Life cycle assessment in early planning of transport systems

Decision support at project and network levels

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Abstract

The Swedish Climate Policy Framework implies that the Swedish transport sector must reduce its greenhouse gas emissions to nearly zero by 2045. Previous studies have – using life cycle assessment – shown that indirect greenhouse gas emissions from the vehicle and infrastructure life cycle are significant and should be considered in transport policy and planning of transport systems, in addition to direct emissions of vehicle operation.

The aim of this thesis is to contribute with knowledge on climate impact and primary energy use of transport systems for decision-support in early planning at project and network levels, and evaluate and demonstrate how life cycle climate impact and primary energy use can be assessed in early planning. This thesis includes three papers that contribute to achieving this aim. Paper I developed a methodological approach to assess annual climate impact and primary energy use of Swedish road, rail, air, and sea transport infrastructure at a network level. Paper II then expanded this system to the assessment of the Swedish transport system at a network level, including national and international freight and passenger transport by road, rail, air, and sea. At the project level, Paper III examined how LCA can be used as decision-support in choice of road corridor, considering the practical prerequisite of data availability in early planning and usefulness of results in the decision-making process.

Paper I showed that the annual climate impact of Swedish transport infrastructure is around 3 million tonnes CO_2 equivalents and that the annual primary energy use is around 27 TWh. Road infrastructure accounted for the largest proportion of impacts – around 70% of the climate impact and around 80% of the energy use. Paper II showed that the annual climate impact of the Swedish transport system was around 44 million tonnes CO_2 equivalents and the primary energy use was around 178 TWh. Road transport and aviation together accounted for 90% of the climate impact and primary energy use. Indirect impacts were significant, especially for road and rail transport, accounting for 30% of the total climate impact and primary energy use. Paper III found that (1) collection of project specific data should focus on parameters that differentiate the road corridors, that can be influenced in early planning, and that are not directly related to the road length and (2) life cycle assessment based models used in early planning should include nation specific generic data approved by the national road authority.

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Preface

This thesis was written as part of two different research projects.

Paper I and Paper II were written as part of the project *Scenarios with a life cycle perspective – Decision Support for Strategic Choices in Transport* funded by the Swedish Energy Agency. The aim of that project was to first assess the current climate impact and energy use of the Swedish transport sector from a life cycle perspective and to, based on that assessment, analyse how the total emissions and the total energy use may change under different future scenarios. Paper I and Paper II contribute to the assessment of the current transport system.

Paper I and Paper II were written in close collaboration with the Swedish Transport Administration who contributed by identifying research questions that are of relevance to stakeholders in planning of the Swedish transport system. They also provided knowledge about what data is available on the Swedish transport system and how this data best could be used to provide relevant decision-support.

Paper III is based on my master's thesis which was written as part of the project *Life Cycle Assessment in Environmental Impact Assessment of Road Infrastructure (LICCER)* funded by the ERA-NET Road Programme. The aim of the LICCER project was to develop a life cycle assessment model that can be used in early planning of road infrastructure to support decision on road location. Paper III brings together learnings from a project case study and a workshop one use of life cycle assessment in early planning of road infrastructure.

Abstract

The Swedish Climate Policy Framework implies that the Swedish transport sector must reduce its greenhouse gas emissions to nearly zero by 2045. Previous studies have – using life cycle assessment – shown that indirect greenhouse gas emissions from the vehicle and infrastructure life cycle are significant and should be considered in transport policy and planning of transport systems, in addition to direct emissions of vehicle operation.

The aim of this thesis is to contribute with knowledge on climate impact and primary energy use of transport systems for decision-support in early planning at project and network levels, and evaluate and demonstrate how life cycle climate impact and primary energy use can be assessed in early planning. This thesis includes three papers that contribute to achieving this aim. Paper I developed a methodological approach to assess annual climate impact and primary energy use of Swedish road, rail, air, and sea transport infrastructure at a network level. Paper II then expanded this system to the assessment of the Swedish transport system at a network level, including national and international freight and passenger transport by road, rail, air, and sea. At the project level, Paper III examined how LCA can be used as decision-support in choice of road corridor, considering the practical prerequisite of data availability in early planning and usefulness of results in the decision-making process.

