalized cost** - Reduced node costs **Efficiency** - Decreased node times	**Efficiency** - Secondary impacts on transport network utilization (e.g. reducing bottlenecks for accessing terminals)?	**Efficiency** - More efficient handling leads to increased throughput and that volumes in terminals experience less space constraints **Enablers & barriers** - Technology and infrastructure within the terminals
F	**I**	Degree of automation and digitalization of shipper and receiver handling processes (e.g loading and unloading), including warehouses, cross-docking and distribution centers (Parcel level)			**Generalized cost** - Reduced node costs **Service level** - Changed service level - No scheduling limitations resulting from human involvement in processes		**Enablers & barriers** - Need for investments **Structural changes** - Interoperability & standardization of digital and physical interfaces

6.1.2 Electrification impact mechanisms

Electrification impacts first and foremost include reduced generalized costs, but could also enable services to be conducted in a different and possibly more efficient manner. Thus, electrification technologies could have significant impacts on the transport system. For both the passenger and freight sector, it could for example lead to a change in the modal distribution and market structure. Due to the similar nature of electrification system impacts, this section will present the impacts of BEV implementation for all passenger and freight modes together, even though they are considered separately in the morphological box and the subsequent impact mechanism table. Charging infrastructure was however considered separately.

One possible impact of BEV implementation is present in the material flows and activities layer: structural changes as new types of components would be required to produce and maintain BEVs. There is currently a growing battery industry in the EU (Fossilfritt Sverige 2019; 2020) and Sweden. Large-scale domestic production of batteries could affect the supply system, which has relied on imported materials during the last decades. To what extent this would affect the implementation of BEVs in Sweden is however uncertain.

Several impacts have been added in the transport services layer, which have implications for decisions made in the transport market. As previously mentioned, BEVs have a lower operating cost since charging is cheaper than conventional fuels. This reduction in marginal operating cost leads to a reduced generalized cost. As discussed previously, budget is a significant restriction for passenger (Nelldal and Svalgård 2013) and freight transport buyers' (José Holguín-Veras et al. 2021) mode selection. A decreased monetary cost could therefore lead to a shift in the modal distribution. As railbound vehicles in Sweden already are electrified to a large extent, the modal distribution could shift from trains to road vehicles such as cars or trucks. Furthermore, decreases in the perceived societal marginal cost due to the negative environmental consequences of ICEV transports could lead to increased preference for road and aerial transport. Finally, enablers and barriers for this parameter include increased investment costs and access to charging infrastructure, although the former is expected to reduce with time.

Charging infrastructure

As charging infrastructure is required for large-scale implementation of all types of BEVs, from private cars to ships and ferries, it is considered an enabler of electrification. Thus, it would not generate new needs for material flows or activities. However, increased access to charging infrastructure would lead to a higher demand for BEV transportation as actors will want to minimize their generalized transport costs. More services would be able to be electrified. These two impacts are represented in the transport services layer, and have further effects in the transport market. For road modes, the so-called range anxiety could decrease for both freight and passenger transportation, resulting in more utilization of BEVs and private BEV ownership. Route choices would be determined by charging availability.

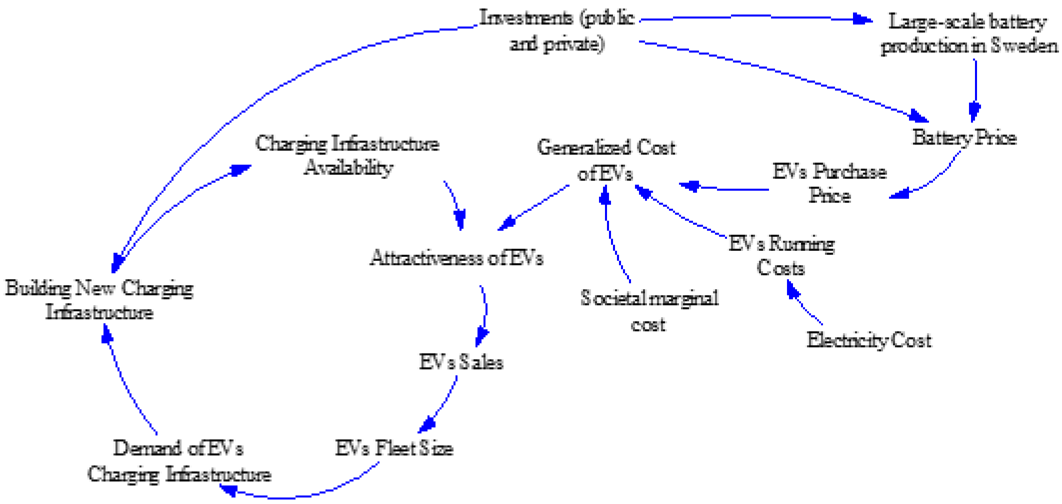

Figure 6.9. Causal relationships of electrification parameters.

Table 6.4. Impact mechanism table for each electrification parameter included in the morphological analysis, illustrating direct and indirect effects, enablers and barriers and structural changes.

Freight Pass. Both	Parameter		Activities and material flows	Transport market	Transport services	Traffic market	Infrastructure
P	J	Share of battery electric vehicles in passenger vehicle fleet	**Structural changes** - Need for other components in the vehicle industry	**Transport decisions** - Route choices - Mode choice	**Generalized cost** - Reduced marginal cost of driving **Mobility preferences** - Reduced perceived societal marginal costs **Enablers & barriers** - Increased investment/capital cost		
P	K	Implementation of battery electric buses in public transport	**Structural changes** - Need for other components in the vehicle industry		**Generalized cost** - Reduced marginal cost of operating and riding **Enablers & barriers** - Increased investment/capital cost		
F	L	Share of battery electric trucks in road freight transport	**Structural changes** - Need for other components in the vehicle industry	**Transport decisions** - Route choices - Mode choice	**Generalized cost** - Reduced marginal cost of driving and transporting **Barriers** - Increased investment/capital cost		
P+F	M	Electrification of marine transport			**Generalized cost** - Reduced marginal cost of operating **Enablers & barriers** - Increased investment/capital cost		
P+F	N	Electrification of air transport		**Modal distribution** - More demand for domestic flights	**Generalized cost** - Reduced marginal cost of operating **Mobility preferences** - Reduced perceived "societal marginal costs" for air transport **Enablers & barriers** - Increased investment/capital cost		
P	O	Charging infrastructure coverage		**Mobility preferences** - Transport by BEV more attractive **Technology adoption** - More electrified transportation services and ownership.	**Generalized cost** - If charging is not combined with breaks for drivers, labor costs could increase.	**Technology adoption** - Increase in possible routes	
F	P	Charging infrastructure coverage		**Mobility preferences** - Transport by BEV more attractive **Technology adoption** - More electrified transportation services and ownership		**Technology adoption** - Increase in possible routes	

6.1.3 Digitalization impact mechanisms

Parameter Q: Cellular network connectivity level, coverage and quality (4G, 5G etc.)

Connectivity is considered a baseline for other technological development through the supply chain and is essential to automation as well as digitalization. Connectivity could increase both freight and passenger transport demand as it could increase transport convenience and accessibility. In addition, it affects transport decisions in both transport and traffic markets, including transport decisions (e.g. mode choice) and infrastructure decisions (vehicle choice, transport mode choice). Furthermore, connectivity could lead to increased efficiency of transport services by improving availability, productivity and reliability, leading to cost reductions and demand increase. Connectivity infrastructure is an essential enabler of the parameter.

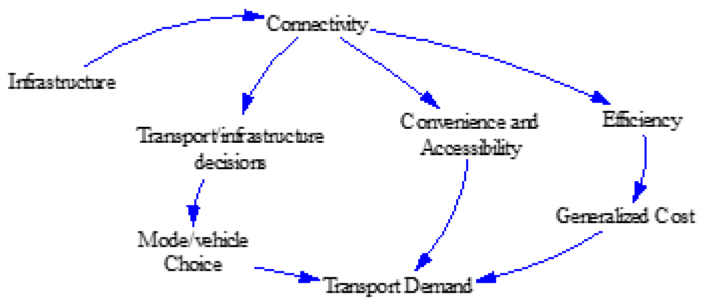

Figure 6.10. Causal relationships of connectivity.

Parameter R: Use of emerging ride and vehicle sharing services

At first glance, vehicle and ride sharing increase demand due to a reduction in generalized costs (transaction costs). More precisely, two different demand loops are possible in this parameter: Firstly, more sharing vehicles have led to increased efficiency and subsequently lower transport work. Secondly, more sharing vehicles have led to efficiency and reduced costs, and then larger demand and transport work. Loop dominance analysis is a vital issue here. Furthermore, in the transport services layer, a larger shared vehicle fleet could lead to a reduction in the number of privately owned vehicles, and subsequently the total amount of road vehicles. Sharing ride and vehicles could also lead to improved transport efficiency as fill rates could become higher, which further could affect congestion. In the traffic market, transport decisions such as route choices could be altered. So could the supply of transport infrastructure, as freight vehicle manufacturers could start providing transport capacity as a service in addition to selling vehicles. Infrastructural enablers and barriers for this parameter include vehicle sharing platforms and access to connectivity.

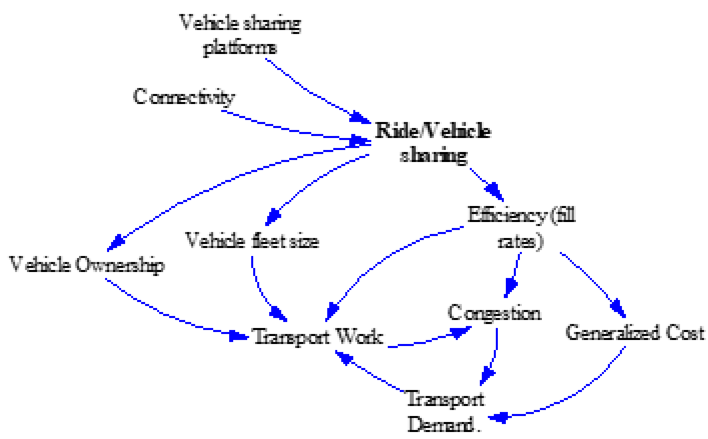

Figure 6.11. Causal relationships of ride/vehicle sharing.

Parameter S: Level of circularity of supply chains

An increasingly circular economy changes consumption patterns as well as material flows and thereby affects the demand for freight transport. More precisely, material-based consumption would decrease due to recycling, reselling and repair. Circularity could also lead to a higher demand for short-distance, peer-to-peer transports and C2C trades, especially in urban areas. In the transport market, transport decisions could be affected due to the transparency that the circular economy requires (e.g. to communicate which products are circular). In parallel, infrastructure decisions have been altered in the traffic market because well-informed customers would force companies to change their infrastructures to obey the circular economy. Finally, shared information between different levels of the supply chain and platforms for second-hand products and recycling are infrastructural enablers & barriers.

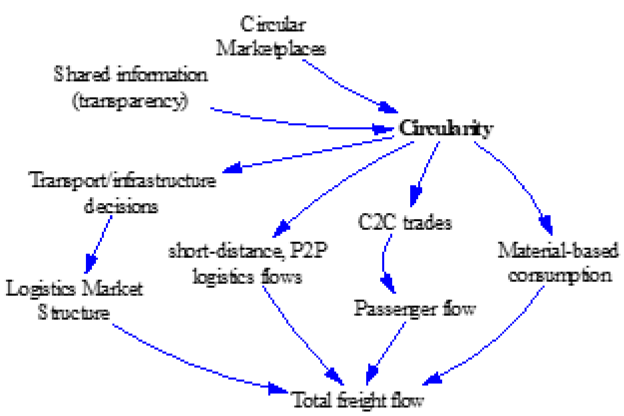

Figure 6.12. Causal relationships of circularity.

Parameter T: Use of online activities

Teleworking could lead to an increased tendency to relocate to non-urban areas where housing costs are lower. In combination with less daily trips to and from the workplace, private expenditures could decrease. Other factors affecting transport demand include:

- More leisure trips (e.g. going to summer houses or visiting distant friends more frequently)
- Less need for business trips (on all geographical levels)
- More digital social contacts (will it replace or complement physical contact?)
- Longer trips (both passenger and freight) due to sprawl (van de Riet, de Jong, and Walker 2007)
- Utilizing online platforms for various purposes (e.g. healthcare) reduces travel demand.

On the other hand, if people relocate from urban to non-urban areas, freight transport work could increase as goods would need to be delivered to more distant locations. Furthermore, online activities could remove some temporal restrictions that affect transport efficiency. For example, a result of increased teleworking could lead to more flexible working hours, which in turn could lead to milder rush hours and improved public transport capacity. There could also be less need for car fleets owned by companies and public actors. Finally, connectivity is the main enabler for the parameter.

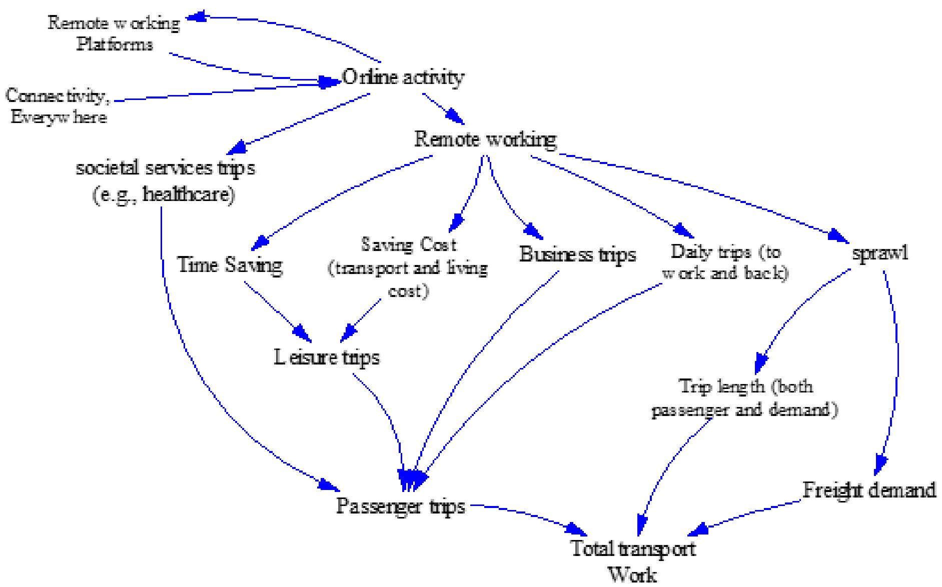

Figure 6.13. Causal relationships of online activity.

Parameter U: Utilization of freight smart platforms (marketplaces) to match supply and demand

Utilizing smart platforms could increase freight demand due to improved convenience and accessibility as well as reduced costs. The generalized cost could be reduced as freight transports become cheaper and more timely. This could also lead to increased service levels and logistics efficiency in the form of higher fill rates. In the transport market, the openness of transport networks and supply/demand matching are important efficiency parameters. There, some changes could occur regarding shipment sizes and frequencies. For instance, consolidating freight flows leads to higher load factors, the use of larger vehicles and opportunities for other modes than trucks for long haul transports. For example, larger shipment sizes would make rail and barge more attractive. Furthermore, the transport network and industry structure (e.g. truck ownership structures and location of nodes) could change.

Infrastructural enablers and barriers for this parameter include creating platforms where actors can share information and communicate. These platforms could stimulate actors to use information brokers, information exchange facilities, and regional dispatching systems. In order to create market platforms, there is a need for economical methods to determine the optimal way of sharing costs and revenue fairly between the actors involved.

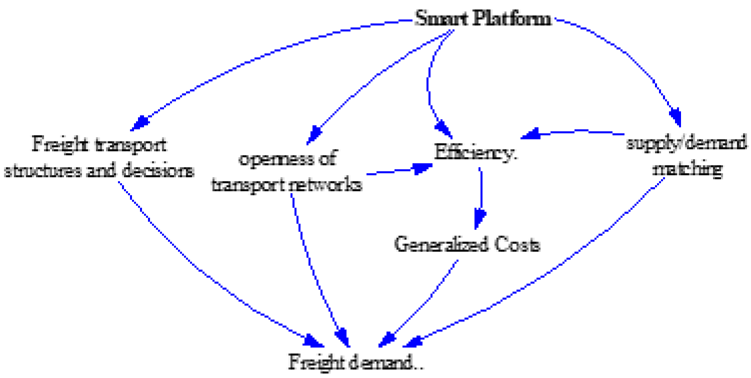

Figure 6.14. Causal relationships of smart platforms.

Parameter V: Access to information and degree of data sharing for decision making and transport network optimization, e.g. MaaS (passenger) improved synchromodality (freight)

A larger degree of data sharing and access to information could lead to increased convenience and accessibility as well as reduced costs by improving access to information and sharing relevant data. This could result in an increased passenger and freight transport demand. Two different demand loops are possible in this layer: First, more sharing information has led to increased efficiency and subsequently lower transport work. Second, more sharing information has led to efficiency and reduced costs (transaction costs), and then larger demand and transport work.

Moreover, other freight and passenger transport decisions could be made due to access to information and data sharing. Specifically, fill rates in the freight sector could increase as a result of more cooperation between shipping companies. In the passenger sector, real time information about traffic flows could increase the system efficiency. In the traffic market, data sharing could lead to a more efficient use of the available capacity. However, one condition for this is a synchronized interface between different modes.

There are several enablers and barriers. As seen in the alternative scenarios (see Section 5.2) the development of data sharing is heavily dependent on political and organizational regulations, as data might be confidential to both individuals and businesses. This is represented in the traffic market. Other enablers and barriers, in the infrastructure layer, include connectivity, improved efficiency and reduced cost of intermodal transportation terminals (van de Riet, de Jong, and Walker 2007), decision support systems and data sharing platforms.

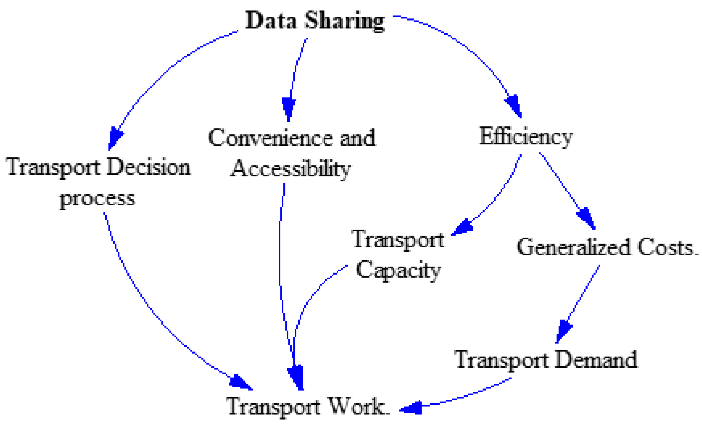

Figure 6.15. Causal relationships of data sharing.

Parameter W: E-commerce

Increased levels of e-commerce could both lead to economic growth and be a result of it. It could also lead to an increased transport activity in the freight sector. In the passenger sector, some trips could be replaced by delivery trips. However, some of these could be replaced by other types of trips, if it is assumed that there is a constant travel budget. An important aspect regarding e-commerce is that trading between companies (B2B commerce) constitutes a larger market than that between companies and consumers (B2C commerce) (van de Riet, de Jong, and Walker 2007).