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Sammanfattning

Sveriges klimatpolitiska ramverk implicerar att transportsektorns utsläpp av växthusgaser ska vara nära noll år 2045. Tidigare studier har, genom att använda livscykelanalys, visat att indirekta växthusgasutsläpp från tillverkning och underhåll av infrastruktur och fordon kan utgöra en betydande del av transportsektorns utsläpp. Därför måste dessa indirekta utsläpp beaktas i planering av transportsystem vid sidan av de direkta utsläppen från fordonsdrift.

Syftet med den här avhandlingen är att bidra med kunskap om transportsystems klimatpåverkan och energianvändning som kan användas som beslutsunderlag i tidig planering på projekt- och nätverksnivå, samt att utvärdera och visa hur livscykelpåverkan kan beräknas i tidig planering. Avhandlingen innehåller tre artiklar som bidrar till att uppfylla detta syfte. Artikel 1 utvecklade ett sätt att beräkna årlig klimatpåverkan och energianvändning av svensk transportinfrastruktur på en nätverksnivå. Artikel II utvidgade systemgränserna till att inkludera hela det svenska transportsystemet på en nätverksnivå, inklusive inrikes och utrikes godstransport och personresor). Artikel III undersökte hur livscykelanalyser kan användas som beslutsunderlag vid val av vägkorridor på en projektnivå med fokus på datainventering och relevans av resultat för beslutsfattning.

Artikel I fann att den årlig klimatpåverkan av svensk transportinfrastruktur är runt 3 miljoner ton koldioxidekvivalenter och att den årliga energianvändningen är runt 27 TWh. Vägar stod för runt 70% av klimatpåverkan och runt 80% av energianvändningen. Artikel II fann att den årliga klimatpåverkan av det svenska transportsystemet är runt 44 miljoner ton koldioxidekvivalenter och att den årliga energianvändningen är runt 178 TWh. Vägtransporter och luftfart stod tillsammans för 90% av klimatpåverkan och energianvändningen. Indirekta utsläpp bidrog till 30% av klimatpåverkan. Artikel III fann att (1) datainventeringen för det specifika projektet bör fokusera på parametrar som särskiljer de olika vägkorridorerna, som kan påverkas i tidig planering och som inte är direkt relaterade till väglängden, samt (2) modeller som är baserade på livscykelanalys och är tänkta att användas i tidig planering bör inkludera generisk data som är representativ för det land där modellen ska användas och som är godkänd av den nationella vägmyndigheten.

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List of publications

Paper I: Liljenström, C., Toller, S., Åkerman, J., Björklund, A., 2018. Annual climate impact and primary energy use of Swedish transport infrastructure. *Submitted manuscript.*

Paper II: Liljenström, C., Åkerman, J., Björklund, A. & Toller, S., 2018. Direct and indirect GHG emissions and energy use of the Swedish transport system. *Manuscript – to be submitted.*

Paper III: Liljenström, C., Miliutenko, S., O'Born, R., Brattebø, H., Birgisdóttir, H., Toller, S., Lundberg, K. & Potting, J., 2018. Life cycle assessment as decision-support in choice of road corridor: case study and stakeholder perspectives. *Submitted manuscript.*

Contribution of the author:

The co-authors and I together defined the methodological approach and the scope of Papers I-II. I was responsible for the main part of data collection, modelling, analysis of results, and conclusions in Papers I-II. I was also responsible for writing the papers with input from the co-authors on structure and content of the papers.

I was responsible for writing Paper III, with input from the co-authors on structure and content of the paper. Parts of the paper build on a manuscript that is written by Sofiia Miliutenko as the main author and that is included in Sofiia Miliutenko's doctoral dissertation[1]. The co-authors of the paper designed the model, organised the workshop, and selected the case study. Modelling was done by Sofiia Miliutenko based on data collected by me as part of my master thesis[2].

[1] Miliutenko, S. (2017) *Consideration of life cycle energy use and greenhouse gas emissions for improved road infrastructure planning.* Doctoral thesis. Stockholm, Sweden, KTH Royal Institute of Technology.
[2] Liljenström, C. (2013) *Life Cycle Assessment in Early Planning of Road Infrastructure: Application of The LICCER-model.* Master's thesis. Stockholm, Sweden, KTH Royal Institute of Technology.