In the transport market, generalized costs in the form of time cost, monetary cost, and transaction costs could decrease, while the service level could increase due to a wider access to different products. In addition, efficiency could improve as a result of better delivery scheduling and planning (e.g. night-time deliveries, nominated delivery schedules by customers, flexible scheduling) and higher fill rates. Consequently, companies can achieve higher levels of transport efficiency, load consolidation, and vehicle utilization. Changes are also possible in shipment sizes, frequencies as well as warehousing and consolidation. Moreover, a change in mode choice preference is plausible due to customers' expectations of short lead time and quick deliveries. Road transports are more beneficial than other modes in this regard.

In the transport services layer, freight VKT (more e-commerce has led to more demand and transport work) and transport distances (more accessibility to the products globally through the Internet (van de Riet, de Jong, and Walker 2007)) could increase. In the traffic market, transport decisions such as route and mode choice could be affected, for instance, high-valued products by truck and air and low-valued products by rail and marine (van de Riet, de Jong, and Walker 2007). Finally, infrastructural enablers and barriers for a continued growth in e-commerce include access to connectivity, online tracking platforms, data sharing platforms, AI, etc., and improved terminal and warehouse infrastructure.

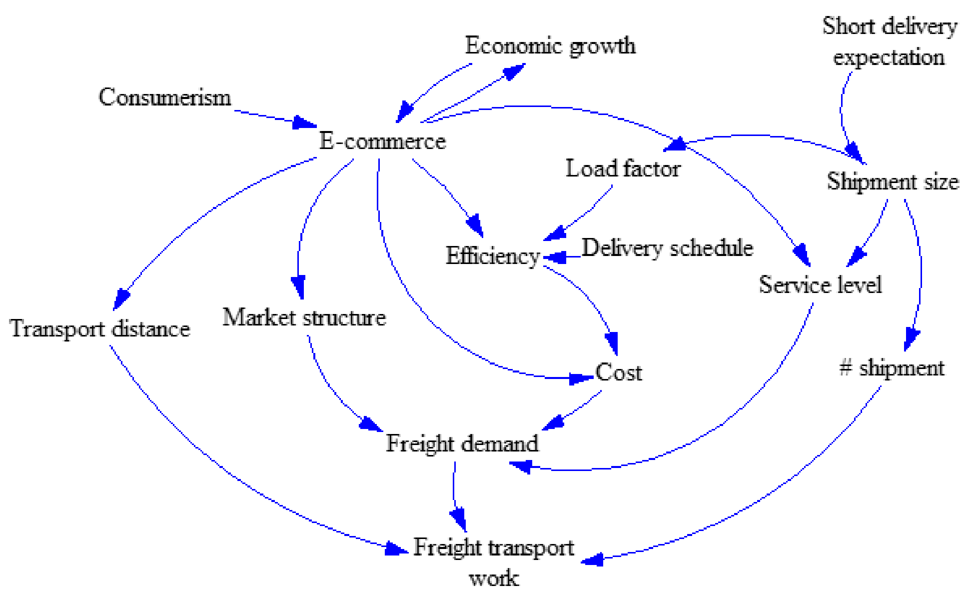

Figure 6.16. Causal relationships of e-commerce.

Table 6.5. Impact mechanism table for each digitalization parameter included in the morphological analysis, illustrating direct effects, enablers and barriers and structural changes.

Freight Pass.		Parameter	Activities and material flows	Transport market	Transport services	Traffic market	Infrastructure
P+F	Q	Cellular network connectivity level, coverage and quality (4G, 5G etc.)	**Transport demand** - Increased convenience - Increased accessibility	**Transport decisions** - Change in transport decisions (e.g. mode choice)	**Efficiency** - Increased availability, productivity and reliability	**Transport decisions** - Change in infrastructure decisions (vehicle choice, transport mode choice)	**Enablers & barriers** - Connectivity infrastructure
P+F	R	Use of emerging ride and vehicle sharing services	**Transport demand** - Cost reduction - Increased efficiency	**Generalized cost** - Reduced transaction costs	**Fleet size** - Reduced vehicle fleet size and ownership **Efficiency** - Increased fill rates - More shared mobility services	**Transport decisions** - Changed route choices **Structural changes** - Change in supply of transport infrastructure	**Efficiency** - Congestion **Enablers & barriers** - Vehicle sharing platforms - Connectivity everywhere
P+F	S	Level of circularity of supply chains	**Society** - Less material-based consumption **Transport market logic** - More short-distance, P2P logistics transport **Structural changes** - C2C trades	**Transport decisions** - Better transport decision due to transparency of circular economy		**Transport decisions** - Other infrastructure decisions	**Enablers & barriers** - Shared information (transparency) - Circular marketplaces
P	T	Use of online activities	**Demographics** - Sprawl **Transport demand** - Less daily commuting - Less business trips - Less societal services trips - More leisure trips - Increased trip lengths	**Generalized cost** - Reduced transportation costs **Mobility preferences** - Improved public transport capacity	**Vehicle fleet** - Fewer company cars		**Enablers & barriers** - Access to connectivity - Remote working platforms
F	U	Utilization of freight smart platforms (marketplaces) to match supply and demand	**Transport demand** - Cost reduction - Increased convenience - Increased accessibility	**Generalized cost** - Decreased generalized and transaction cost **Efficiency** - Changes in shipment size/frequencies - Change in warehousing, consolidation, etc. - Better supply/demand matching - More openness of transport networks **Service level** - Increased service levels	**Efficiency** - Increased fill rates, cooperation, etc.) **Structural changes** - Change in transport network and industry structure (ownership and location)	**Efficiency** - Better supply/demand matching	**Enablers & barriers** - Designing the smart platform - Data sharing (as a prerequisite)
P+F	V	Access to information and degree of data sharing for decision making and transport network optimization, e.g. MaaS (passenger) improved synchromodality (freight)	**Transport demand** - Cost reduction - Increased convenience - Increased accessibility **Modal distribution** - Increased MaaS demand	**Generalized cost** - Reduced transaction costs **Service level** - Higher service level **Transport decisions** - Other freight transport decisions	**Efficiency** - More efficient and optimized transport services **Enablers & barriers** - Digitalized vehicles (at least for higher attribute levels)	**Efficiency** - Increased transport capacity **Enablers & barriers** - Synchronized interface between different modes (for MaaS and synchromodality)	**Enablers & barriers** - Regulations of data sharing - Connectivity - Efficient intermodal transportation terminals - Decision support systems - Data sharing platforms

P+F	**W**	E-commerce	**Transport demand** - Increased freight demand due to economic growth and "consumerism" - Increased freight share **Structural changes** - Mobility preferences - B2B dominates e-commerce	**Service level** - Improved access to products **Generalized cost** - Decreased transaction cost **Efficiency** - Better delivery scheduling and planning - Increased load factors (fill rates) - Changes in shipment size and frequencies - Change in warehousing, consolidation, etc. **Structural changes** - Effective consolidation	**Transport work** - More freight VKT - Increased transport distances	**Transport decisions** - Route choice - Mode choice	**Enablers & barriers** - Connectivity - Online tracking platforms - Data sharing platforms, AI, etc. - Terminal and warehouse infrastructure

6.1.4 Demand impact mechanisms

In order to assess where and in what manner the parameters would impact the transport system, a mapping was conducted based on the demand impact mechanisms (DIMs) described in sub-section 2.3.7 and illustrated in Figure 6.17. The remainder of this subsection will present the mapping and trends found from it.

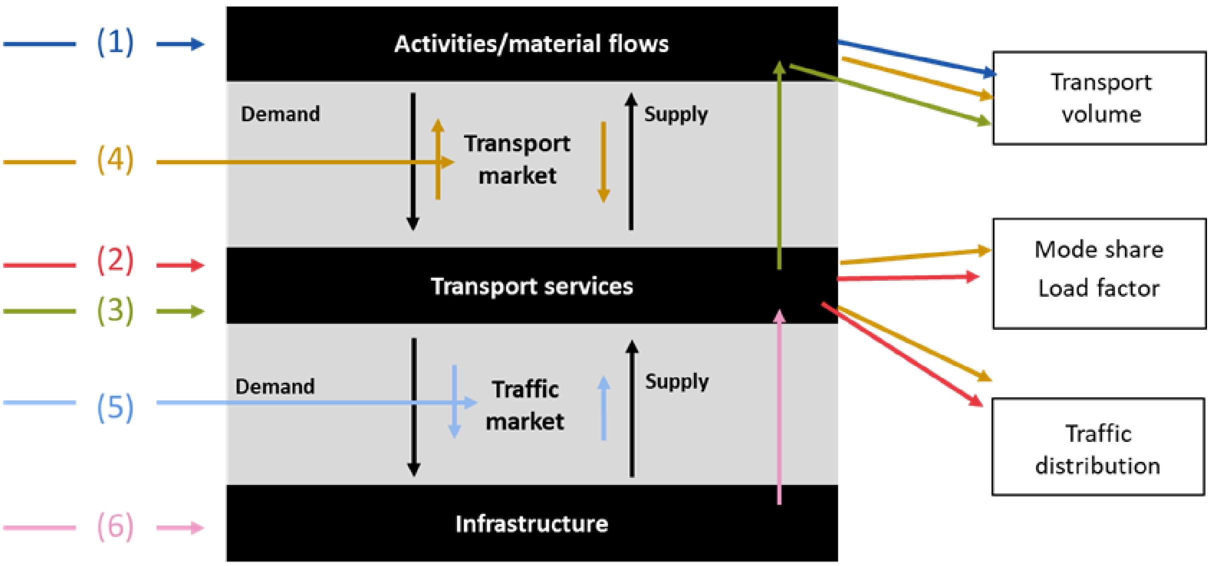

Figure 6.17. Overview of generic demand impact mechanisms for AED.

DIM1: Parameters affecting the system through DIM1 in the digitalization category include S (Circularity), T (Online activities) and W (E-commerce). These could have significant impacts on the mobility of people and goods, as they enable or result in changed activities and material flows. In the automation category, only parameter I (Automated shipper and receiving handling processes) is represented. The impacts of parameter I, as shown in Table 6.6, relate to new options for consumers to utilize deliveries.

DIM2: Most parameters, with the exception of Q (Connectivity), S (Circularity) and W (E-commerce) impact the system through DIM2. One reason is that Q, S and W do not constitute new services and do not affect the generalized cost separately. However, as discussed throughout the report and shown in Table 6.6, the access to connectivity is an important enabler for most other technologies.

DIM3: Similarly to DIM2, a majority of the parameters affect the system through DIM3. The exceptions include S (Circularity), U (Freight smart platforms) and V (Data sharing) as these parameters would not affect the generalized costs.

DIM4: Most parameters affecting the system through DIM4 are present in the digitalization category. One common aspect among the parameters is that they could increase system efficiency and reduce inertia. While that is a common impact from other parameters as well, there is a larger degree of uncertainty for those, whereas the parameters affecting the system through DIM4 have a more certain outcome regarding efficiency.

DIM5: Only parameters Q (Connectivity), R (Ride and vehicle sharing) and V (Data sharing) affect the system through DIM5. The reason is that these parameters could enable more efficient ways of utilizing the available infrastructure.

DIM6: Some parameters could impact the system through DIM6, i.e. through changes in the supply of infrastructure that indirectly affects transport services and demand. The parameters deemed to affect the system through DIM6 were those directly related to infrastructure.

Table 6.6. Demand impact mechanism mapping.

	Parameter	DIM1	DIM2	DIM3	DIM4	DIM5	DIM6
A	Automated heavy trucks		■	■			
B	Automated light trucks		■	■			
C	Automated passenger road vehicle		■	■			
D	Automated buses		■	■			
E	Smart railway		■	■	■		■
F	Automatic train operation (ATO)		■	■			■
G	Smart shipping		■	■			■
H	Automated intermodal terminals		■	■			■
I	Automated shipper and receiver handling processes	■	■	■			
J	Electrification of passenger vehicle fleet		■	■			
K	Electrification of buses		■	■			
L	Electrification of trucks		■	■			
M	Electrification of marine transport		■	■			
N	Electrification of air transport		■	■			
O	Passenger charging infrastructure		■	■			■
P	Freight charging infrastructure		■	■			■
Q	Connectivity			■	■	■	■
R	Ride and vehicle sharing		■	■	■	■	
S	Circularity	■			■		
T	Online activities	■	■	■			
U	Freight smart platforms		■		■		
V	Data sharing		■		■	■	
W	E-commerce	■		■	■		■

As seen in Table 6.6, a majority of the parameters could impact the system through DIMs 2 and 3. Thus, the introduction of the AED technologies included in this study are most likely to change transport market decisions and furthermore transport patterns such as mode, vehicle and route choice. Behaviors and patterns could also be changed indirectly as a result of lower generalized costs, which in turn could lead to changed transport decisions in terms of localization supply chain strategies. Automation and electrification parameters first and foremost affect the system through DIM2 and DIM3, with some exceptions. Digitalization parameters tend to be broader in scope and could affect the system through most DIMs. Connectivity and e-commerce are the parameters which affect the most DIMs.

6.2 Examples of combined effects of AED per scenario and impacts on drivers of demand

In this section, examples of combined effects of AED will be presented for each scenario. These examples will then be discussed in terms of their impact on the drivers of freight and passenger demand introduced in sections 2.1 and 2.2.

6.2.1 Partnership Society

As the scenario *Partnership Society* intends to illustrate a business-as-usual case in regards to attitudes towards data sharing and the environmental sustainability paradigm, it represents a future that is similar to the early 2020s. The activities and material flows have grown in line with the economy and population, but the characteristics of the demand remain similar. Transport services have first and foremost become cheaper and easier to access, due to electrification and digitalization respectively. While there are automated freight vehicles in service, for example trucks operating without a driver on certain parts of the highway network and on some urban distribution tours, AVs have not been established enough in any mode to radically change the transport market. Since passenger vehicles are not yet automated to a significant extent, automation has not affected the generalized cost for regular drivers. However, the increased availability of BEVs has lowered the monetary and societal marginal cost, which has led to more incentives to purchase and utilize a private car for those living and working in non-urban areas. Here, route choices have also been affected as charging infrastructure still is not as accessible as conventional gas stations. In cities, sharing has become the dominant vehicle ownership mode due to the increased popularity and accessibility of ride and vehicle sharing services established in the late 2010s.

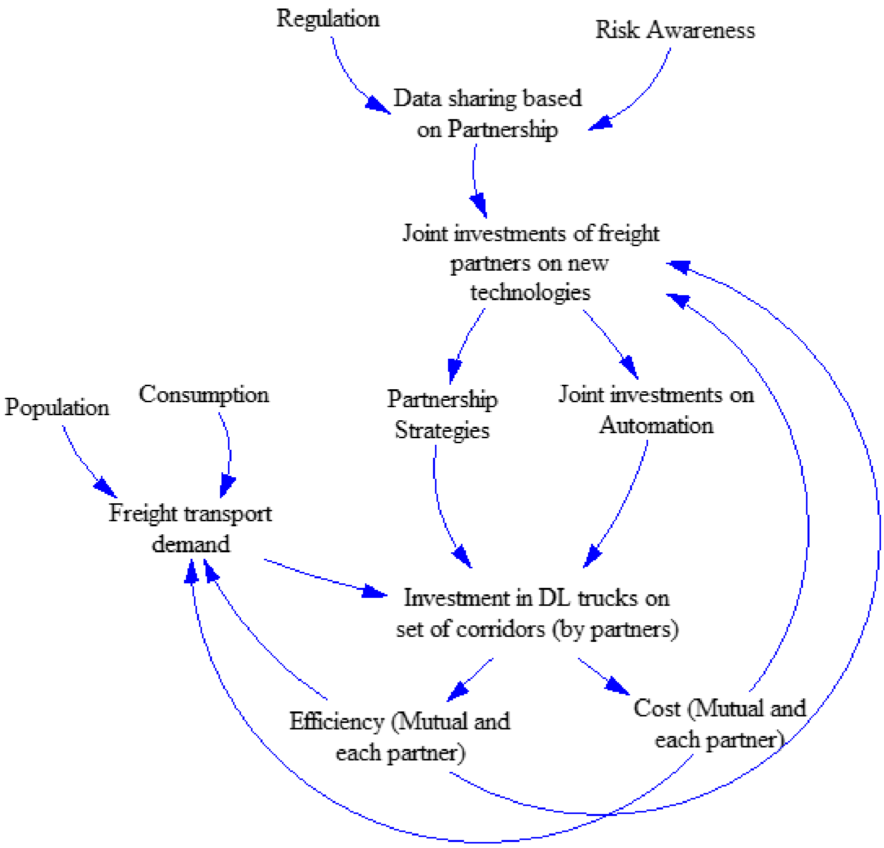

Figure 6.18. Examples of causal relationships in the Partnership Society scenario.

Infrastructure characteristics also remain similar as in 2020, but some barriers that were hindering the implementation of AED technologies have been handled. For example, the highway routes where driverless features are available have been adapted to accommodate the new technology. Outside these highway corridors digital infrastructure is lacking (with the exception of urban areas). As AED development in marine, aerial and railbound modes has not advanced to the same extent as for road transportation, the routes and types of material flows these modes are utilized for have not changed. However, due to advancements in automation of terminal handling processes, the traffic market has seen an increased demand for intermodal transports.

In conclusion, more efficient and less costly transports have led to some impacts in the transport system. However, it is uncertain whether these changes have affected the demand parameters presented in section 2.3 since there could either be a decrease in total VKT due to more efficiently organized transports, or an increase as a result of a higher demand for activities and material flows combined with more flexible transport services.

Main impacts on freight transport demand

The economic structure of the freight sector remains largely the same as around 2020. As the trade patterns have not changed, the spatial characteristics of the freight flows remain similar. However, the introduction of new services could have led to more instant deliveries and increase in the amount of delivery trips. Facilities in different nodes are expected to be located in similar places as they were around 2020. Some terminals have been fully automated, which has led to better conditions for intermodal transport and lower generalized costs. However, it is worth noting that marine and rail modes have not developed as much as those on road in terms of electrification and automation. These two technologies significantly affect the generalized cost as labor and fuel are major expenditures for transport buyers and suppliers, leading to the deployment of more frequent and smaller trucks for deliveries.

Impacts on drivers of passenger transport demand

In the passenger transport sector, continued digitalization has led to some changes in the economic structure, such as more flexible working hours and an increased preference for e-commerce. As more things are connected, some new services could have been introduced which would affect this driver. The main changes to mode characteristics in this scenario are electrification of passenger cars, automation of terminals and increased connectivity. There has been a rise in ride and vehicle sharing in cities, and combined with static activity demand characteristics, this could lead to less transport activity in urban areas.

6.2.2 Social Engineering 2.0

In the societal and technological paradigm of Social Engineering 2.0, environmental conscientiousness and circularity are the main drivers. Therefore, there has been an increased demand for circular materials and goods. Activities such as working and shopping have shifted from being primarily physical to being performed online, and these digitalized services and lifestyles have led to more people moving away from cities to non-urban areas. The transport service supply has seen a large-scale implementation of automation, electrification and digitalization in all modes. This has led to more efficient and less costly transportation of both passengers and goods. However, as the population mainly is located in non-urban areas, ride and vehicle sharing services have not developed as much as in other scenarios. Regarding freight transport services, the dominance of e-commerce has led to a variety of new delivery services. As they are automated to some extent, the generalized cost for goods transport has decreased further. In the transport market, the new types of demand and supply of services has resulted in a new logic. It is mostly cost-related, specifically due to large-scale electrification.

Regarding infrastructure, charging stations are accessible in almost all geographical locations. Widespread connectivity has been critical in enabling technological development and increased implementation of teleworking and online shopping. It has also contributed to fully automated terminal handling processes, which in turn has led to better conditions for intermodal transports. These conditions combined with a large degree of smart rail and marine related technologies have made the modal distribution for freight vehicles increasingly diversified. It is uncertain what the modal distribution is for passenger transports. The AED development in private passenger cars and decentralization of the population could have led to a larger preference for car transport. However, technological advancements in the rail sector and the societal focus on solving the climate crisis could have led to an increased preference for train transport.