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Abbreviations

CED	Cumulative energy demand
EEIOA	Environmentally extended input output analysis
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LICCER	Life Cycle Consideration in Environmental Impact Assessment of Road Infrastructure
RQ	Research question
STA	Swedish Transport Administration

1. Introduction

Reducing the transport sector's climate impact is of one of the main challenges to reach climate targets. Globally, the transport sector accounts for almost one quarter of energy related greenhouse gas (GHG) emissions (Sims et al., 2014). Also in Sweden, the transport sector is one of the main emitters of GHG, accounting for about one third of national GHG emissions (Swedish Environmental Protection Agency, 2018; 2017a). The Swedish transport sector accounts for one quarter of Swedish final energy use (Swedish Energy Agency, 2017).

The Swedish parliament has adopted goals related to reduced GHG emissions of transport. By 2045, Sweden is to have no net emissions of GHG into the atmosphere (Government Offices of Sweden, 2018). This indicates that also the transport sector must reduce its GHG emissions to nearly zero by that year. By 2030, GHG emissions from domestic transport, excluding domestic aviation, are to be reduced by 70% compared to 2010 (Government Offices of Sweden, 2018).

Although direct GHG emissions and energy use of vehicle operation often dominates the GHG emissions and energy use of transport systems, previous studies have – using life cycle assessment (LCA) – concluded that indirect GHG emissions and energy use are significant and should be considered in transport policy and planning of transport systems (Chester and Horvath, 2009; Huang et al., 2015; Jonsson, 2005; 2007; Miliutenko et al., 2012a; Rahman et al., 2014). These indirect impacts occur during fuel production, the vehicle life cycle (manufacturing, maintenance, and scrapping), and the infrastructure life cycle (construction, operation, maintenance, reinvestment, and demolition). For example, according to Chester and Horvath (2009), indirect GHG emissions could represent more than 40% of the total GHG emissions of road and rail transport. According to Jonsson (2005), indirect energy use represents 45% of the total energy use in the Swedish road transport sector and 64% in the rail transport sector. If indirect impacts are not considered when planning for emission and energy reduction measures, there is a risk of shifting environmental burdens from vehicle operation to other life cycle stages and not reducing the total impacts of the transport system.

Planners and policy-makers in the transport sector show a growing interest in LCA as a decision-support tool to reduce the climate impact of transport systems. For example, the EU has developed green public procurement criteria for road infrastructure (Garbarino et al., 2016). LCA has also been implemented in procurement of road infrastructure in the Netherlands (Keijzer et al., 2015) and is now being used by the Swedish Transport Administration (STA) in the planning and procurement of road and rail infrastructure (Swedish Transport Administration, 2018a; Toller and Larsson, 2017).

In the transport sector, LCA can be implemented at different levels of decision-making to plan for emission and energy reduction measures: the network level and the project level (Butt et al., 2015). LCAs at the project level assess environmental impacts of specific construction projects. LCAs at the network level focus instead on the transport system and therefore include several construction projects. Both project and network level LCA may include direct and indirect impacts of vehicles and fuels, in addition to impacts of infrastructure.

LCA is also applicable at different decision stages in the planning process of transport systems: early planning and late planning (Butt et al., 2015). This thesis focuses on LCA based decision-support in early planning at both project and network levels. The greatest opportunity to influence life cycle impacts of infrastructure and vehicles occur in the early planning stage (Karlsson et al., 2017). At the network level, decisions made in early planning concerns measures to solve the identified need for transport, such as transport mode (road, rail, air, sea) and the choice between new construction and improvement of existing transport infrastructure) (Butt et al., 2015). At the project level, decisions made in early planning concerns location of the infrastructure, which influences route length and construction type (for example bridge, tunnel, or plain road) (Karlsson et al., 2017; Miliutenko et al., 2014).

1.1. Aim and research questions

The aim of this thesis is to contribute with knowledge on climate impact and primary energy use of transport systems for decision-support in early planning at project and network levels and to evaluate and demonstrate how life cycle climate impact and primary energy use can be assessed in early planning.

This thesis includes three papers that contribute to achieving this aim. Paper I developed a methodological approach to assess annual climate impact and primary energy use of Swedish road, rail, air, and sea transport infrastructure at a network level. Paper II then expanded this system to the assessment of the Swedish transport system at a network level, including national and international freight and passenger transport by road, rail, air, and sea. At the project level, Paper III examined how LCA can be used as decision-support in choice of road corridor, considering the practical prerequisite of data availability in early planning and usefulness of results in the decision-making process.

The thesis focuses on the following research questions (RQ):

1. What is the contribution of different forms of infrastructure, activities, components, and construction materials to the annual climate impact and primary energy use of Swedish transport infrastructure at a network level? (Paper I)
2. What is the contribution of different transport modes and activities to the annual climate impact and primary energy use of the Swedish transport system at a network level? (Paper II)
3. What inventory data is needed to enable use of LCA as decision-support in choice of road corridor, and how can this inventory data be retrieved? (Paper III)

Answers to these research questions may help stakeholders involved in planning of transport systems to identify measures for reduced climate impact and energy use of transport systems, by for example:

- Showing environmental hotspots of the transport system (RQ1-2)
- Providing data that can be used to compare the climate impact of planned measures in the national transport plan with the climate impact of the current situation (RQ1)
- Indicating what actors in the transport system can take measures to reduce climate impact and energy use (RQ1-2)
- Providing prerequisites to develop LCA based calculation models for specific decision purposes, such as choice of road corridor (RQ3)

2. Research context

This thesis was written in the context of using LCA for decision-support in two situations: (1) when planning the transport system (at the network level) to reach national climate and energy targets and (2) in choice of road corridor (at the project level) to reduce the climate impact and energy use of a specific road construction project. This section describes LCA and how LCA has been used previously for assessment of transport systems at a project and network level and also the planning process of Swedish transport infrastructure.

2.1. Life cycle assessment

Life cycle assessment (LCA) quantifies potential environmental impacts throughout the life cycle of a product or a service – from raw material extraction to production, use, and final disposal (ISO 14044:2006).

An LCA study consists of four phases conducted iteratively (ISO 14044:2006):

1. Goal and scope definition – establishing the purpose of the study and deciding on details about the system being studied, including choice of system boundaries and functional unit
2. Life cycle inventory (LCI) – collecting necessary input and output data to meet the goals of the study
3. Life cycle impact assessment (LCIA) – translating inventory data to environmental impact contribution
4. Life cycle interpretation – summarising and discussing results from the LCI and LCIA

There are different types of LCA answering different types of questions. Attributional LCA describes environmental flows to and from a product life cycle, whereas a consequential LCA describes how environmental flows will change is response to a specific decision (Curran et al., 2005). The appropriate LCA method depends on the purpose of the study (Butt et al., 2015).

2.2. Life cycle assessment of transport systems

This thesis focuses on two levels of decision-making: the project level and the network level. At the project level, LCA can be used to assess environmental impacts of specific construction projects (Butt et al., 2015). At the network level, LCA can be used to assess environmental impacts of transport systems (Butt et al., 2015).

2.2.1. Project level

Several LCAs have been conducted for different forms of infrastructure, vehicles, and fuels. Several LCAs of infrastructure have been used to assess impacts of road and railway construction projects (Barandica et al., 2013; Jones et al., 2017) and specific components of such projects, like tunnels (Miliutenko et al., 2012a) and bridges (Du et al., 2014; Hammervold et al., 2013). LCAs of ports, fairway channels, and airports are less common; however, a few such studies are available, including life cycle inventories (Stripple et al., 2016; Uppenberg et al., 2003; Wang et al., 2016; Winnes et al., 2016). LCA has also been used to assess the impacts of different forms of vehicles and fuels (Girardi et al., 2015).

To support the integration of LCA in planning of infrastrucutre projects, different calculation tools and models have been developed (Miliutenko et al., 2014). Miliutenko et al. (2014) found that most of these models are suitable for use in later planning stages, such as the design stage, where the road location is known.

In what planning stage the LCA is conducted determines availability of data required to complete the LCA (Butt et al., 2015). In early project planning, material quantities are not yet available for the specific construction project. Environmental performance must therefore be evaluated based on limited amount of input data. Calculation models that require specific information on material quantities, material types, and construction activities, provide information that is of limited use in early planning. Rather, LCA based models used in early planning must provide results that are useful to the decision-making process based on accessible data.

Paper III examined how LCA based models can be used as decision-support in early planning of road infrastructure with specific focus on the balance between availability of input data to the calculation model and usefulness for decision-making.

2.2.2. Network level

The starting point for Papers I-II was the lack of decision-support showing what activities currently contribute most to the annual climate impact and energy use of Swedish transport infrastructure and transport system at a network level. This form of decision-support is necessary to avoid sub-optimal decisions that may arise when accounting for only direct GHG emissions and energy use.

Methodological choices are determined by the goal of the study (Butt et al., 2015). Papers I-II provide decision-support when planning for emission and energy reduction measures to reach national climate and energy targets. In that context, there are two important prerequisites of decision-support at the network level: (1) it assesses annual impacts of current activities in the transport system and (2) it is detailed enough to enable assessment of environmental hotspots (Papers I-II).