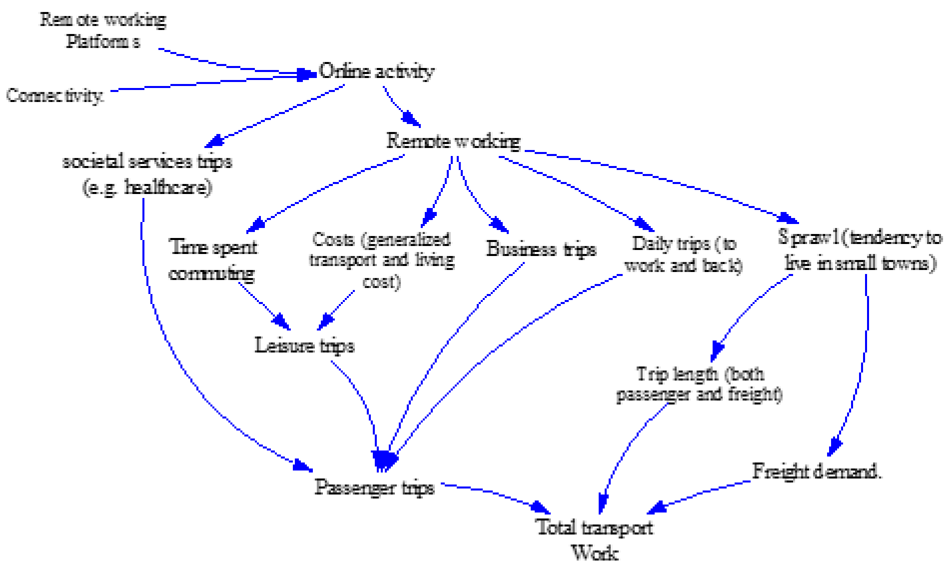

Figure 6.19. Examples of causal relationships in the Social Engineering 2.0 scenario.

Examples of impacts on drivers of freight demand

As a consequence of public opinion and policy making, consumer demand for circular products has skyrocketed. However, since lifestyles remain similar as in 2021 the type of goods consumed has not been significantly affected. Regarding the economic structure, trade patterns have changed as goods to a larger extent need to be delivered in non-urban areas. As most work is performed online, time routines have changed and the temporal requirements on freight flows have loosened. Markets have been enlarged and the amount of delivery trips has increased.

The logistic system also has had to adapt to the largely circular economy. Terminal handling and delivery processes have been fully automated, which has led to lower generalized costs throughout the transport chain. As for mode characteristics, this has led to a higher service quality and less transport times for all modes. However, rail and marine transport have developed the furthest. Road transport has seen some advancements in automation, but as the driver still needs to be on board while the vehicles are operating, the major decrease in generalized cost is that which results from electrification. However, intermodal marine or rail transports benefit from both a high level of automation and a large degree of electrification, leading to the conclusion that these modes would constitute a larger share of the modal distribution.

Impacts on drivers of passenger demand

For passenger transports, it can be assumed that the average trip length has become longer due to the decentralized spatial structure, and would probably classify as regional or inter-regional. Since most activities such as working and shopping are performed online, leisure trips are most common. This has led to a change in time routines, as schedules become more flexible. Traffic congestions have become less common as a result. Since highway automation has been enabled for passenger cars, the generalized cost has decreased along with the value of time spent in the vehicle. In addition, the large efforts made on electrification in all modes has decreased the generalized cost even further. It is however uncertain whether the total amount of travel time and transport volume has decreased as the time previously spent on work-related trips now could be spent on those for leisure.

6.2.3 Swimming in Data

In the scenario Swimming in Data, the demand characteristics for activities and material flows have not changed significantly since the 2010s. However, increased data sharing and network-based organizations have enabled many new transport services. Much data can be retrieved from the fully driverless freight vehicles and SAE level 4 passenger cars, which can be used to further optimize these services and decrease transport costs. Labor costs for road freight transports have been completely removed. Electrification has also been widely implemented, which lowers costs even further. However, as cities are the commercial grounds for the new services, they are only accessible in some non-urban areas. The extensive data sharing has also affected efficiency and made it increasingly convenient to utilize intermodal transports that are shipped with an optimal load factor. However, non-road modes such as rail and marine have not seen the same level of development, which has led to an increased share of road vehicles in the modal distribution for both freight and passenger vehicles. One possible result of this is that route choices are made based on service availability.

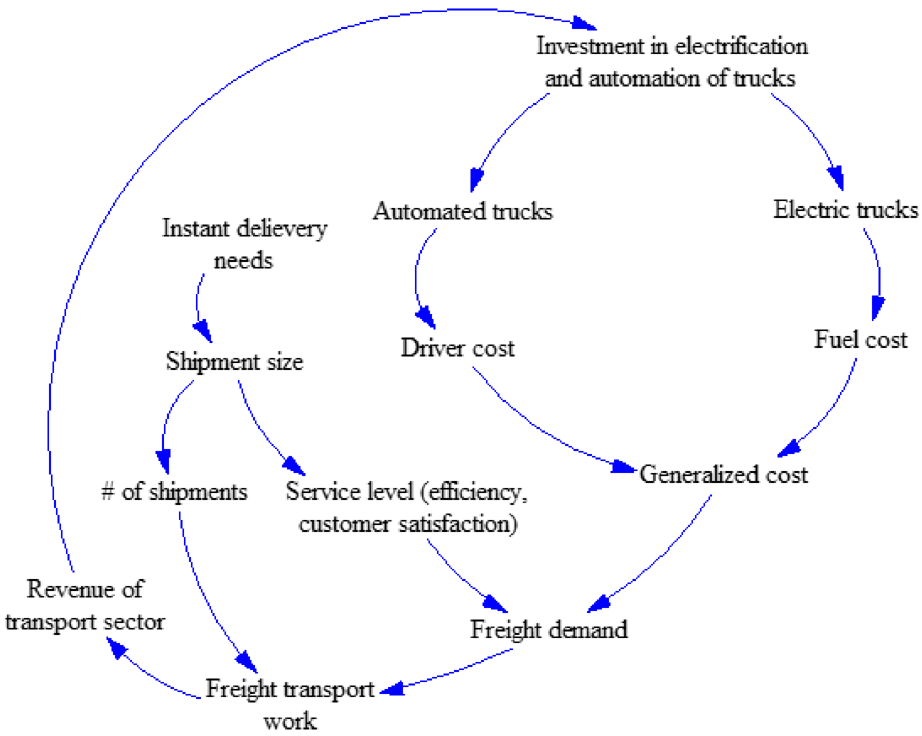

Figure 6.20. Examples of causal relationships in the Swimming in Data scenario.

Examples of impacts on drivers of freight demand

There are several impacts on the drivers of freight demand. Spatially, consumption has been concentrated in cities, which has led to changes in the economic structure in the form of new trade patterns and spatiotemporal characteristics of freight flows. There are beneficial conditions for instant, mass-individualized deliveries and thus the variety of consumed goods could have increased. This variety is due to a broader selection of suppliers for consumers to choose from, which in turn is a result of increased e-commerce and digitalization. The temporal requirement on freight flows have also changed, as driverless trucks have removed the need for scheduling to consider human constraints.

In the logistics system, more efficient and flexible freight transport has led to physical changes as the location of nodes have adapted to instant deliveries. Nodes such as distribution centers will have been located closer to cities, where a large share of the population lives. The optimal shipment size has become lower as a result of these shorter distances combined with electrification that reduces fuel costs as well as automation of trucks and terminals which has removed labor costs. It is now more cost-efficient to deploy more and smaller trucks. This is especially true for road transports, as other modes have not advanced as much in terms of AED.

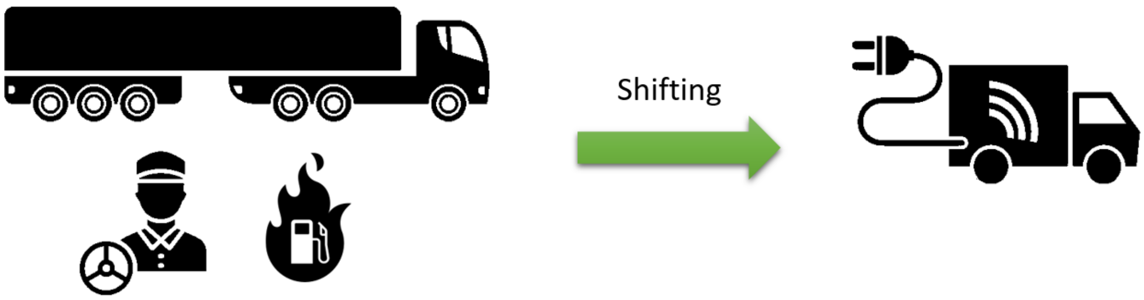

Figure 6.21. Illustration of an example about change in shipment size, fuel cost, and driver cost due to technological progress.

Examples of impacts on drivers of passenger demand

Regarding drivers of passenger transport demand, the spatial structure has been affected as the population has been concentrated in cities. For example, the average travel distances could become shorter. The increased population density in cities is balanced by a decrease in non-urban areas, with the potential effect of a more efficient public transport system in cities and vice versa. E-commerce, teleworking and other online activities have changed the economic structure. Online activities could also have affected time routines leading to more evenly distributed traffic flows.

In cities, new transport services have created a different way of using mobility. Private car ownership levels are expected to have become lower as sharing is dominant. However, in non-urban areas, cars could have become even more critical than they were around 2020 if less funds are spent on public transport. Furthermore, the generalized cost of privately owned cars would be lower due to automation and electrification, especially on regional and inter-regional trips where the value of time would decrease as an autopilot could operate the vehicle on highways. Therefore, the modal distribution could differ significantly between urban and non-urban areas. The transport volume is expected to increase in both cases, as the generalized cost is lower and there is a large selection of mobility services to choose from in cities.

6.3 Comparison of demand impacts between scenarios

The *Base Scenario* has primarily seen development in electrification and less progress has been made in other technological fields. This could have led to differences in the characteristics and magnitude of the impacts on the drivers of demand, between the scenarios. These differences will be discussed in this section.

6.3.1 Demand impact mechanisms comparison

A comparative mapping of the parameters' effect on demand impact mechanisms (DIMs) in the four scenarios was conducted and can be found in Table 6.7. In the table, the relative magnitude of each parameter's impact is shown based on which attribute (i.e. level of technological development) it has reached.

Table 6.7. Demand impact mechanisms per scenario and parameter. Green represents an increase in transport demand, red represents a decrease and yellow represents an uncertain development. The strength of the impact is illustrated through the depth of the color. In the Base Scenario column, a black cell shows that the parameter is not in the scope of the base forecasts.

DIM	Parameter	Base Scenario	Partnership Society	Social Engineering 2.0	Swimming in Data
1	I				
	S				
	T				
	W				
2	A				
	B				
	C				
	D				
	E				
	F				
	G				
	H				
	I				
	J				
	K				
	L				
	M				
	N				
	O				
	P				
	R				
	T				
	U				
	V				
3	A				
	B				
	C				
	D				
	E				
	F				
	G				
	H				
	I				
	J				
	K				
	L				
	M				
	N				
	O				
	P				
	Q				
	R				
	T				
4	E				
	Q				
	R				
	S				
	U				
	V				
5	Q				
	R				
	S				
6	E				
	F				
	G				
	H				
	O				
	P				
	Q				

The mapping shows that the alternative scenarios will affect the DIMs to a larger extent than the base scenario. Unsurprisingly, due to significant technological development, the *Social Engineering 2.0* and *Swimming in Data* scenarios could experience the strongest effects on DIMs and consequently experience the largest system impacts. However, as shown in both Table 6.6 and 6.7, the majority of the parameters would affect DIMs 2 and 3, meaning (in short) that they would impact the transport service supply and demand. However, this partly is a result of the study's deliberate focus on changes in activities, material flows and transport services. Table 6.7 furthermore shows that a majority of the parameters are expected to increase the transport demand.

6.3.2 Transport demand

In terms of transport demand, the base scenario (in line with the base forecasts) assumes an increase parallel with economic growth and decreased transport costs. For freight vehicles, it is assumed to increase by around 50 % until 2040. Passenger transport work is expected to increase by 28 %. With the introduction of AED as represented by the alternative scenarios, the transport demand is affected through impacts on certain drivers of demand (as discussed in section 6.2) and DIMs. In *Partnership Society*, these impacts were not deemed to differ significantly from the base scenario. While a few new services enabled by advancements in automation and digitalization could lead to a larger utilization of primarily road modes, the differences would probably not make the transport demand significantly different from that presented in the base forecasts. Examples of these services include automation of terminal handling processes as well as more advanced ride and vehicle sharing.

Social Engineering 2.0 provides an alternative scenario that differs more from the *Base Scenario*. The drivers of demand have first and foremost been affected by automation, electrification and decentralization. For passengers, trips have become longer and the generalized cost of road modes has been lowered due to electrification (lower societal and marginal cost) and automation (lower value of time spent in the car). The major developments in rail and marine modes could also have increased the transport demand. Freight transport demand could also have increased as a result of e-commerce growth.

Finally, *Swimming in Data* could see a dramatic increase in freight transport demand due to significant AED development which has led to large generalized cost reductions. One example is that fully automated trucks, terminals and delivery systems have removed labor costs and scheduling restrictions. Simultaneously, electrification has removed fuel expenditures. A result of this in the road freight sector could be instant, mass-individualized transports which leads to increased freight transport demand as a larger amount of trucks would be deployed with a shorter frequency. In addition, the higher service level that accompanies this development could increase consumer demand. For passenger transports, the transport demand could increase in both urban and non-urban areas. Although the increased urban populations would lead to shorter average trips, the new services introduced by AED (such as driverless, electric taxis) could lead to lower generalized costs and thus an increased transport demand. In non-urban areas, people would have to travel longer distances to perform activities such as working, which as in urban locations would lead to a larger transport demand. Especially in combination with generalized travel cost reductions from automation and electrification.

In conclusion, each alternative scenario would lead to increased transport demand compared to the *Base Scenario* as a result of AED development. *Partnership Society* closely resembles the *Base Scenario*, although slightly more development in automation and digitalization has lowered the generalized cost and thus increased the transport demand. *Social Engineering 2.0* illustrates a scenario in which mainly electrification has lowered the generalized cost. However, the transport demand in this scenario is also affected significantly by the decentralized population. In *Swimming in Data*, there are major differences from the *Base Scenario* as a result of large AED developments. This shows that all technological development that is not included in the *Base Scenario* could lead to substantial differences in the transport demand, compared to what is currently presented in the base forecast for 2040.

6.3.3 Modal distribution

The modal distribution in the base scenario is primarily constituted by road vehicles for both passenger (80 %) and freight (47 %) transportation. In *Partnership Society*, the distribution is uncertain. Road modes have seen the largest AED technological development, but automated terminals have led to better conditions for intermodal transports. The decrease in labor costs for road freight transport also implies that road modes would keep a larger share of the distribution. This contrasts *Social Engineering 2.0*, in which marine and rail modes have developed the furthest. Combined with highly automated terminal handling and delivery processes, this scenario has the best conditions for intermodal freight transports. It is thus likely that the modal distribution would shift in favor of rail and marine modes. For passenger transport, it is uncertain if the improved railbound modes are able to compete with the generalized cost decreases that accompany electrified private cars with highway autopilot functions. However, since time routines such as working hours have changed, people could be more inclined to use public transport.

The significant differences between urban and non-urban areas in *Swimming in Data* could lead to a geographical divide in the scenario’s modal distribution for passengers. Within cities, public transport and shared road modes would dominate, while less development of these modes in non-urban areas would lead to a preference for privately owned cars. Since SAE level 4 automation has been implemented in most passenger cars, the generalized cost would decrease along with the value of time spent in the car. Regarding freight transport, the instant deliveries that were discussed in subsection 6.3.2 could lead to a stronger preference for road modes such as light and heavy trucks. In addition, rail and marine modes have not developed as much as in other scenarios in terms of AED, and it is likely that this could shift the distribution further towards road modes.

In conclusion, the modal distribution is not expected to differ significantly from the *Base Scenario* in any alternative scenario, with the exception of *Social Engineering 2.0* where it could shift in favor of marine and rail modes. In *Swimming in Data*, it is worth noting that the way of which road vehicles are utilized could change in cities, as there could be more shared and less privately owned cars. However, only the technological development presented in the scenario *Social Engineering 2.0* could lead to substantial differences in modal distribution compared to what is currently presented in the base forecasts for 2040.

6.3.4 Combined effects on transport demand and modal distribution per scenario

The following subsection will present the main factors affecting transport demand and modal distribution that have been identified through the study and discussed in the impact analysis. The effects are presented for each scenario, and relative changes compared to the base scenario are indicated with arrows.

Table 6.8. Factors affecting transport demand and modal distribution in the Partnership Society scenario, compared with the base scenario. Decrease is indicated by ▼, no change by ▬ and increase by ▲.

Partnership Society			
Effects on transport demand	Both	Cheaper and more accessible transport services due to digitalization	▲
		More platform-based companies, more links between suppliers and consumers	▲
		Efficient traffic flows, due to higher fill rates and optimized route planning	▲
		Less BEV implementation	▼
	Freight	More instant deliveries, more delivery trips	▲
		More partnerships among companies based on data sharing has led to increased efficiency	▲
		Increased utilization of driverless trucks has led to lower generalized costs	▲
		Automated goods handling process and reduced generalized cost	▲
	Passenger	More ride and vehicle sharing in cities combined with static demand characteristics for activities	▲ ▼
		Altered economic structure, more flexible working hours and more reliance on e-commerce	▼
		Less electrified buses implementation in public transport	▲ ▼
Effects on transport modes	Road	Infrastructural investments in road transportation in comparison with other modes	▬
	Rail	Advancements in automation of terminal handling processes has led to more demand for intermodal transports	▲
	Marine	Advancements in automation of terminal handling processes has led to more demand for intermodal transports	▲

Table 6.9. Factors affecting transport demand and modal distribution in the Social Engineering 2.0 scenario, compared with the base scenario. Decrease is indicated by ▼, no change by ▬ and increase by ▲.

Social Engineering 2.0			
Effects on transport demand	Both	Decentralization of population	▲
		Electrification has led to lower societal and marginal transport costs, and consequently a reduced generalized cost	▲
		Automation has led to decreases in value of time spent in cars, labor costs (for freight transports) and thus lower generalized cost	▲
	Freight	Increased average delivery frequencies and trips lengths	▲
		Strong e-commerce growth	▲
		Less short-distance P2P logistics transport in cities	▼
	Passenger	Decentralization of population has led to increased average trip lengths (classified as regional or inter-regional)	▲
		Use of online activities have led to decreased frequencies of passenger trips, e.g. fewer commuting and business trips as well as societal services trips	▼
		More leisure trips if time budget for transport remains constant	▲
		Less ride and vehicle sharing in cities	▲ ▼
Effects on transport modes	Road	Decentralization could have led to a larger need for private passenger cars	▲
		Larger share of battery electric road vehicles	▲
		Less infrastructural investments in road transportation in comparison with other modes	▼
	Rail	Decentralized population	▲
		Fully automated terminal handling processes has led to higher demand for intermodal transports	▲
		More advancement in smart railways and automatic train operation (ATO)	▲
	Marine	Decentralized population	▲
		Fully automated terminal handling processes has led to more demand for intermodal transports	▲
		More advancement in smart shipping (a high level of automation and a large degree of electrification)	▲

Table 6.10. Factors affecting transport demand and modal distribution in the Swimming in Data scenario, compared with the base scenario. Decrease is indicated by ▼, no change by ▬ and increase by ▲.

Swimming in Data			
Effects on transport demand	Both	More data sharing and network-based organizations has led to new convenient transport services	▲
		Higher grade of electrification has led to large generalized cost reductions	▲
		Development in automation has led to large generalized cost reductions	▲
		Centralization of population in cities	▲ ▼
	Freight	Short distance deliveries in cities combined with electrification and automation of trucks and terminals has led to a lower optimal shipment size as well as more and smaller trucks	▲
		More e-commerce	▲
		Driverless trucks has led to more efficient scheduling without human constraints and subsequently more efficient and flexible freight transports	▲
		Decreased average length of freight flows in urban areas	▼
		Increased average length of freight flows in non-urban areas	▲
		Fully automated trucks, terminals and delivery systems have resulted in removed labor costs and scheduling restrictions, and thus large generalized cost reductions	▲
		Implementation of solutions for last-mile delivery challenges such as autonomous electric distribution vehicles, delivery robots, integrated pick-up/delivery boxes	▲
	Passenger	More ride and vehicle sharing has led to lower generalized costs but also increased transport efficiency	▲ ▼
		Less private car ownership in urban areas and more dependency on private cars in non-urban areas	▲ ▼
		More efficient public transport system in cities	▲
		Urban areas: shorter average trips but more frequent, lower generalized costs (because of AED development such as driverless, electric taxis), more transport demand	▲
		Non-urban areas: longer average trips but less frequent, lower generalized costs (autopilot decreases VoT), more transport demand	▲
		More flexible working hours and more reliance on e-commerce	▼
Effects on transport modes	Road	Other modes have not advanced as much as road in terms of AED	▲
		More instant deliveries have led to increased preference for road modes such as light and heavy trucks	▲
	Rail	More data sharing, efficient intermodal transports that are shipped with an optimal load factor	▲

		Fully automated terminals and distribution centers	▲
	Marine	More data sharing, efficient intermodal transports that are shipped with an optimal load factor	▲
		Fully automated terminals and distribution centers	▲

7. Conclusions

The aim of this prestudy was to investigate how developments within automation, electrification and digitalization (AED) may affect the demand for passenger and freight transport in Sweden in terms of transport activity (ton-kilometers TKM and passenger-kilometers PKM), traffic activity (vehicle kilometers traveled VKT), modal distribution and other characteristics of the transport system, in order to assess whether Trafikverket's current base forecasts for 2040 are still robust when accounting for developments and impacts of AED. The remainder of this section presents the study’s conclusions as responses or discussions around the three research questions. In order to answer the research questions, a theoretical framework regarding transport demand was introduced based on several established models, theoretical concepts and frameworks from the literature. By analyzing previous literature and insights from workshops conducted during the prestudy, potential impacts of AED on transport demand could be identified.

Research question 1: What emerging AED related transport technologies and transport services may affect transport demand, modal distribution and transport system characteristics? Through what mechanisms?

- Several of the automation technologies included in this study could directly and indirectly enable new services and make already existing ones more efficient. The reasons and mechanisms for this differ among the modes as well as the passenger and freight sectors. In the passenger sector, high-level private automated cars could lead to large decreases in the value of the time spent in cars, since the driving task is removed and the time could be spent on other things (such as working or entertainment). This decrease in the value of time could subsequently lead to incentives for using private cars and to travel more. For road freight vehicles, removing the driver (entirely or for some routes) would lead to major labor cost decreases which could result in both an increased preference for the mode and increases in transport demand. In this case, some new restrictions could however emerge as drivers currently perform other tasks, such as loading and unloading goods. In this regard, automated terminals are important enablers. Efficient terminals are also a key factor for improved intermodal transports. Impacts from automation in the rail and marine modes neither include changes in value of time nor labor costs for drivers. However, automatic train operation (ATO) could lead to more robustness and a higher capacity in the rail network, and smart shipping solutions could lead to increased efficiency. These factors could lead to increased preferences for rail and marine transports in both the passenger and freight sectors. Finally, development in digitalization is fundamental to realize automation technologies and services.

- Electrification could, for all modes, primarily have a large impact on costs since BEVs are cheaper to operate and mitigate less greenhouse gas emissions than ICEVs. These two factors could lead to increases in transport demand. Since Swedish rail transport already is electrified to a large extent, these benefits would affect the attractiveness of road, air and marine modes. When investigating how the electrification parameters could affect the transport system, it was shown that they (similarly to the automation parameters) first and foremost could affect the system through direct and indirect changes in the transport service supply. This is since electrification would primarily affect the generalized cost due to less fuel and societal costs. However, charging infrastructure was also considered as an electrification technology, and could impact the supply of infrastructure and lead to new activity and trade patterns.

- The digitalization technologies included in this study are broad in scope, but belong to two distinct categories: digital services and digital infrastructure. The impact analysis shows that digital services could lead to direct changes in transport demand and modal distribution since transport decision characteristics could change. For example, an increased use of online activities could potentially lead to less passenger trips whereas smart freight platforms could result in more time and cost efficient intermodal transports. Digital infrastructure parameters are, as previously discussed, enablers for several other AED technologies. This implies that they could have a more indirect effect on the transport demand and modal distribution. Furthermore, several digitalization technologies could impact every level of the system from infrastructure to activities and material flows.

Research question 2: How can the combined effects of plausible combinations of developments within AED affect transport demand, modal distribution and transport system characteristics?

- In order to structure the assessment of combined effects from AED development, three alternative scenarios were used: Partnership Society, Social Engineering 2.0 and Swimming in Data. These scenarios illustrated technological and societal developments contrasting the base scenario. Generally, the identified impacts on transport demand relate to changes in costs and efficiency. These changes would become even larger than when only considering separate technologies. For example, the removal of labor costs for drivers due to automation and decreased fuel costs due to electrification could significantly decrease the total cost for road freight transports. Furthermore, the technologies could be either drivers or results of certain societal factors, such as the spatial distribution of the population or attitudes towards data sharing, which in turn affect the characteristics of performed activities and material flows. However, the combinations in each scenario were mainly found to impact the system through direct and indirect changes in the transport service supply. These impacts are however uncertain, since AED technologies could both lead to increases and decreases in demand, depending on how transports are organized. For example, ride and vehicle sharing could potentially lead to more efficient transports and a decrease in traffic activity (VKT), but this efficiency could lead to a higher demand for utilizing these types of services, resulting in more transport activity (PKM).

- Effects from combined AED development on the modal distribution depend on the relative advancement of each mode. All scenarios, with the exception of Social Engineering 2.0, imply that AED development could lead to a dominance of road transports in the freight sector and a surge in the use of private cars in the passenger sector. This road mode dominance is a result of the previously discussed cost reductions and improvements in efficiency. In Social Engineering 2.0, rail and marine modes have developed more than or to the same extent as road modes. In this scenario, it is therefore uncertain which mode will be dominant for both passenger and freight transports. Furthermore, the modal distribution would be affected by the economic and spatial structure of the scenarios. For example, an increasingly decentralized population combined with centralized decision making could lead to improved and more attractive mass transit services such as commuter rails.

Research question 3: Are the estimates regarding transport demand, the modal distribution and/or the transport system characteristics provided by the current base forecasts for 2040 robust when accounting for developments and impacts of AED?

- The conducted impact analysis implies that all AED combinations provided by the three scenarios Partnership Society, Social Engineering 2.0 and Swimming in Data could lead to increased transport demand in relation to the estimates of the base forecasts. The modal distribution is not likely to change significantly in any scenario, with the exception of Social Engineering 2.0 where rail and marine modes could claim a larger share. A set of common factors found through the study are presented in Table 7.1.

While there is a large degree of uncertainty regarding the future development of AED, it has been shown that if the currently emerging technologies continue to develop, the estimates of the current base forecasts regarding transport demand would likely not be robust.

- It has been shown that the impacts of AED development in the scenarios not only differ due to the level of technological development but societal trends as well. Simultaneously, AED *is* a societal trend that will affect what activities people perform and what type of demand there is for goods. This complicates the findings in the study. As the base forecasts are intended to be used for national infrastructure planning, they are based on the most likely future scenarios. By choosing to evaluate other scenarios, it is clear that there would be substantial differences. However, the scenarios were needed to narrow the research scope and to reach the aim of the study, i.e. to illustrate what potential impacts there are from AED development that is not already covered in the base forecasts.

- Finally, the study has shown that there is a need to assess and evaluate transportation technologies from a service perspective and not only a technological one. Even though the transport demand of some scenarios would be similar to that of the base forecasts, new services could change the system through other mechanisms which would require changes in national infrastructure planning.

Table 7.1. Comparison between scenarios based on common factors affecting transport demand and modal distribution, compared with the base scenario. Minor decrease ▼, No change ▬, Minor increase ▲, Increase ▲ ▲, Major increase ▲ ▲ ▲.

Effects on...	**Category**	**Main factors**	**Partnership Society**	**Social Engineering 2.0**	**Swimming in Data**
Transport demand	Both	Electrification advancement	▼	▲ ▲	▲
		Automation advancement	▲	▲ ▲	▲ ▲ ▲
		Data sharing	▲	▬	▲ ▲ ▲
		Spatial distribution of population	▬	▲ ▲	▼
	Freight	E-commerce growth	▲	▲ ▲	▲ ▲ ▲
		Higher delivery frequencies	▲	▲	▲ ▲ ▲
		Longer average distance deliveries	▬	▲ ▲ ▲	▼
	Passenger	Flexible working hours due to remote-working	▲	▲ ▲	▲
		Efficient public transport system in cities	▬	▼	▲
		Private car ownership	▬	▲ ▲	▼
Modal distribution	Road	Share of road transport	▬	▼	▬
	Rail	Share of rail transport	▬	▲ ▲	▬
	Sea	Share of marine transport	▬	▲ ▲	▬

8. Future work

Based on the extensive, but inconclusive work on transport demand impacts of AED performed in this prestudy, numerous potential future studies and areas for future work are identified and listed below.

- Improved trend analysis - refinement of the AED parameter set. For this prestudy, an initial scoping and analysis of the numerous sub-trends within AED was conducted and compiled in the form of a morphological box. However, there is potential for improvement in several areas. a) Refining the selection and definition of the parameters: are there other relevant AED trends which have been omitted? Are the current parameters clearly defined? b) Refining the selection and description of attributes: are the attributes accurate descriptions of plausible developments within each parameter? c) Clarifying the relationships between the parameters and different domains of the transport system, e.g. for types of trips/freight flows, urban/non-urban, user groups, etc.). These areas can be addressed in multiple ways, but a combination of a systematic and critical survey on both academic and, in particular, non-academic technology trend literature and reports in combination with a workshop series, interviews, focus groups or surveys with a broad set of external domain experts is a straightforward alternative.
- Assessment of the Swedish national transport demand model systems' ability to represent various aspects of AED and capture relevant impacts of AED on transport demand. This prestudy has covered a wide range of AED-related developments and mechanisms through which these may affect transport demand. A next step could be to map these AED-developments and impact mechanisms to the SAMGODS and SAMPERS systems to gain an understanding of if, how and how well various (combinations of) AED developments and impacts could be represented and captured, as well as the availability or gaps of data for input parameters, etc. This assessment should also include the steps for generating input model data (e.g. for SAMGODS the generation of PWC matrices and vehicle cost parameters). This could guide both future incorporation of AED in future forecasting work but also inform future model requirements.
- Assessment of AED impacts by using the Swedish national transport demand model systems. An initial estimation of some of the effects of AED, e.g. through changes in the costs and characteristics for various transport modes, could be performed with the current model systems. This would include a considerable effort to derive input parameters. However, such a study would naturally be constrained by limitations of the

model systems and the available input data, but could provide indicative estimates for some of the AED demand impact mechanisms and it is therefore recommended that this is performed after, or in combination with the previous suggestion.

- Surveying the literature on effects of AED on activity and logistic systems, i.e. through DIM1. The primary focus in this prestudy has been how AED may affect transport services and how that, in turn, affects transport demand. However, one reflection is that it is likely that the effects of technological development on the activity system and logistic systems, land-use, trade patterns, etc. will be highly important factors for future transport demand. This would be highly important for Trafikverket's forecasting work since it is possible that historical relationships between, for instance, economic development and transport volumes will be affected by an increasing introduction of AED technologies more broadly in society. To complement the findings in this report, which only covers a small selection of these effects, a more focused literature survey on the topic would be beneficial.
- Analysis of short- and long-term responses of supply chains and inventory networks to changed freight transport services due to AED and their effects on transport demand (i.e. DIM 3). For instance, the location and use of logistics facilities such as distribution centers is typically sensitive to freight transport and logistic costs meaning that AED in general, and automation in particular, may lead to changes in the spatial structure of inventory networks. A possible approach for studying these effects is proposed by Davydenko et al. (2021).
- Deepening the impact analysis by assessing impacts more systematically for various types of trips, geographies, regions, commodity types, etc.. The introduction, uptake and impacts of AED will be highly heterogeneous and affect different parts of the (different "slices" of total transport demand) in highly different ways. A natural next step from this prestudy would be to analyze the impacts of the identified AED trends on different demand slices.
- Development of a crude tool for first-order quantitative assessments of aggregate transport demand effects. This prestudy provide a broad understanding of AED trends that could affect transport demand and also through what mechanisms such effects could materialize. As a next step, it would be useful to develop a simple quantitative tool for making rough assessments of the impacts of AED on transport demand. For instance, this could be constructed by utilizing data from the base forecasts broken down in relevant categories (as discussed the previous paragraph) and then introduce parameters for representing relative changes in demand per category based on assumed effects of AED per model parameter guided by the impact analysis in this prestudy.

- A deep dive into emerging or changing transport services and business models resulting from the AED development. While there has been an ambition in this prestudy to analyze how transport services will be affected by AED, there is much more that can be done within this field and this should be a prioritized area so that a deeper understanding of how the business and market logics for various actors on the future transport market may look like.
- Utilizing forecasting methods from the field of future-oriented technology analysis (FTA) to improve the foresight on plausible AED development paths and their relative feasibility. It is yet highly uncertain what development we can “expect” within different AED trends, and what scenarios are more likely than others within the coming 10, 20, 30 years ahead. Such assessments have been outside the scope of this prestudy, but is an important topic for future work.

9. References

AB Volvo. 2019. “Vera’s First Assignment: Volvo Trucks Presents an Autonomous Transport between a Logistics Centre and Port.” Press release. June 13, 2019. https://www.volvogroup.com/en-en/news/2019/jun/news-3336083.html.

———. 2020. “Why Autonomous Transport Will Happen in Quarries and Light Mining First.” Press release. September 7, 2020. https://www.volvoautonomoussolutions.com/en/news/press-releases/2020/sep/why-autonomous-transport-will-happen-in-quarries-and-light-mining-first.

———. 2021. “Volvo Partners with Aurora to Accelerate the Deployment of Autonomous Transport Solutions.” Press release. March 30, 2021. https://www.volvogroup.com/en-en/news/2021/mar/news-3932948.html.

Ackerman, Evan. 2021. “Robot Trucks Overtake Robot Cars: This Year, Trucks Will Drive Themselves on Public Roads with No One on Board.” *IEEE Spectrum*, January 2021.

ALICE. 2019. “Zero Emissions Logistics 2050 Roadmap ALICE.”

Almlöf, Erik, Mikael Nybacka, and Anna Pernestål. 2020. “Will Public Transport Be Relevant in a Self-Driving Future? A Demand Model Simulation of Four Scenarios for Stockholm, Sweden.” *Transportation Research Procedia* 49: 60–69. https://doi.org/10.1016/j.trpro.2020.09.006.

Altuntaş Vural, Ceren, Violeta Roso, Árni Halldórsson, Gabriella Ståhle, and Marina Yaruta. 2020. “Can Digitalization Mitigate Barriers to Intermodal Transport? An Exploratory Study.” *Research in Transportation Business & Management* 37 (December): 100525. https://doi.org/10.1016/j.rtbm.2020.100525.

Álvarez, Asunción, and Tom Ritchey. 2015. “Applications of General Morphological Analysis” 4 (1): 41.

Andersson, Alexandra, and Daniel Kulin. 2019. “Elbilsläget 2018.Pdf.” Power Circle.

Bamberg, Sebastian, Marcel Hunecke, and Anke Blöbaum. 2007. “Social Context, Personal Norms and the Use of Public Transportation: Two Field Studies.” *Journal of Environmental Psychology* 27 (3): 190–203. https://doi.org/10.1016/j.jenvp.2007.04.001.

Ben-Akiva, Moshe, and Gerard de Jong. 2013. “The Aggregate-Disaggregate-Aggregate (ADA) Freight Model System.” In *Freight Transport Modelling*, edited by Moshe Ben-Akiva, Hilde Meersman, and Eddy Van de Voorde, 69–90. Emerald Group Publishing Limited. https://doi.org/10.1108/9781781902868-004.

Bieser, Jan, and Lorenz Hilty. 2018. “Assessing Indirect Environmental Effects of Information and Communication Technology (ICT): A Systematic Literature Review.” *Sustainability* 10 (8): 2662. https://doi.org/10.3390/su10082662.

Bin, Elisa, Claudia Andruetto, Yusak Susilo, and Anna Pernestål. 2021. “The Trade-off Behaviours between Virtual and Physical Activities during the First Wave of the COVID-19 Pandemic Period.” *European Transport Research Review* 13 (1): 14. https://doi.org/10.1186/s12544-021-00473-7.

Bishop, Richard. 2020. “Driverless Trucking Not Slowing Down But The Ride Is Getting Bumpier.” Forbes. September 20, 2020. https://www.forbes.com/sites/richardbishop1/2020/09/20/driverless-trucking-not-slowing-down-but-the-ride-is-getting-bumpier/.

Bontekoning, Yvonne, and Hugo Priemus. 2004. “Breakthrough Innovations in Intermodal Freight Transport.” *Transportation Planning and Technology* 27 (5): 335–45. https://doi.org/10.1080/0308106042000273031.

Borgh, Martin, Mathias Broman, Viktor Daun, Joanne Ellis, Olov Lundbäck, Vendela Santén, and Magnus Wikander. 2018. “Elektrifiering av sjöfarten - en nulägesbeskrivning av teknik och marknadsläge inom maritim elektrifiering och analys av behov och möjligheter för elektrifiering inom sjöfarten,” 53.