The literature reviews in Papers I-II identified several network level studies that have, using different methodological approaches, assessed annual impacts of transport infrastructure (Guo et al., 2017; Huang et al., 2015; Keijzer et al., 2015; Loijos et al., 2013; Toller et al., 2013; Toller et al., 2011) and transport systems (Aihara et al., 2007; Chester and Horvath, 2009; Jonsson, 2005; 2007; Lenzen, 1999; Rahman et al., 2014; Schlaupitz, 2008). However, no studies were found that fulfil the two prerequisites stated above.

Several network level studies, for example Jonsson (2005; 2007), Keijzer et al. (2015), Rahman et al. (2014), and Schlaupitz (2008) calculate annual impacts by dividing the full life cycle impacts of constructing the infrastructure stock by an assumed lifetime of the infrastructure. However, impacts of past production do not influence the possibilities to reduce impacts of the present transport system; thus this approach is of limited relevance when planning measures to reach current environmental targets.

Another approach to assessment of annual impacts is the use of already annualised data based on environmentally extended input output analysis (EEIOA) (Aihara et al., 2007; Toller et al., 2011). However, because such data is aggregated with a low level of detail, this method can only provide a general understanding of the impacts. For example, in Sweden, construction and maintenance of transport infrastructure cannot easily be separated from other types of construction work (Toller et al., 2013; Toller et al., 2011). This approach is therefore of limited use when planning for emission reduction measures.

A third approach to assessment of annual impacts is to quantify impacts of present activities in the transport system, by using a so-called 'bottom-up approach'. The literature review in Paper I identified studies that assess current impacts of transport infrastructure such as tunnels (Huang et al., 2015), concrete roads (Loijos et al., 2013), and highways (Guo et al., 2017). Due to the limited scope of these studies, they cannot show what forms of infrastructure, activities, and material contribute most to impacts in the infrastructure network as a whole, a requirement when planning to reach national climate targets. Toller et al. (2013) include a broader scope, assessing annual emissions of Swedish road and rail infrastructure based on annual production rate estimated from statistical data, existing infrastructure stock, and results from previous LCAs. However, the statistical data and the data used from previous LCAs are uncertain and the study cannot be used to identify what activities currently contribute most to emissions of Swedish transport infrastructure.

In Paper II, an important difference to previous network level studies including indirect impacts of transport systems is the geographical boundaries. It was considered important to include not only domestic transport and infrastructure, but also international transport due to the continuous increase in emissions of international shipping and aviation (Swedish Environmental Protection Agency, 2017b). Paper II assessed climate impact and energy use of the Swedish transport system including domestic freight transport, import of goods to Sweden, and Swedish inhabitants' national and international travel. Paper II also complements Swedish official statistics on transport related emissions according to the production perspective (Swedish Environmental Protection Agency, 2017b) and the consumption perspective (Swedish Environmental Protection Agency, 2017c), by using other system boundaries and thereby provide other insights on significant hotspots in the transport network. These differences are further discussed in section 5.1.

2.3. Planning of Swedish transport infrastructure

Swedish transport infrastructure consist of around 580 000 km roads (whereof 98 500 km state-owned roads, 42 300 km municipal streets and roads, and 436 000 km private roads) (Swedish Association of Local Authorities and Regions, 2018; Swedish Transport Administration, 2018b), 15 400 km railways (Transport Analysis, 2016a), 280 km of metro (Transport Analysis, 2016a) , 280 km of tramway tracks (Transport Analysis, 2016a), 40 airports (Transport Analysis, 2016b), and 50 public ports (Swedish Transport Administration, 2011). This infrastructure is owned, maintained, and operated by different actors, including the STA, county councils, municipalities, and private actors. Paper I included all forms of infrastructure, regardless of owner and manager.

Planning of transport infrastructure is made in several steps (Swedish Transport Administration, 2017a), where LCA can be used from the initial transport plan to the completion of individual construction projects (Butt et al., 2015; Miliutenko et al., 2014).

The STA is responsible for long-term planning of the transport system (Swedish Transport Administration, 2017b). The long-term plan for developing the transport system is made in the national transport plan including an intermodal perspective (roads, railways, ports, and airports) and various measures such as new construction, reconstruction, operation, and maintenance (Swedish Transport Administration, 2016).

When suggesting measures to solve identified problems, the STA has a four-step principle (Swedish Transport Administration, 2017a):

1. Rethink: measures that can influence transport demand and choice of transport mode, for example taxes, fees, and speed limits
2. Optimise: measures that may lead to more efficient use of the infrastructure stock, for example travel planners and logistics solutions
3. Improve: limited reconstruction projects, for example widening of roads and dredging of fairway channels.
4. Invest: new investments and larger reconstruction projects, for example building bypass roads and new railways, and extending single-tracks to double-tracks.

New investment in road infrastructure is planned according to a process governed by legislation (Swedish Transport Administration, 2017a). Where and how the road should be constructed is described in the road plan (Swedish Transport Administration, 2017a). Paper III was written in this context – planning where to construct a new road. Once the road plan is established, construction documents, containing technical specifications and requirements, are prepared (Swedish Transport Administration, 2017a).

3. Methods

A combination of methods was used to answer the research questions of this thesis (Table 1). LCA was used in Papers I-III; however, because Papers I-II and Paper III support different types of decisions, LCA was applied in different ways (section 3.1). Papers I-II involved literature reviews to support method development (section 3.2). Paper III involved stakeholder involvement in development of an LCA based model for decision-support in choice of road corridor (section 3.3) and a case study where the model was applied to a road construction project (section 3.4).

TABLE 1 METHODS USED TO ANSWER THE RESEARCH QUESTIONS (RQ)

Method	RQ1	RQ2	RQ3
Application of LCA	■	■	■
Literature review to support method development	■	■	
Stakeholder involvement in model development			■
Case study			■

3.1. Application of LCA

3.1.1. LCA models used

In Papers I-II, the LCA software SimaPro version 8 (https://simapro.com/) was used to model the infrastructure and transport system and to visualise results. The calculation model Klimatkalkyl version 4 (http://webapp.trafikverket.se/Klimatkalkyl/Modell) used as a source of inventory data (see section 3.1.3), was integrated to the SimaPro model. Klimatkalkyl has been developed by the STA and provides default material and energy use for construction, operation, maintenance, and reinvestment of Swedish road and rail infrastructure (Toller and Larsson, 2017).

In Paper III, the Excel based model Life Cycle Considerations in Environmental Impact Assessment of Road Infrastructure (LICCER) (Potting et al., 2013a) was used to examine how LCA can be used as decision-support in choice of road corridor. The LICCER model quantifies life cycle climate impact and primary energy use of infrastructure (plain road, bridge, and tunnel) and traffic in different road corridors (Potting et al., 2013a).

3.1.2. Goal and scope definition

In Papers I-II, the goal of applying a life cycle perspective was to estimate the annual climate impact and primary energy use of Swedish transport infrastructure and the Swedish transport system and to investigate the environmental hotspots of the system. In Paper III, the goal of using LCA was to identify requirements on LCA based models applied in early planning. All three papers were based on attributional LCA because they describe a system as it can be observed or, in Paper III, as it can be expected to look in the future.

In Paper III, the functional unit was "Road infrastructure enabling annual traffic between 'A' and 'B' over an analysis time horizon of a defined number of years" – the default functional unit in the LICCER model (Brattebø et al., 2013). The analysis time horizon was set to 20 years in Paper III. The term functional unit was not used in Papers I-II because the papers involved using methods from LCA rather than conducting and LCA; however, Papers I-II included delimited scopes of assessment. The scope of assessment in Paper I was the Swedish transport infrastructure a specific year – including road infrastructure (state-owned, private, and municipal), rail infrastructure (state-owned railways, non-state-owned railways, tramways, metro, and industrial tracks), airports with scheduled and non-scheduled traffic, and ports and fairway channels. The scope of assessment in Paper II was infrastructure, vehicles, and fuel required for Swedish inhabitants' national and international travel, for domestic freight transport, and for the import of goods to Sweden – by road, rail, air, and sea.

The three papers included different life cycle stages and parts of transport systems (Table 2). All papers included transport infrastructure. In addition, Papers II-III included vehicles and fuels. While Paper III included only vehicle operation and fuel and electricity production, Paper II also included the stages of the vehicle life cycle (manufacturing, maintenance, and scrapping). In all papers, each activity included raw material extraction and production of infrastructure components, vehicles, and fuels. Material transport was included for materials that are used in large quantities and have low GHG emissions during manufacturing (road salt and excavated rock and soil) as well as asphalt (Paper I).