Börjeson, Lena, Mattias Höjer, Karl-Henrik Dreborg, Tomas Ekvall, and Göran

Finnveden. 2006. “Scenario Types and Techniques: Towards a User’s Guide.” *Futures* 38 (7): 723–39. https://doi.org/10.1016/j.futures.2005.12.002.
Buchman, Eytan. 2021. “Rate Comparison and Marketplaces—The Platform Era and Global Freight.” In *Disrupting Logistics: Startups, Technologies, and Investors Building Future Supply Chains*, edited by Christian Wurst and Luca Graf, 65–77. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-61093-7_6.
Burul, Dona, and David Algesten. n.d. “Life Cycle Assessment of Distribution Vehicles Battery Electric vs Diesel Driven (Scania).Pdf.” Scania Group.
Cambridge dictionary. 2021. “Electrification.” 2021. https://dictionary.cambridge.org/dictionary/english/electrification.
Chan, Ching-Yao. 2017. “Advancements, Prospects, and Impacts of Automated Driving Systems.” *International Journal of Transportation Science and Technology* 6 (3): 208–16. https://doi.org/10.1016/j.ijtst.2017.07.008.
Chen, Chun-Miin (Jimmy), and Yajun Lu. 2020. “Shipment Sizing for Autonomous Trucks of Road Freight.” *The International Journal of Logistics Management* ahead-of-print (ahead-of-print). https://doi.org/10.1108/IJLM-01-2020-0052.
Chottani, Aisha, Greg Hastings, John Murnane, and Florian Neuhaus. 2018. “Distraction or Disruption? Autonomous Trucks Gain Ground in US Logistics.” McKinsey & Company. https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/distraction-or-disruption-autonomous-trucks-gain-ground-in-us-logistics.
Chung, Gina, Dora Virag, Dr Nikolaus Bubner, Dr Philipp Bodenbenner, and Joseph Noronha. 2016. “LOGISTICS TREND RADAR,” 55.
Combes, François. 2014. “Inventory Theory and Freight Transport Modelling.” In *Modelling Freight Transport*, 89–115. Elsevier. https://doi.org/10.1016/B978-0-12-410400-6.00005-7.
Creutzig, Felix, Martina Franzen, Rolf Moeckel, Dirk Heinrichs, Kai Nagel, Simon Nieland, and Helga Weisz. 2019. “Leveraging Digitalization for Sustainability in Urban Transport.” *Global Sustainability* 2: e14. https://doi.org/10.1017/sus.2019.11.
Curtis, Carey, Sam McLeod, John Hultén, Fredrik Pettersson-Lofstedt, Alexander Paulsson, and Claus Hedegaard Sørensen. 2021. “Knowledge for Policy-Making in Times of Uncertainty: The Case of Autonomous Vehicle Model Results.” *Transport Reviews* 41 (4): 478–98. https://doi.org/10.1080/01441647.2020.1857885.
Daduna, Joachim R. 2020. “Automated and Autonomous Driving in Freight Transport - Opportunities and Limitations.” In *Computational Logistics*, edited by Eduardo Lalla-Ruiz, Martijn Mes, and Stefan Voß, 12433:457–75. Lecture Notes in Computer Science. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-59747-4_30.
Davydenko, Igor Y, Lorant A Tavasszy, and Hans Quak. 2021. “On the Cost Elasticity of Inter-Regional Distribution Structures: A Case Study for the Netherlands,” 18.
De Jong, Gerard. 2008. “34. Value of Freight Travel-Time Savings.” In *Handbook of Transport Modelling (2nd Edition)*, edited by David A. Hensher and Kenneth J. Button. Emerald, Inc. https://app.knovel.com/hotlink/pdf/id:kt00A1UNG3/handbook-transport-modelling/value-freight-travel.
Dijck, José van, Thomas Poell, and Martijn de Waal. 2018. *The Platform Society: Public Values in a Connective World*. Oxford University Press.
Doll, Georg, Eike Ebel, Kersten Heineke, Martin Kellner, and Charlotte Wiemuth. 2020. “Private Autonomous Vehicles - The Other Side of the Robo-Taxi Story (Doll et al., 2020).Pdf.” McKinsey & Company.
Egbue, Ona, and Suzanna Long. 2012. “Barriers to Widespread Adoption of Electric Vehicles: An Analysis of Consumer Attitudes and Perceptions.” *Energy Policy* 48 (September): 717–29. https://doi.org/10.1016/j.enpol.2012.06.009.
Einride. 2018. “The World’s First Self-Driving Truck on Public Roads — to Be

Introduced in Sweden." April 18, 2018. https://www.einride.tech/the-worlds-first-self-driving-truck-on-public-roads-to-be-introduced-in-sweden.
———. 2020. "Einride Launches Next-Generation Pod, Makes Autonomous e ..." Einride, Intelligent Technologies for Movement. October 8, 2020. https://www.einride.tech/press/einride-launches-next-generation-pod-makes-autonomous-electric-transport.
———. 2021. "SKF and Einride Enter into Partnership for Testing Auton ..." Einride, Intelligent Technologies for Movement. March 16, 2021. https://www.einride.tech/press/skf-and-einride-enter-into-partnership-for-testing-autonomous-and-electric.
Emilsson, Erik, and Lisbeth Dahllöf. 2019. "Lithium-Ion Vehicle Battery Production," 47.
Encyclopedia Britannica. 2021. "Automation | Technology, Types, Rise, History, & Examples." Encyclopedia Britannica. 2021. https://www.britannica.com/technology/automation.
"Encyclopedia of Information Science and Technology, Fourth Edition." n.d. https://www.igi-global.com/dictionary/it-strategy-follows-digitalization/7748.
Engholm, Albin. 2021. "Driverless Trucks in the Swedish Freight Transport System: An Analysis of Future Impacts on the Transport System and the Emerging Innovation System." KTH Royal Institute of Technology.
Engholm, Albin, Anna Björkman, Yuri Joelsson, Ida Kristoffersson, and Anna Pernestål. 2020. "The Emerging Technological Innovation System of Driverless Trucks." *Transportation Research Procedia* 49: 145–59. https://doi.org/10.1016/j.trpro.2020.09.013.
https://doi.org/10.1016/j.trpro.2020.09.013.
Engholm, Albin, Ida Kristoffersson, and Anna Pernestål. 2021. "Impacts of Large-Scale Driverless Truck Adoption on the Freight Transport System." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3774193.
Engholm, Albin, Anna Pernestål, and Ida Kristoffersson. 2020. "Cost Analysis of Driverless Truck Operations." *Transportation Research Record: Journal of the Transportation Research Board* 2674 (9): 511–24. https://doi.org/10.1177/0361198120930228.
Engström, Johan, Richard Bishop, Steven E. Shladover, Michael C. Murphy, Laurence O'Rourke, Tom Voege, Bob Denaro, Richard Demato, and Divya Demato. 2019. "Deployment of Automated Trucking: Challenges and Opportunities." In *Road Vehicle Automation 5*, edited by Gereon Meyer and Sven Beiker, 149–62. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-94896-6_13.
ERTRAC. 2019. "Long Distance Freight Transport -A Roadmap for System Integration of Road Transport." Brussels, Belgium: ERTRAC. https://www.ertrac.org/uploads/documentsearch/id56/ERTRAC-Long-duty-Freight-Transport-Roadmap-2019.pdf.
Ferguson, Dave. 2020. "Introducing R2, Nuro's Next Generation Self-Driving Vehicle." *Nuro* (blog). February 6, 2020. https://medium.com/nuro/introducing-r2-nuros-next-generation-self-driving-vehicle-a9974ff6c2e0.
Flämig, Heike. 2016. "Autonomous Vehicles and Autonomous Driving in Freight Transport." In *Autonomous Driving*, edited by Markus Maurer, J. Christian Gerdes, Barbara Lenz, and Hermann Winner, 365–85. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-48847-8_18.
Flodén, Jonas, Fredrik Bärthel, and Edith Sorkina. 2017. "Transport Buyers Choice of Transport Service – A Literature Review of Empirical Results." *Research in Transportation Business & Management* 23 (June): 35–45. https://doi.org/10.1016/j.rtbm.2017.02.001.
Fossilfritt Sverige. 2019. "Färdplan För Fossilfri Konkurrenskraft: Fordonsindustrin - Lätta Fordon."
———. 2020. "Färdplan För Fossilfri Konkurrenskraft: Fordonsindustrin - Tunga

Fordon.”
Fulton, Lewis M., Jacob Mason, and Dominique Meroux. 2017. “Three Revolutions in Urban Transportation.” UCDavis, ITDP. https://steps.ucdavis.edu/wp-content/uploads/2017/05/ITDP-3R-Report-v6-1.pdf.
Ghandriz, Toheed, Bengt Jacobson, Leo Laine, and Jonas Hellgren. 2020. “Impact of Automated Driving Systems on Road Freight Transport and Electrified Propulsion of Heavy Vehicles.” *Transportation Research Part C: Emerging Technologies* 115 (June): 102610. https://doi.org/10.1016/j.trc.2020.102610.
Government of Netherlands. 2019. “Smart Shipping: Comprehensive Automation in the Maritime Sector.” Onderwerp. Ministerie van Algemene Zaken. May 20, 2019. https://www.government.nl/topics/maritime-transport-and-seaports/smart-shipping-comprehensive-automation-in-the-maritime-sector.
Hagberg, Johan, Malin Sundstrom, and Niklas Egels-Zandén. 2016. “The Digitalization of Retailing: An Exploratory Framework.” *International Journal of Retail & Distribution Management* 44 (7): 694–712. https://doi.org/10.1108/IJRDM-09-2015-0140.
Harris, Irina, Yingli Wang, and Haiyang Wang. 2015. “ICT in Multimodal Transport and Technological Trends: Unleashing Potential for the Future.” *International Journal of Production Economics* 159 (January): 88–103. https://doi.org/10.1016/j.ijpe.2014.09.005.
Hartmann, Evi, Hendrik Birkel, and Matthias Kopyto. 2021. “Outsourcing Logistics Functions.” In *International Encyclopedia of Transportation*, 102–6. Elsevier. https://doi.org/10.1016/B978-0-08-102671-7.10227-1.
Hawkins, Jason, and Khandker Nurul Habib. 2019. “Integrated Models of Land Use and Transportation for the Autonomous Vehicle Revolution.” *Transport Reviews* 39 (1): 66–83. https://doi.org/10.1080/01441647.2018.1449033.
Henriksson, Malin, Jacob Witzell, and Karolina Isaksson. 2019. “All Change or Business as Usual? The Discursive Framing of Digitalized Smart Accessibility in Sweden.” In *Transportation Research Procedia*, 41:625–36. Elsevier. https://doi.org/10.1016/j.trpro.2019.09.112.
Holguín-Veras, José, Lokesh Kalahasthi, Shama Campbell, Carlos A. González-Calderón, and Xiaokun (Cara) Wang. 2021. “Freight Mode Choice: Results from a Nationwide Qualitative and Quantitative Research Effort.” *Transportation Research Part A: Policy and Practice* 143 (January): 78–120. https://doi.org/10.1016/j.tra.2020.11.016.
Holguín-Veras, Jose, Ning Xu, Gerard de Jong, and Hedi Maurer. 2011. “An Experimental Economics Investigation of Shipper-Carrier Interactions in the Choice of Mode and Shipment Size in Freight Transport.” *Networks and Spatial Economics* 11 (3): 509–32. https://doi.org/10.1007/s11067-009-9107-x.
Holland-Letz, Daniel, Matthias Kässer, Benedikt Kloss, and Thibaut Müller. 2021. “Mobility’s Future: An Investment Reality Check,” 9.
Hook, Andrew, Victor Court, Benjamin K Sovacool, and Steve Sorrell. 2020. “A Systematic Review of the Energy and Climate Impacts of Teleworking.” *Environmental Research Letters* 15 (9): 093003. https://doi.org/10.1088/1748-9326/ab8a84.
Huang, Yantao, and Kara M. Kockelman. 2020. “What Will Autonomous Trucking Do to U.S. Trade Flows? Application of the Random-Utility-Based Multi-Regional Input–Output Model.” *Transportation* 47 (5): 2529–56. https://doi.org/10.1007/s11116-019-10027-5.
International Transport Forum. 2021. *ITF Transport Outlook 2021*. ITF Transport Outlook. OECD. https://doi.org/10.1787/16826a30-en.
ITF. 2017. “Managing the Transition to Driverless Road Freight Transport.” Case-Specific Policy Analysis. Paris, France: OECD Internation Transport Forum. https://www.itf-oecd.org/sites/default/files/docs/managing-transition-driverless-road-freight-transport.pdf.

Jaller, Miguel, Carlos Otero, Elham Pourrahmani, and Lew Fulton. 2020. “Automation, Electrification, and Shared Mobility in Freight.” Research report PSR-UCD-18-24. UCDavis. https://escholarship.org/uc/item/91h9v9zm.
Jansson, Emil. 2020. “Automatic train operation i Sverige,” 29.
Jennings, Dylan, and Miguel Figliozzi. 2019. “Study of Sidewalk Autonomous Delivery Robots and Their Potential Impacts on Freight Efficiency and Travel.” *Transportation Research Record: Journal of the Transportation Research Board* 2673 (6): 317–26. https://doi.org/10.1177/0361198119849398.
Jong, Gerard C de, and Odette van de Riet. 2008. “The Driving Factors of Passenger Transport,” 24.
Jong, Gerard de. 2021. “Value of Time in Freight Transport.” In *International Encyclopedia of Transportation*, 321–25. Elsevier. https://doi.org/10.1016/B978-0-08-102671-7.10061-2.
Jong, Gerard de, and Jaap Baak. 2020. “Method Report - Logistics Model in the Swedish National Freight Model System.” Significance. https://www.trafikverket.se/contentassets/ab220f9016154ef7a8478555560bb280/2020/method-report-of-the-logistics-model-in-the-swedish-national-freight-model-system.pdf.
Jong, Gerard de, and Moshe Ben-Akiva. 2007. “A Micro-Simulation Model of Shipment Size and Transport Chain Choice.” *Transportation Research Part B: Methodological* 41 (9): 950–65. https://doi.org/10.1016/j.trb.2007.05.002.
Jong, Gerard de, Arno Schroten, Huib van Essen, Matthijs Otten, and Pietro Bucci. 2010. “Price Sensitivity of European Road Freight Transport – towards a Better Understanding of Existing Results.” Report 9012-1. Significance. https://www.transportenvironment.org/sites/te/files/media/2010_07_price_sensitivity_road_freight_significance_ce.pdf.
Kågeson, Per. 2019. “Klimatmål på villovägar? ESO-rapport 2019: En ESO-rapport om politiken för utsläppsminskningar i vägtrafiken.” 2019:5. Rapport till Expertgruppen för studier i offentlig ekonomi. Finansdepartementet. https://eso.expertgrupp.se/wp-content/uploads/2018/12/2019_5-Klimatmal-pa-villovagar.pdf.
Kayikci, Yasanur. 2018. “Sustainability Impact of Digitization in Logistics.” *Procedia Manufacturing* 21: 782–89. https://doi.org/10.1016/j.promfg.2018.02.184.
Khalili, Siavash, Eetu Rantanen, Dmitrii Bogdanov, and Christian Breyer. 2019. “Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World.” *Energies* 12 (20): 3870. https://doi.org/10.3390/en12203870.
Klimatpolitiska rådet. 2019. “Klimatpolitiska rådets rapport.” https://www.klimatpolitiskaradet.se/wp-content/uploads/2019/09/kprrapport190426.pdf.
Klöckner, Christian A., and Thomas Friedrichsmeier. 2011. “A Multi-Level Approach to Travel Mode Choice – How Person Characteristics and Situation Specific Aspects Determine Car Use in a Student Sample.” *Transportation Research Part F: Traffic Psychology and Behaviour* 14 (4): 261–77. https://doi.org/10.1016/j.trf.2011.01.006.
Koopmans, Carl, Wim Groot, Pim Warffemius, Jan Anne Annema, and Sascha Hoogendoorn-Lanser. 2013. “Measuring Generalised Transport Costs as an Indicator of Accessibility Changes over Time.” *Transport Policy* 29 (September): 154–59. https://doi.org/10.1016/j.tranpol.2013.05.005.
Kristoffersson, Ida, and Anna Pernestål Brenden. 2018. “Scenarios for the Development of Self-Driving Vehicles in Freight Transport.” In *Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria*.
Krstić, Mladen Dragan, Snežana Radoman Tadić, Nikolina Brnjac, and Slobodan Zečević. 2019. “Intermodal Terminal Handling Equipment Selection Using a Fuzzy Multi-Criteria Decision-Making Model.” *PROMET - Traffic&Transportation* 31 (1): 89–100. https://doi.org/10.7307/ptt.v31i1.2949.

Kulmala, Risto, Juhani Jääskeläinen, and Seppo Pakarinen. 2019. “The Impact of Automated Transport on the Role, Operations and Costs of Road Operators and Authorities in Finland.” Traficom Research Reports 6/2019. Finnish Transport and Communications Agency Traficom. https://www.traficom.fi/sites/default/files/media/publication/EU_EIP_Impact_of_Automated_Transport_Finland_Traficom_6_2019.pdf.
Lammgård, Catrin, Dan Andersson, and Linda Styrhe. 2013. “Purchasing of Transport Services: A Survey among Swedish Shippers.” In , 18. Gothenburg, Sweden.
Landborn, John, Lennart Nordberg, and Bo-Lennart Nelldal. 1981. *Lastbil Eller Järnväg? : Val Av Transportlösning För Långväga Godstransporter i Sverige. D. 2 Undersökning Av Företagens Val Av Transportlösning*. Stockholm.
Leviäkangas, Pekka. 2016. “Digitalisation of Finland’s Transport Sector.” *Technology in Society* 47 (November): 1–15. https://doi.org/10.1016/j.techsoc.2016.07.001.
Litman, Todd. 2019. “Understanding Transport Demands and Elasticities.”
———. 2021. “Autonomous Vehicle Implementation Predictions.” Victoria Transport Policy Institute. https://www.vtpi.org/avip.pdf.
Liu, Liang, Taesung Hwang, Sungwon Lee, Yanfeng Ouyang, Bumsoo Lee, Steven J. Smith, Christopher W. Tessum, et al. 2019. “Health and Climate Impacts of Future United States Land Freight Modelled with Global-to-Urban Models.” *Nature Sustainability* 2 (2): 105–12. https://doi.org/10.1038/s41893-019-0224-3.
Lumsden, Kenth. 2006. *Logistikens Grunder: Teknisk Logistik*. Studentlitteratur.
Lundberg, Sofia. 2006. “Godskunders värderingar av faktorer som har betydelse på transportmarknaden = Freight customers’ valuations of factors of importance in the transportation market.” Stockholm: Avdelningen för trafik och logistik, Kungliga Tekniska högskolan.
Machado, Cláudia, Nicolas de Salles Hue, Fernando Berssaneti, and José Quintanilha. 2018. “An Overview of Shared Mobility.” *Sustainability* 10 (12): 4342. https://doi.org/10.3390/su10124342.
Martinsen, Uni, and Maria Björklund. 2012. “Matches and Gaps in the Green Logistics Market.” *International Journal of Physical Distribution & Logistics Management*.
McNally, Michael G. 2008. “The Four-Step Model.” In *The Handbook of Transport Modeling Ch3 The Four-Step Model.Pdf*.
Melander, Lisa, Anna Dubois, Klas Hedvall, and Frida Lind. 2019. “Future Goods Transport in Sweden 2050: Using a Delphi-Based Scenario Analysis.” *Technological Forecasting and Social Change* 138 (January): 178–89. https://doi.org/10.1016/j.techfore.2018.08.019.
Milakis, Dimitris, Bart van Arem, and Bert van Wee. 2017. “Policy and Society Related Implications of Automated Driving: A Review of Literature and Directions for Future Research.” *Journal of Intelligent Transportation Systems* 21 (4): 324–48. https://doi.org/10.1080/15472450.2017.1291351.
Miskolczi, Márk, Dávid Földes, András Munkácsy, and Melinda Jászberényi. 2021. “Urban Mobility Scenarios until the 2030s.” *Sustainable Cities and Society* 72 (September): 103029. https://doi.org/10.1016/j.scs.2021.103029.
Monios, Jason, and Rickard Bergqvist. 2019. “The Transport Geography of Electric and Autonomous Vehicles in Road Freight Networks.” *Journal of Transport Geography* 80 (October): 102500. https://doi.org/10.1016/j.jtrangeo.2019.102500.
———. 2020. “Logistics and the Networked Society: A Conceptual Framework for Smart Network Business Models Using Electric Autonomous Vehicles (EAVs).” *Technological Forecasting and Social Change* 151 (February): 119824. https://doi.org/10.1016/j.techfore.2019.119824.
Moschovou, T, E I Vlahogianni, and A Rentziou. 2019. “Challenges for Data Sharing in Freight Transport.” *Working Paper Series*, 13.
Müller, Stephan, and Felix Voigtländer. 2019. “Automated Trucks in Road Freight

Logistics: The User Perspective.” In *Advances in Production, Logistics and Traffic*, edited by Uwe Clausen, Sven Langkau, and Felix Kreuz, 102–15. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-13535-5_8.
Nasir, Mohammed Haneef Abdul, Andrea Genovese, Adolf A. Acquaye, S.C.L. Koh, and Fred Yamoah. 2017. “Comparing Linear and Circular Supply Chains: A Case Study from the Construction Industry.” *International Journal of Production Economics* 183 (January): 443–57. https://doi.org/10.1016/j.ijpe.2016.06.008.
Naula, T, and L Ojala. 2002. “Advanced Logistics Services in the Baltic States (AD LOG).” *PUBLICATIONS OF THE MINISTRY OF TRANSPORT AND COMMUNICATIONS-TEDIM WORKING PAPER*.
Nelldal, Lennart, and Stehn Svalgård. 2013. “Scenariobaserad prognosmodell - förstudie,” 86.
Nicolaides, Doros, David Cebon, and John Miles. 2018. “Prospects for Electrification of Road Freight.” *IEEE Systems Journal* 12 (2): 1838–49. https://doi.org/10.1109/JSYST.2017.2691408.
Noussan, Michel, and Simone Tagliapietra. 2020. “The Effect of Digitalization in the Energy Consumption of Passenger Transport: An Analysis of Future Scenarios for Europe.” *Journal of Cleaner Production* 258 (June): 120926. https://doi.org/10.1016/j.jclepro.2020.120926.
Paulsson, Alexander, and Claus Hedegaard Sørensen. 2020. “Smart Mobility and Policy Instruments: Broadened Definitions and Critical Understandings.” In *Shaping Smart Mobility Futures: Governance and Policy Instruments in Times of Sustainability Transitions*, edited by Alexander Paulsson and Claus Hedegaard Sørensen, 1–16. Emerald Publishing Limited. https://doi.org/10.1108/978-1-83982-650-420201001.
Pernestål, Anna, Albin Engholm, Marie Bemler, and Gyözö Gidofalvi. 2021. “How Will Digitalization Change Road Freight Transport? Scenarios Tested in Sweden.” *Sustainability* 13 (1): 304. https://doi.org/10.3390/su13010304.
Pernestål, Anna, Albin Engholm, Ida Kristoffersson, and Johanna Jussila Hammes. 2020. “The Impacts of Automated Vehicles on the Transport System and How to Create Policies That Target Sustainable Development Goals.” In *Shaping Smart Mobility Futures: Governance and Policy Instruments in Times of Sustainability Transitions*, edited by Alexander Paulsson and Claus Hedegaard Sørensen, 37–53. Emerald Publishing Limited. https://doi.org/10.1108/978-1-83982-650-420201003.
PostNord. 2021. “E-Barometern Årsrapport 2020. Stockholm: PostNord.”
Power Circle. 2021a. “Elbilsstatistik.” Elbilsstatistik. 2021. https://www.elbilsstatistik.se.
———. 2021b. “Elbilsstatistik: Laddbara Bilar i Sverige 2012-2021.” Elbilsstatistik. 2021. https://www.elbilsstatistik.se/elbilsstatistik.
———. 2021c. “Vad är smart laddning? Faktablad fr¨m Power Circle,” 16.
Reimers, Jan Otto. 2018. “Introduction of Electric Aviation in Norway,” 74.
Reis, Vasco, and Rosário Macário. 2019. “Forces Shaping the Freight Transport Sector.” In *Intermodal Freight Transportation*, 1–11. Elsevier. https://doi.org/10.1016/B978-0-12-814464-0.00001-3.
Rezvani, Zeinab, Johan Jansson, and Jan Bodin. 2015. “Advances in Consumer Electric Vehicle Adoption Research: A Review and Research Agenda.” *Transportation Research Part D: Transport and Environment* 34 (January): 122–36. https://doi.org/10.1016/j.trd.2014.10.010.
Riet, Odette van de, Gerard de Jong, and Warren Walker. 2007. “Drivers of Freight Transport Demand and Their Policy Implications.” In *Building Blocks for Sustainable Transport*, edited by Adriaan Perrels, Veli Himanen, and Martin Lee-Gosselin, 73–102. Emerald Group Publishing Limited. https://doi.org/10.1108/9780857245168-005.
Rodrigue, Jean-Paul. 2020. *The Geography of Transport Systems*. Fifth edition. Abingdon, Oxon ; New York, NY: Routledge/Taylor & Francis Group.
Rotem-Mindali, Orit, and Jesse W. J. Weltevreden. 2013. “Transport Effects of E-Commerce: What Can Be Learned after Years of Research?” *Transportation* 40 (5):

867–85. https://doi.org/10.1007/s11116-013-9457-6.
Sachse, Carsten, and Fredric Almkvist. 2020. “Prognos för persontrafiken 2040 - Trafikverkets Basprognoser 2020-06-15,” 40.
SAE International. 2018. “SAE International Releases Updated Visual Chart for Its ‘Levels of Driving Automation’ Standard for Self-Driving Vehicles.” 2018. https://www.sae.org/site/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles.
———. 2021. “SAE J3016 Visual Chart.” https://www.sae.org/binaries/content/assets/cm/content/blog/sae-j3016-visual-chart_5.3.21.pdf.
Scania. 2019. “A New Cabless Concept – Revealing Scania AXL.” https://www.scania.com/content/dam/group/press-and-media/news/2019/a-new-cabless-concept-revealing-scania-axl-190924.pdf.
———. 2021. “Scania Tests Self-Driving Truck in Motorway Traffic.” https://mb.cision.com/Main/209/3278498/1367216.pdf.
Scania Group. 2020. “Scania Launches Fully Electric Truck with 250 Km Range.”
Shen, Dayong, Jiayuan Hu, Tianheng Zhai, Tao Wang, and Zhongshan Zhang. 2019. “Parallel Loading and Unloading: Smart Technology towards Intelligent Logistics.” In *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 847–51. Bari, Italy: IEEE. https://doi.org/10.1109/SMC.2019.8913852.
Sheveleva, Anna, and Evgeny Rogov. 2021. “Organization of Remote Work in the Context of Digitalization.” Edited by D. Rudoy, A. Olshevskaya, and N. Ugrekhelidze. *E3S Web of Conferences* 273: 12042. https://doi.org/10.1051/e3sconf/202127312042.
Shift2Rail.org. 2019. “Innovation in the Spotlight: Towards Unattended Mainline Train Operations (ATO GoA 4).” Shift2Rail. September 30, 2019. https://shift2rail.org:443/highlight/innovation-in-the-spotlight-towards-unattended-mainline-train-operations-ato-goa4/.
———. 2021. “Mission and Objectives.” Shift2Rail. 2021. https://shift2rail.org:443/about-shift2rail/mission-and-objectives/.
Shladover, Steven E. 2018. “Connected and Automated Vehicle Systems: Introduction and Overview.” *Journal of Intelligent Transportation Systems* 22 (3): 190–200. https://doi.org/10.1080/15472450.2017.1336053.
Short, Jeffrey, and Dan Murray. 2016. “Identifying Autonomous Vehicle Technology Impacts on the Trucking Industry.” Arlington, Virginia: American Transport Research Institute. http://truckingresearch.org/wp-content/uploads/2016/11/ATRI-Autonomous-Vehicle-Impacts-11-2016.pdf.
Simoni, Michele D., Erhan Kutanoglu, and Christian G. Claudel. 2020. “Optimization and Analysis of a Robot-Assisted Last Mile Delivery System.” *Transportation Research Part E: Logistics and Transportation Review* 142 (October): 102049. https://doi.org/10.1016/j.tre.2020.102049.
Simpson, Jesse R., Sabyasachee Mishra, Ahmadreza Talebian, and Mihalis M. Golias. 2019. “An Estimation of the Future Adoption Rate of Autonomous Trucks by Freight Organizations.” *Research in Transportation Economics*, August, 100737. https://doi.org/10.1016/j.retrec.2019.100737.
Sindi, Safaa, and Roger Woodman. 2021. “Implementing Commercial Autonomous Road Haulage in Freight Operations: An Industry Perspective.” *Transportation Research Part A: Policy and Practice* 152 (October): 235–53. https://doi.org/10.1016/j.tra.2021.08.003.
Skjött-Larsen, Tage, Ulf Paulsson, and Sten Wandel. 2003. “Logistics in the Öresund Region after the Bridge.” *European Journal of Operational Research* 144 (2): 247–56. https://doi.org/10.1016/S0377-2217(02)00391-0.
Soteropoulos, Aggelos, Martin Berger, and Francesco Ciari. 2019. “Impacts of Automated Vehicles on Travel Behaviour and Land Use: An International Review of

Modelling Studies.” *Transport Reviews* 39 (1): 29–49. https://doi.org/10.1080/01441647.2018.1523253.
Sovacool, Benjamin K., and Jonn Axsen. 2018. “Functional, Symbolic and Societal Frames for Automobility: Implications for Sustainability Transitions.” *Transportation Research Part A: Policy and Practice* 118 (December): 730–46. https://doi.org/10.1016/j.tra.2018.10.008.
Statistiska centralbyråns bibliotek. 2021. “Allt Fler Arbetar Hemifrån.” Statistiska Centralbyrån. 2021. http://www.scb.se/pressmeddelande/allt-fler-arbetar-hemifran/.
Stefansson, Gunnar. 2006. “Collaborative Logistics Management and the Role of Third-party Service Providers.” Edited by Britta Gammelgaard and Remko van Hoek. *International Journal of Physical Distribution & Logistics Management* 36 (2): 76–92. https://doi.org/10.1108/09600030610656413.
Sundin, Jonathan. 2017. “Väg eller järnväg vid transporter av gods – vad säger litteraturen? En förstudie.” TSJ 2017-3780. Transportstyrelsen. https://www.transportstyrelsen.se/4a771c/globalassets/global/publikationer/marknadsovervakning/litteraturstudie-vag-jarnvag.pdf.
Tavasszy, Lorant. 2008. “Freight Modeling: An Overview of International Experiences.” In , 10.
———. 2018. “Innovation and Technology in Mutlimodal Supply Chains.” International Transport Forum Discussion Papers. Paris: OECD Publishing. https://www.itf-oecd.org/sites/default/files/docs/innovation-technology-multimodal-supply-chains.pdf.
Tavasszy, Lóránt A. 2020. “Predicting the Effects of Logistics Innovations on Freight Systems: Directions for Research.” *Transport Policy* 86 (February): A1–6. https://doi.org/10.1016/j.tranpol.2019.11.004.
Tavasszy, Lóránt A., Kees Ruijgrok, and Igor Davydenko. 2012. “Incorporating Logistics in Freight Transport Demand Models: State-of-the-Art and Research Opportunities.” *Transport Reviews* 32 (2): 203–19. https://doi.org/10.1080/01441647.2011.644640.
Tavasszy, Lorant, Michiel de Bok, Zahra Alimoradi, and Jafar Rezaei. 2020. “Logistics Decisions in Descriptive Freight Transportation Models: A Review.” *Journal of Supply Chain Management Science* 1 (3): 13.
Tavasszy, Lóránt, and Gerard de Jong. 2014. “Introduction.” In *Modelling Freight Transport*, 1–12. Elsevier. https://doi.org/10.1016/B978-0-12-410400-6.00001-X.
Teoh, Eric R. 2021. “Effectiveness of Front Crash Prevention Systems in Reducing Large Truck Real-World Crash Rates.” *Traffic Injury Prevention* 22 (4): 284–89. https://doi.org/10.1080/15389588.2021.1893700.
Toger, Marina, Karima Kourtit, Peter Nijkamp, and John Östh. 2021. “Mobility during the COVID-19 Pandemic: A Data-Driven Time-Geographic Analysis of Health-Induced Mobility Changes.” *Sustainability* 13 (7): 4027. https://doi.org/10.3390/su13074027.
Tongur, Stefan, and Mats Engwall. 2017. “Exploring Window of Opportunity Dynamics in Infrastructure Transformation.” *Environmental Innovation and Societal Transitions* 25 (December): 82–93. https://doi.org/10.1016/j.eist.2016.12.003.
Toy, Jordan, Ben Gesing, Jonathan Ward, Joseph Noronha, and Philipp Bodenbenner. 2020a. “The Logistics Trend Radar 5th Edition.” Troisdorf, Germany: DHL Customer Solutions & Innovation.
Trafikverket. 2018. “Trafikverkets Omvärldsanalys 2018.” 2018:180. Trafikverket. https://trafikverket.ineko.se/Files/en-US/51419/Ineko.Product.RelatedFiles/2018_180_trender_i_transportsystemet_trafikverkets_omv%C3%A4rldsanalys_2018.pdf.
———. 2019. “Sveriges järnvägsnät.” Text. Trafikverket. 2019. https://www.trafikverket.se/resa-och-trafik/jarnvag/Sveriges-jarnvagsnat/.
———. 2020a. “ASEK 7.0.Pdf.”
———. 2020b. “PM Förutsättningar För Fordon, Drivmedel Och Körkostnader i

Basprognos 2020.Pdf.”
———. 2021. “Regeringsuppdrag - Analysera Förutsättningar Och Planera För En Utbyggnad Av Järnvägar.Pdf.”
Traton group. 2020. “The Traton Group and TuSimple Agreed on Global Partnership for Autonomous Trucks.” Press release. September 30, 2020. https://www.volkswagenag.com/en/news/2020/09/traton_tusimple.html.
Viscelli, Steve. 2018. “Driverless? Autonomous Trucks and the Future of the American Trucker.” Center for Labor Research and Education, University of California, Berkely and Working Partnerships USA. http://driverlessreport.org/files/driverless.pdf.
Volvo Trucks. 2021. “Eldrivna lastbilar.” 2021. https://www.volvotrucks.se/sv-se/trucks/trucks/alternative-fuels/electric-trucks.html.
Wadud, Zia. 2017. “Fully Automated Vehicles: A Cost of Ownership Analysis to Inform Early Adoption.” *Transportation Research Part A: Policy and Practice* 101 (July): 163–76. https://doi.org/10.1016/j.tra.2017.05.005.
Wadud, Zia, Don MacKenzie, and Paul Leiby. 2016. “Help or Hindrance? The Travel, Energy and Carbon Impacts of Highly Automated Vehicles.” *Transportation Research Part A: Policy and Practice* 86 (April): 1–18. https://doi.org/10.1016/j.tra.2015.12.001.
Wandel, S, C Ruijgrok, and T Nemoto. 1992. “Relationships among Shifts in Logistics, Transport, Traffic and Informatics-Driving Forces, Barriers, External Effects and Policy Options.” *Logistiska Framsteg-Nordiska Forskningsperspektiv På Logistik Och Materialadministration, Studentlitteratur, Lund*, 96–136.
Wang, Yingli, and Joseph Sarkis. 2021. “Emerging Digitalisation Technologies in Freight Transport and Logistics: Current Trends and Future Directions.” *Transportation Research Part E: Logistics and Transportation Review* 148 (April): 102291. https://doi.org/10.1016/j.tre.2021.102291.
WEF. 2016. “Digital Transformation of Industries - Logistics Industry.” White Paper REF 100616. World Economic Forum.
Wikström, Petter. 2020. “Prognos för godstransporter 2040 - Trafikverkets Basprognoser 2016,” 84.
Xiao, Yi, Zhuo Chen, and Levi McNeil. 2021. “Digital Empowerment for Shipping Development: A Framework for Establishing a Smart Shipping Index System.” *Maritime Policy & Management*, February, 1–14. https://doi.org/10.1080/03088839.2021.1894364.
Zarif, Rasheq, Chris Starks, Andy Sussman, Anusha Kukreja, and Sam Abidi. 2021. “Autonomous Trucks Leads the Way.” *Deloitte Insights*, February 17, 2021. https://www2.deloitte.com/us/en/insights/focus/future-of-mobility/autonomous-trucks-lead-the-way.html/#endnote-sup-6.
Zhang, Runsen, and Shinichiro Fujimori. 2020. “The Role of Transport Electrification in Global Climate Change Mitigation Scenarios.” *Environmental Research Letters* 15 (3): 034019. https://doi.org/10.1088/1748-9326/ab6658.

Appendix A. Deepened analysis on the impacts of automation in (road) freight transport

Several studies have assessed how automated driving systems could affect the total cost of ownership (TCO) for heavy trucks, assuming that the technology is mature and that driverless operations are legal. Wadud (2017) estimates changes in TCO for three truck types, 38t trailer-trucks, 18 tonne rigid trucks and 7,5t rigid trucks based on UK cost data. In Wadud's baseline (most likely) scenario, reductions in annual TCO are calculated to around $14 000 (22,6%) for 7.5t rigid trucks, $15 500 (19,5%) for 18t rigid trucks and $19 800 (15%) for 38t trailer trucks. Engholm et al. (2020) use a similar approach and calculate changes in TCO per TKM for three different scenarios and four truck types using Swedish data, see Table A.1.

Table A.1. Changes in TCO per TKM for driverless trucks compared to manually driven trucks by (Engholm et al. 2020).

	16 ton	24 ton	40 ton	60 ton
Pessimistic scenario	-23%	-16%	-14%	-12%
Intermediate scenario	-45%	-37%	-33%	-29%
Optimistic scenario	-58%	-52%	-48%	-43%

Ghandriz et al. (2020) study how automated driving may affect the profitability of truck electrification. They use an optimization approach to find the minimal TCO for driverless battery-electric and driverless internal combustion engine trucks for transport missions between a single origin and a single destination with varying route characteristics (e.g. distance, road hilliness, etc.). TCO is 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 replacing manually driven internal combustion engine trucks depending on trip distance.

These three studies collectively conclude that there is a potential for significant reductions in ownership and operating costs for driverless trucks compared to manually driven trucks. This would lead to reduced prices for road transport given sufficient competition. The studies by (Engholm et al. 2020) and Wadud (2017) suggest that these cost savings are robust also for fairly large increases in truck acquisition costs due to automated driving technology costs. The main reason is that reductions in driver costs, which by far is the most significant cost reduction component, is substantially larger than increases in costs due to more expensive vehicle technologies[14]. Ghandriz et al. (2020) estimate that driver cost reductions correspond to 35%-55% of total cost savings. Since driver costs are more or less uncorrelated with truck size, this means that the relative cost reduction (e.g. per TKM) is more substantial for smaller trucks than larger trucks which suggests that automated driving to some extent reduces the economy of scale benefits premiering larger trucks.

The extent of achievable labor cost reduction is an important parameter for the cost saving potential of driverless trucks but it is also an uncertain parameter. This is since automated driving systems only automate a subset, i.e. the driving task, of the tasks truck drivers typically perform (Flämig 2016) and that driverless trucks at SAE level 4 may require temporary driving assistance when operated outside their operating design domain. Solving the non-driving tasks that truck drivers typically perform, and supporting the automated driving system, will incur costs for driverless trucks that offset the cost reduction obtained by eliminating driver costs. However, the exact extent of this cost offset is uncertain and will vary for different transport applications. The tasks that need to be solved in alternate ways for driverless trucks, hereafter denoted as 'driverless operations support', can be categorized in three areas[15].

1. Supervising or supporting the automated driving system when operating outside its operational design domain by a remote human operator.
2. Non-driving tasks such as route planning, access management, document handling, administration, load surveillance, etc.
3. Activities at the "nodes", e.g. loading, unloading, charging, cleaning, load securing, vehicle inspection,etc.

One alternative for the first two categories of tasks is to base the solutions on using remote human operators, often conceptualized in the form of a "control tower" (Zhao, Darwish, and Pernestål 2020). The costs for such solutions are not yet well-researched, but can be assumed to be a function of the technology investment costs (software, hardware and, possibly, connectivity infrastructure), labor costs for operators, which in turn depend on the number of trucks that can be served by one operator (on average) and other operating costs (facilities, technology, etc.). For category 2, it may be feasible that, in time, a substantial amount of tasks

[14] As an example, to offset the cost reduction, truck acquisition costs would need to increase by 230% for the 40t truck in the intermediate scenario in the study by (Engholm et al. 2020).

[15] It is not obvious how to model these labor costs for driverless trucks when performing TCO analysis. Wadud 2017 accounts for these costs by keeping a fraction of the annual driver labor costs in the TCO also for driverless trucks. (Engholm et al. 2020) separate labor costs into two types, node costs (e.g. loading and unloading), which are assumed unchanged for driverless trucks compared to manually driven trucks, and link costs, for which a fraction of the driver costs is assumed to be required for remote support by human operators. Ghandriz et al. (2020) assume that loading and unloading of driverless trucks is automated and explicitly model costs (investments, operating- and time-costs) for various alternative technology solutions. Regarding other non-driving tasks, these are assumed to consist of a labor component and a technology investment component

can be digitized, however, for this to be feasible on a large scale, likely a broader digitalization of freight transport is required. The need for alternative solutions for activities in the nodes (category 3) is dependent on what tasks the truck driver is currently performing which differ substantially between different transport applications (e.g. commodity type) but likely also between individual flows depending on the specific logistical processes and infrastructure at individual senders and receivers. There may be several feasible solutions (and combinations thereof), for handling these tasks such as automation, see e.g (Ghandriz et al. 2020), using staff in terminals or sending/receiving facilities or process innovation. The need for, and costs of, driverless truck operations support may act as a restriction (see Section 2.3) affecting the feasibility for driverless truck transport services. As previously suggested, the extent of this restriction will most likely vary substantially for different transport flows. For instance, this could be a severe restriction for using driverless trucks for less-than-truckload services operating pick-up tours and distribution tours with multiple stops for which the truck driver currently is responsible for loading and unloading. For other applications, such as line-haul between distribution terminals, this may be much less of a restriction. Furthermore, it is feasible that the need for operational changes and investments required for driverless truck operations support may, even if profitable, act as a form of inertia for selecting driverless truck services.

The TCO-based studies that have been discussed so far (Wadud 2017; Ghandriz et al. 2020; Engholm, Pernestål, and Kristoffersson 2020) assume that driverless trucks can directly substitute manually driven trucks for a given transport assignment. However, one factor to consider is that driverless trucks with limited operating design domains may for some transport assignments require that an alternative transport chain is used compared to a manually driven truck, which would affect transport costs. This is illustrated conceptually by Figure 6.6 which represents transport costs for a simple case with a single origin and single destination. For a manually driven truck, the transport costs for performing this transport mission is composed of a loading cost (the vertical line at the origin), a driving cost (the sloped line between origin and destination) and an unloading cost (the vertical line at the destination). If a driverless truck can be used as a direct substitute to a manually driven truck, for instance as in the use case where an SAE level 4 truck is used for line-haul transport in hub-spoke networks (see Figure 4.4b). In this case, the same cost structure applies to the driverless truck but with possible changes to the node costs (in this case assumed equal to manually driven trucks) and reduced driving costs which is indicated by the reduced slope of the driving cost line compared to the manually driven truck case. However, if an alternative type of transport chain is required also the cost structure is affected. One such case is a so-called hub-to-hub model with truck transfer (see Figure 4.4c) where the driverless truck can not perform the “first/last-mile” of the route. In this case, a manual truck would first be loaded and driven to a transfer terminal in which the goods are loaded into a driverless truck (or a trailer is swapped). This adds additional node costs for the transfer (the dashed vertical line), as well as transport time. Then, the driverless truck is driven to a transfer terminal located closely to the destination where the reversed process takes place. The overall economic performance for this driverless truck operating model is therefore a tradeoff of the extent of the added transfer costs and the reduced driving costs for the driverless truck leg, which is a function of the distance of this leg. A similar principle applies to the case with remote driving for the "first/last-mile", although that instead of additional node costs, there is an increase in the driving cost during the remote driving (assuming that remote driving is more expensive than driving with a driver on board) that offsets the cost reduction during the driverless truck leg.

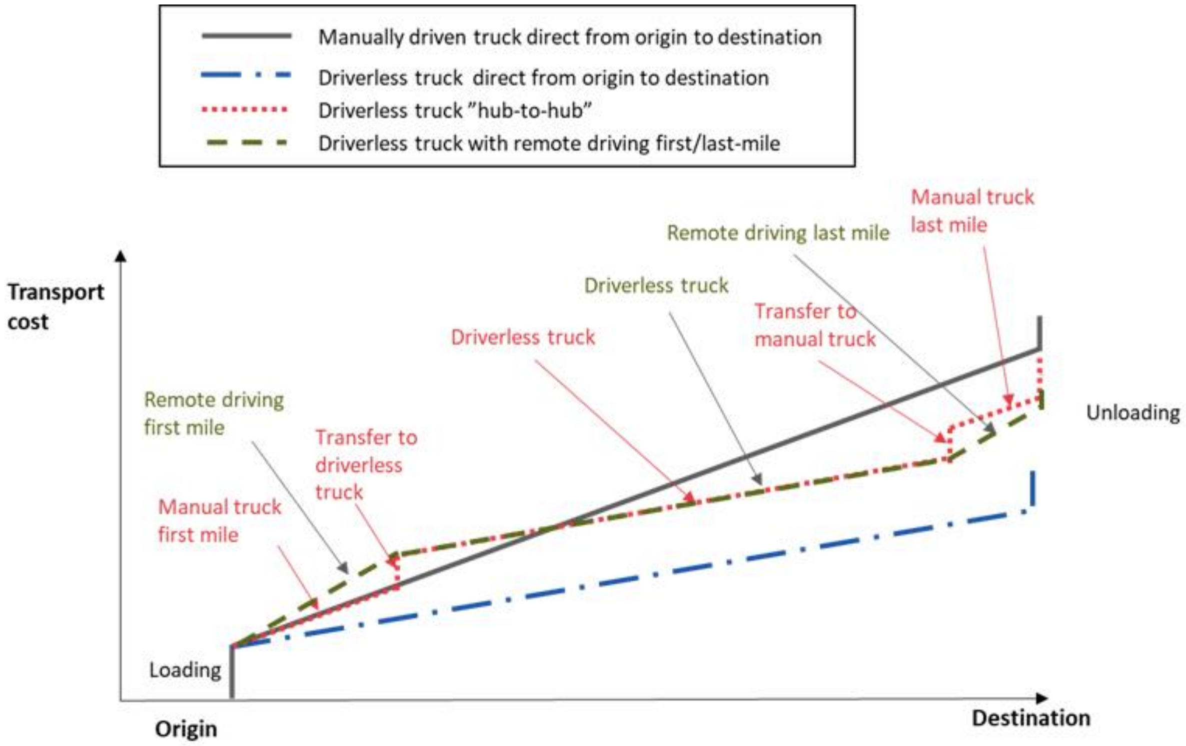

Figure A.1. Schematic illustration of the principles for transport costs for three driverless truck operating compared to a direct manually driven truck road transport. The cases illustrated in the figure assume node costs to be equal for driverless trucks and manually driven trucks. Figure developed by the authors based on research by Engholm (2021).

A large-scale use of the hub-to-hub model (attributes A2 and A3), may have considerable effect on the organization and geography of road transport. Monios and Berqvist (2019) anticipate that driverless trucks operating between transfer hubs at major destinations along the highway network (compare with Figure 6.4c), may lead to that road transport networks become similar to multimodal transport networks with driverless trucks performing long-haulage between transfer terminals, and with electrified, manually driven trucks performing the pre-and post-haulage.

Another aspect is that for long-distance transport, driverless trucks may be able to shorten transport lead times since the currently mandated hour of service restrictions that apply to manually driven trucks would reasonably not apply for driverless trucks (Short and Murray 2016) and thereby increase the average speed. Conversely, this means that truck utilization could also be increased. The reduction in lead times would decrease the inventory carrying cost during transit (Y in Eq. 1, Section 2.3) which would mean that (holding everything else equal, including transport costs) optimal shipment sizes would increase for driverless trucks (Chen and Lu 2020). Also, the reduced lead times means that the achievable transport range for a given cost would increase which could lead to a centralization of inventory localization (Chen and Lu 2020). On the other hand, the reduction in transport costs (Engholm, Pernestål, and Kristoffersson 2019; Wadud 2017; Ghandriz et al. 2020), would (holding everything else equal), lead to smaller optimal shipment sizes for driverless trucks.

Given the above discussion, it seems plausible that driverless trucks could affect both transport volumes, the modal split and the organization of road transport (e.g. through the use of transfer hubs). However, literature that quantifies these impacts on transport demand on a system-level (e.g. regional or national) is scarce with, to the authors knowledge, only a few peer-reviewed studies available.

Engholm et al. (2021)[16] use the Samgods model to analyze scenarios for a large-scale introduction of driverless trucks for Swedish freight transport flows. The analysis is based on Samgods' 2017 baseline scenario without driverless trucks, which is then modified to study various scenarios with driverless trucks. In Table 6.2, a brief summary of key results for some of the investigated scenarios is provided. In the scenario "All trucks driverless", where driverless trucks are assumed to have fully substituted manually driven trucks, road TKM on Swedish territory increases by over 20% as a result of modal shifts from rail (for which TKM is reduced by around 30%) and sea transport (-~20%). There is a relatively larger increase in road VKT which is due to that a larger share of smaller truck types are used compared to the baseline scenario. In the scenario "Hub-to-hub", in which one SAE level 4 driverless truck type that is capable of operating between road terminals in the network (equivalent to the truck transfer use case in Figure A.4c) complements the manually driven truck fleet, substantial but less drastic effects are observed, in line with what can be predicted from Figure A.6. In both scenarios the operating costs for driverless trucks are based on the intermediate cost scenario in (Engholm et al. 2020), Table 6.1.

[16] The cited paper is a preprint (version before peer-review), a peer-reviewed journal article will soon be published.

Table A.2. Summary of a selection of scenarios and results from Engholm et al. (2021).

Scenario	Road TKM [M TKM]	Road share of total TKM	Road VKT [M VKT]	Total logistics costs for all flows [M€]
Baseline	50 200	48%	2 700	22 400
All trucks driverless	61 100 +22%	60% +12pp	3 700 +35%	20 700 -8%
Hub-to-hub	55 700 +11%	54% +6pp	3 100 +15%	21 200 -5%

Another key finding in Engholm et al. (2021) is that the impacts of driverless trucks vary significantly between different commodity types, in particular in the Hub-to-hub scenario in which the access to road terminals for truck transfers located closely to origin and destination locations are important.

Further analysis of the output data from the study by Engholm et al. (2021) reveals that driverless trucks are associated with reductions in shipment sizes, although the observed effects are rather small. For instance, a smaller shipment size is chosen for 1.5% of the total number for freight flows in the All trucks driverless scenario compared to the baseline scenario, which leads to a decrease in average shipment size of 0.44 tonnes. For the subset of transport flows that are performed by road transport only in the baseline scenario (i.e. transport chains involving one or several truck legs, but no other transport modes), 2% foresee a decrease in shipment size and the average shipment size decreases by 0.24 tonnes. For the subset of transport flows performed with other modes or multimodal chains including road transport, 1.2% of flows foresee a decrease in shipment size choice and the average shipment size decreases by 0.6 tonnes. Figure A.2 shows a histogram, and mean values, of the change in shipment size for the transport flows in which there is a change in shipment size. The figure suggests that the change in shipment size is larger in non-road flows which is likely because of that many of these flows underwent modal shifts from rail or sea to road which naturally is associated with reduced shipment sizes.

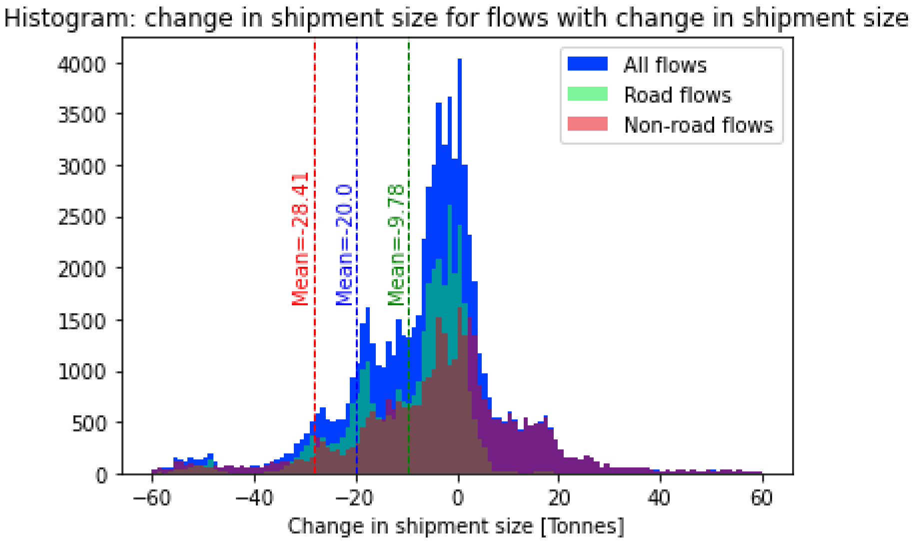

Figure A.2. Histogram of changes in shipment size for road transport flows. The X-axis is truncated at +/- 60 tonnes which hides a large left-hand side tail for non-road flows. Figure is developed by the authors based on data from Engholm et al. (2021).

There are some important limitations of the findings from Engholm et al. (2021). Firstly, since the Samgods model uses a fixed, inelastic demand (i.e. fixed freight volumes between a given production and consumption zone and commodity type), the obtained findings represent effects of driverless trucks through the demand impact mechanism 2 (DIM 2 in Section 2.3.7), i.e. there is no feedback between changed transport costs and total transport volumes. Similarly, warehousing locations (i.e. patterns of inventory networks) are fixed and determined exogenously (through Samgods' use of fixed so-called "PWC matrices"). In other words, the observed effects can be interpreted as impacts of driverless trucks assuming the freight transport system and logistics system as of 2017. Secondly, no changes in transport lead times (average speeds) are modeled for driverless trucks compared to manually driven trucks.

Huang and Kockelman (2020) uses a multiregional input-output model with a random-utility-based mode-choice model that includes road and rail transport (the "RUMBRIO" model to study the impacts of driverless trucks on freight flows and trade patterns in the U.S. In contrast to the Samgods model used by Engholm et al. (2021), RUMBRIO endogenously models origin choices. Under the assumption that driverless trucks reduces road transport costs by 25% compared to manually driven trucks, road TKM increases by 11%, which is due to a combination of mode shifts and due to an increase in total TKM (+4% for domestic, +2% for export) due to changed origin choices. The increase in total TKM is an example of an effect occurring due to DIM 3 (see Section 2.3.7), i.e. that changes in transport supply affect trade patterns and material flows.

While the impacts of driverless trucks on the modal competition are considered in isolation from automation within other domains, road transport will become more competitive compared to the other modes since the marginal costs for road transport would decrease (illustrated by the decreased slope for the dashed red line in Figure 6.8). However, automation of processes within multimodal terminals, harbors and rail terminals could decrease load handling costs and reduce costs for rail, sea and multimodal transport, as is illustrated as reduced fixed costs for rail and sea in Figure 6.8. Therefore, estimating the net impact of automation on the modal shares of freight transport requires a multimodal systems perspective.

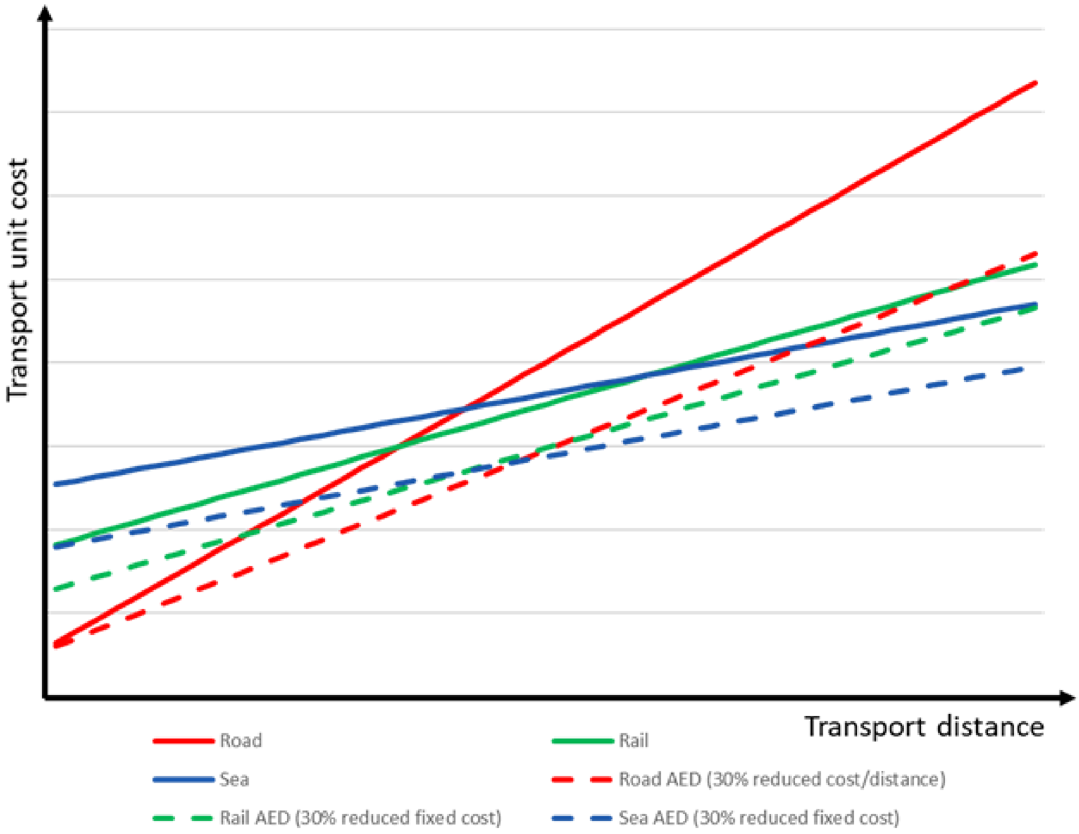

Figure A.3. Illustration of the effects of automation of road transport and rail, sea and multimodal terminals on transport costs. Filled lines represent the current situation and the dashed lines represent the situation after automation technology has become widespread. Note that this is just a conceptual illustration and is not based on any real world data or elaborate calculations.

Appendix B. Summary of freight system framework by Wandel et al. (1992)

Wandel et al. (1992) developed a hierarchical three-layered model to analyze freight transport system components. Figure A.1 shows three layers of material flow, transport flow, and infrastructure in the model.

The first layer (material flow): Manufacturing processes and trading create needs for the movement of material and goods between different nodes via links. Examples of these nodes are production, assembly, storage, and display nodes. Also, the demand for links can be expressed in terms of tons per year, shipment size, frequency, lead time, delivery precision, and flexibility. Aggregated demand of all nodes creates the total demand for freight transport services.

The second layer (transport flow/network): Transport services companies create needs for the flow of load units (including boxes, pallets, containers, swap bodies, and trailers) and vehicles (including trucks, trains, ships, and airplanes) between nodes. Examples of these nodes are modal change, transshipment, sorting, consolidation, and deconsolidation. The supply of transport flow can be expressed with similar parameters of the material flow. In addition, aggregated supply of all transport activities of all nodes creates the total supply of logistics transport services.

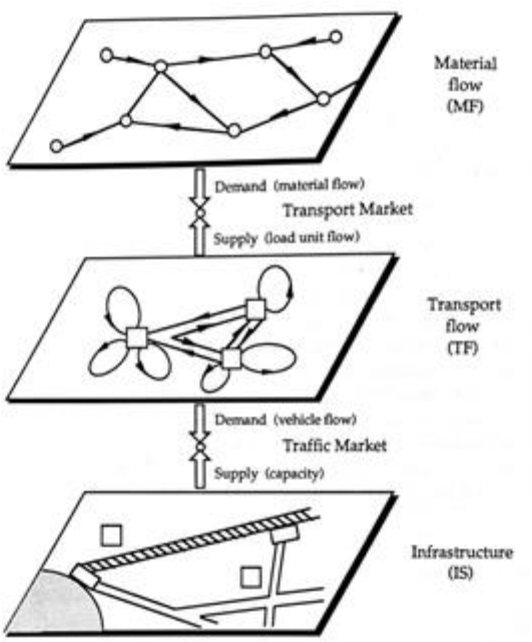

Figure A.1. Three Layers Model of Freight Transport by Wandel et al. (1992).

Transport market: Actual material and load unit flows happen in the transport market where supply and demand are matched. Load factor, unsatisfied demand, service quality level, etc., can be used to evaluate the efficiency of the market. It is possible to have load unit flow without material flow in some specific links and periods, such as backhauls of empty trailers.

The third layer (infrastructure): In this layer, infrastructural networks such as physical nodes and links provide supply opportunities for the previous layers. Traffic systems are described as the physical infrastructure, guideways and interchanges (e.g. roads and intersections, rail tracks and switches, sea passages and harbors, and air corridors and airports, and pipelines), and infrastructure management. This layer creates supply capacity in terms of space and time for vehicle movements.

Traffic market: Actual vehicle flows happen in the traffic market due to the matching between supply and demand. Strategies such as queuing time, priorities, road charges, or traffic restrictions are utilized in the market to allocate limited capacity. In the traffic market, the amount of vehicles per hour, hours of congestion per day, unsatisfied trip demand, trip time reliability, etc., can be used as the efficiency factors of this market.

The initial three layer model by Wandel et al. (1992) has been extended and analyzed in many different studies from various perspectives, including Naula and Ojala 2002; Skjött-Larsen, Paulsson, and Wandel 2003; Stefansson 2006; Lumsden 2006; Martinsen and Björklund 2012; Monios and Bergqvist 2020.

Appendix C. Preliminary version of updated theoretical framework for AED impacts developed in Workshop 3

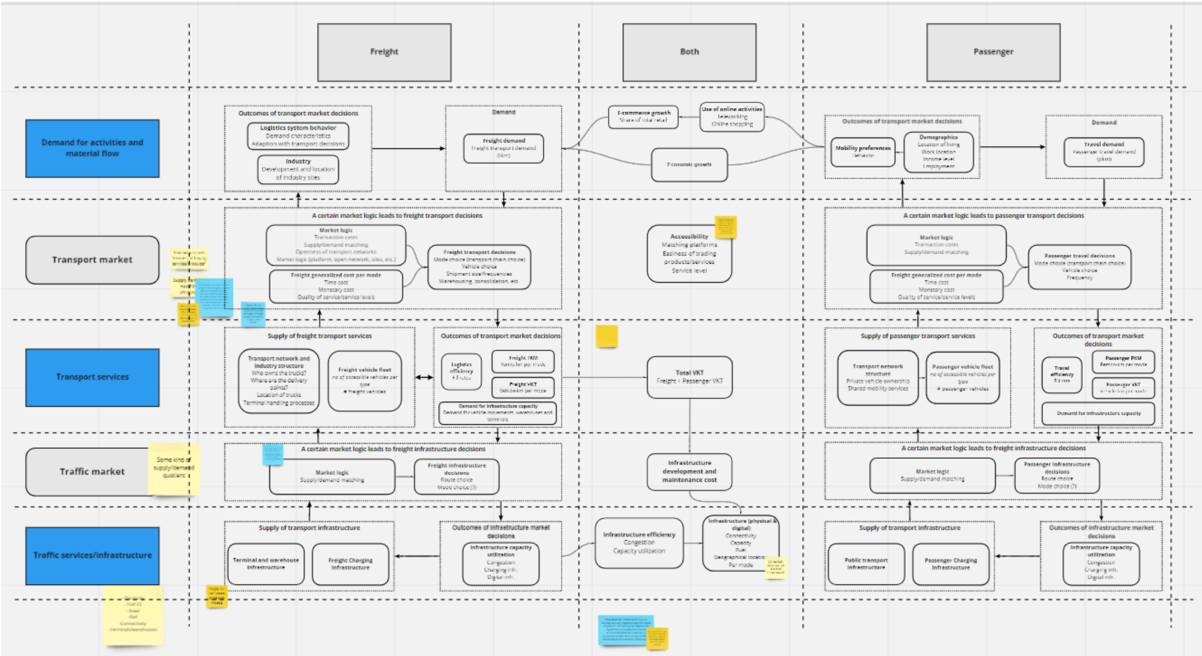

Figure C.1. Research conceptual model.

Appendix D. Background

On a global level, the demand for transport is expected to increase substantially in the coming decades. The forecasted development is driven mainly by expected population growth and economic development resulting in increasing trade and consumption. According to the most recent ITF Transport Outlook, global transport demand would increase by more than 200 % in 2050 compared to 2015 in the baseline scenario. With current decarbonization policies, there would still be a 16 % increase in CO_2 emissions from transportation. Through more efficient policies, a 70 % reduction could be possible (International Transport Forum 2021).

In addition to the demographic and macroeconomic aspects that are the primary factors accounted for in these forecasts, both the academic and grey literature stresses that other technological, social, and economical developments could materialize and have significant impacts on the freight transport system during the coming decades. These could either take place at the societal level and have indirect impacts on freight transport, for instance, an increasingly circular economy that changes consumption patterns and material flows and thereby affect the demand for freight transport, or transport and logistic innovations that directly influence the freight transport system (Trafikverket 2018). Tavasszy (2020) highlights five areas of logistics innovation that could have significant impacts on freight transport in the coming decades, mass-individualized logistics services, globalization dynamics, network integration and synchronization, digitalization, and vehicle technologies. There are many emerging technologies and innovations that are expected to affect logistics and freight transport, within the coming decade, see Figure D.1 for a summary of trends included in the 5th edition of the DHL trend radar (Toy et al. 2020).

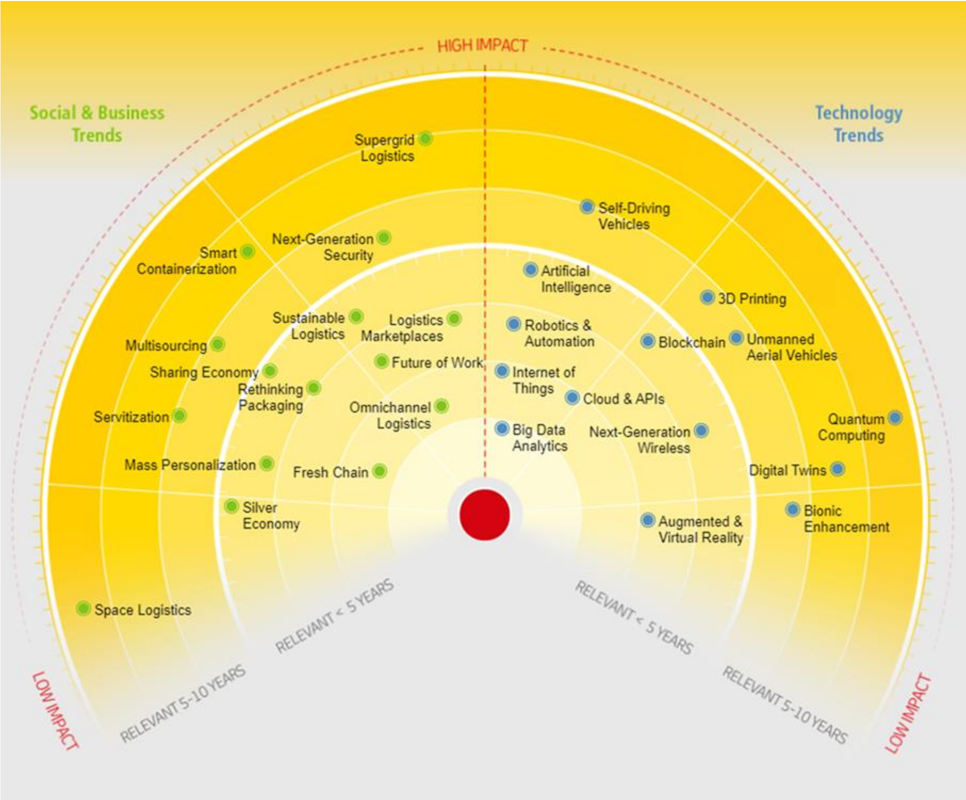

Figure D.1. A summary of the DHL trend radar (Toy et al. 2020).

However, it is currently unclear what alternative coherent combinations of emerging technologies are feasible and what the impacts would be for freight transport and supply chains (Lorant Tavasszy 2018). One ambition to create a holistic framework for integrating emerging technologies within the future freight transport system that has gained widespread interest is the concept of the Physical Internet. Physical Internet intends to drastically increase transport and resource efficiency through an open, standardized, and automated transport network enabled through a continuous exchange of digital information (ALICE 2019). Several publications highlight that digitalization is a critical technological factor to achieve a more efficient logistics and freight transport system since it in various ways can increase asset and resource utilization through better matching of freight demand and supply (Wang and Sarkis 2021; WEF 2016).

A study by Melander et al. (2019) assessed the views of transport experts about the probability, impact and desirability for a set of possible developments within consumer behavior, the transport industry, automation and digitalization, urban transport, energy solutions, and policy and public investments in Swedish freight transport until 2050. There was a high degree of variance in the experts' opinions about the probability of the developments indicating that there is significant uncertainty in how the future freight transport system may look like. The three developments assumed most likely to materialize were 1) all road vehicles are connected and communicate with each other and infrastructure 2) fossil fuels have been replaced by other solutions 3) business models for transport solutions have been subject to dramatic change. The three developments assumed to have the highest impact 1) business models for transport solutions have been subject to dramatic change 2) all trucks are driverless 3) a majority of households use home delivery for all food and consumer products.

From a long-term transport planning perspective, dealing with the potential AED developments is an important but challenging issue. In particular, understanding the possibly substantial impacts on transport demand is an important knowledge area from several planning perspectives. AED needs to be considered when assessing demand for transport infrastructure ("how will AED affect transport demand for various types of transport modes and geographies?") but also for strategic planning issues (e.g. "what are the consequences of AED for our ability to reach societal and sustainability goals?", and "Is there a need for new or changed policy instruments?"). However, addressing these questions are made complicated by the uncertain nature of the AED development which makes it challenging (and potentially even misleading) to create a single AED forecast representing the "most probable development" that can be used within a conventional forecast based planning process. Adding to the complexity is that infrastructure investments in themselves could have an important shaping role of the AED development, for example by investments in infrastructure "enabling" the introduction of automated vehicles (Kulmala, Jääskeläinen, and Pakarinen 2019), or through investments in electric road systems (or other charging solutions) that shapes the landscape for vehicle electrification (Tongur and Engwall 2017). Furthermore, the ability of existing passenger transport demand modeling approaches to provide meaningful estimates of AED impacts have been questioned and it has been suggested that transport models should instead, in this context, rather be used as one of several tools to conceptualize possible futures (Curtis et al. 2021). A related critique of current model systems is targeted at equilibrium-based models that simulate a static scenario event (e.g. a scenario year) which represent system changes as a discrete event (e.g. the addition of new transport infrastructure or a new policy). However, the introduction of new transport technologies (e.g. automated vehicles) will take place as a dynamic process, and the dynamic of this introduction will likely be important for how the transport system co-evolves with the new technology (Hawkins and Nurul Habib 2019).

Appendix E. Methodological considerations

E.1 Using scenarios to study an uncertain future

Scenarios can be used for a variety of purposes and there are several scenario development methods. Börjeson et al. (2006) provide a typology which is summarized in the following paragraphs. The typology separates scenario types based on which strategic question they are associated with, as illustrated in Figure E.1. Two other important aspects for characterising scenarios are the system structure which are the causal relationships within the system and the delineation of internal and external factors (i.e. factors that are controllable or non-controllable for the specific actor).

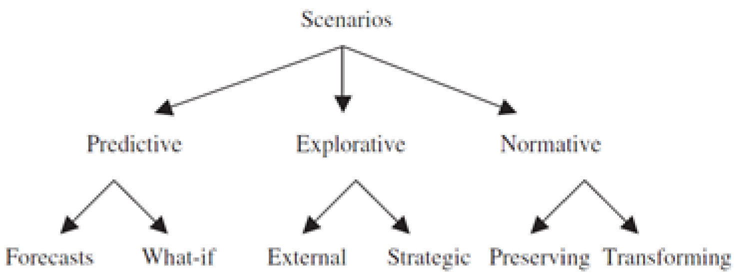

Figure E.1. A scenario typology distinguishing between different categories and types of scenarios by (Börjeson et al., 2006).

Predictive scenarios revolve around the question “what will happen?” and are intended to predict future development. Typically, it is assumed that the current and historical system structure will prevail over time which means that given an accurate system model, the causal response of the system for a given set of external inputs can be estimated. Forecasts are one type of predictive scenarios that are intended to reflect the development assumed to be most likely. Forecasts are therefore, to a large extent, an exercise of identifying the most probable development of external factors. A forecast often acts as a reference point which other plausible developments can be evaluated against. Often, the forecast is accompanied by a number of scenarios representing a span of probable outcomes, for instance by changing the assumptions in one or a few of the external factors to assess the sensitivity for uncertainty in external factors. What-if scenarios are different types of predictive scenarios that are used to assess what will happen given a specific event that influences external and/or internal factors that are important for the system under study. The events studied in what-if scenarios typically constitute a fundamental and clear difference for the system (e.g. whether a large infrastructure investment is carried out or not, or whether a policy package is passed or not). Explorative scenarios address another type of question, namely “what can happen?”. In contrast to focusing on the most probable development, as in predictions, these scenarios are used to understand the nature and variability of several plausible futures. Explorative scenarios are to some degree similar to what-if scenarios but consider more drastic change to the system and also consider developments for which the system structure may change. External explorative scenarios focus on factors beyond the control of the own organisation, while strategic explorative scenarios are used to assess the impacts of strategic decision by the own organisation. Normative scenarios are of a different nature since the point of departure for the analysis is a normatively defined future scenario and revolves around the question "how can a specific target be reached?". The two types of normative scenarios differ in whether the system structure is assumed necessary and possible to change. Preserving scenarios focus on how a target can be reached within the current system structure, often by focusing on identifying the most (cost) efficient path. Transforming scenarios are used when the current development seems to make it infeasible to reach the defined target without changing the system structure.

E.2 Variances in attribute scope and distribution

As shown in Figure E.2, the scope and distribution of the attributes vary for each parameter. In some cases, the first attribute is already a large development compared to today's situation. This is for example the case for many electrification parameters. Other parameters may not be expected to experience a significant development until 2040, which is represented by attributes that are more similar to the current situation.

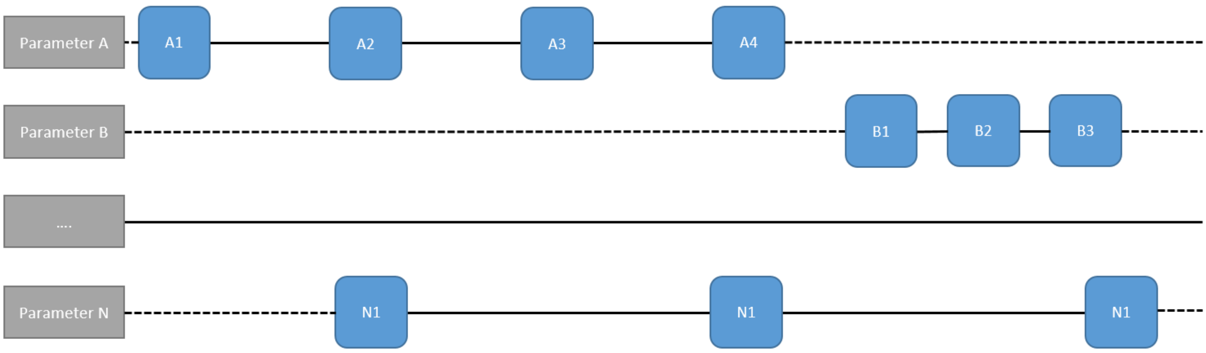

Figure E.2. Illustration of variances in scope and distribution for attributes (blue) of different parameters (grey).

E.3 Mock-up sketch of uncertainty mapping of parameters

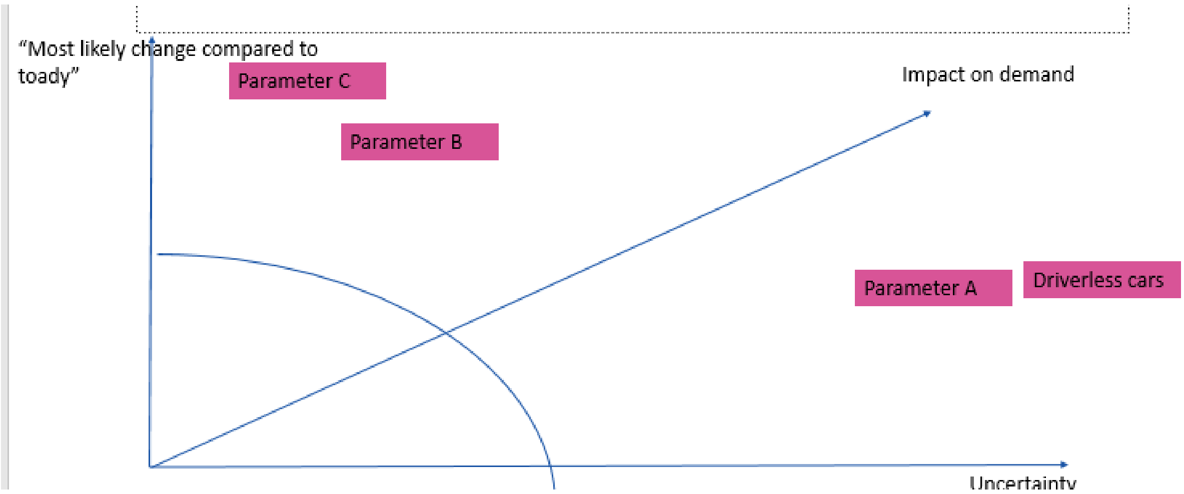

Figure E.3. Illustration of uncertainty mapping of parameters.