TABLE 2 SCOPE OF PAPERS I-III

Level of decision-making	Network			Project		
Part of the system	Infrastructure	Vehicles	Fuels	Infrastructure	Vehicles	Fuels
New production	**PI, PII**	**PII**	**PII**	**PIII**		**PIII**
Operation	**PI, PII**	**PII**		**PIII**	**PIII**	
Maintenance	**PI, PII**	**PII**		**PIII**		
Reinvestment	**PI, PII**			**PIII**		
End-of-life		**PII**		**PIII**		

An important difference between the scope in Papers I-II and the scope in Paper III is the approach that was used to assess annual climate impact and primary energy use.

The LICCER model used in Paper III accounts for the whole life cycle of the construction project – from new construction to demolition. Annual impacts of a component are calculated by dividing the total life cycle impacts with a specified service life (Brattebø et al., 2013). This approach enables comparing impacts of activities that occur at different points during the life cycle, for example infrastructure construction and vehicle operation.

Papers I-II, on the other hand, focus on the current activites in the transport system, rather than on a specific component with a defined service life. This means that activities occurring in the past or in the future were not accounted for. For example, Paper I included present new construction and management (operation, maintenance, and reinvestment) of the present infrastructure stock. In addition, Paper II included present vehicle production, maintenance and operation of the present vehicle stock, and scrapping of vehicles taken out of use. The following activities were however excluded: past production of the vehicle and infrastructure stock and future management and scrapping of new production.

Although Papers I-II both focus on the Swedish transport system at a network level, they do not share the same system boundaries. Paper I covers transport infrastructure *within Sweden* whereas Paper II covers infrastructure and vehicles required for *Swedish transport worldwide* – including national and international passenger transport, domestic freight transport, and import of goods.

The definition of the Swedish transport system in Paper II entails that the scope of Paper II should not include vehicles, infrastructure, and fuel used for travel in Sweden by inhabitants of other countries or for exporting goods from Sweden. Impacts of aviation and shipping were estimated based on the transport demand for these modes, for example fuel and vehicles required per passenger and tonne kilometre. Impacts of road and rail transport were estimated based on number of registered vehicles in Sweden and the quantity of energy used in Sweden for vehicle operation. Some of the vehicles and energy are used for export and by inhabitants of other countries. It was assumed that these values are equivalent to the vehicles and energy used in other countries by Swedish inhabitants and for import to Sweden. For passenger transport, this is likely a valid assumption, since road and rail transport are largely domestic means of transport. However, for international freight transport, this estimation may have a significant outcome on results of the study (see discussion in section 5.2). Additionally, it was assumed that results from Paper I, covering transport infrastructure in Sweden, are representative of global infrastructure requirements due to Swedish transport. These assumptions imply that Paper II can be used to compare direct impacts of domestic road and rail vehicle operation to indirect impacts of Swedish registered vehicles and Swedish infrastructure.

3.1.3. Data inventory

The scopes of Papers I-II cover all transport modes at a network level. Because different actors compile data for different parts of the transport system, data was used from many sources. Average LCI data (Finnveden et al., 2009) was used since the papers are based on attributional LCA.

The data inventory in Paper I included three types of data: (1) type and number of components in new construction and in the infrastructure stock (such as kilometres of single-track railway), (2) type and quantity of material and energy required for construction and management of different components (such as tonne concrete required to construct one kilometre single-track railway), and (3) process data quantifying GHG emissions and primary energy use of material and energy production (such as kg CO2 equivalents per tonne concrete).

Type and number of components was mainly determined based on data from infrastructure holders, such as the STA, and Swedish official statistics (Transport Analysis, 2016a; b; c; d). Material and energy use of infrastructure components was provided from the model Klimatkalkyl, version 4.0 and from statistics and infrastructure holders providing measured energy use for different activities, for example rail infrastructure operation (Transport Analysis, 2016a). Klimatkalkyl was also the main source of process data.

The data inventory in Paper II included two types of data: (1) type and number of vehicles (in new production, in the stock, and taken out of use) and type and quantity of energy used in vehicle operation, and (2) process data. Inventory data for infrastructure was provided from Paper I. Type and quantity of different vehicles and fuels was provided mainly through personal communication with traffic operators (Norrköping municipality, Stockholm County Council, and Västtrafik), the Swedish rail vehicle register (received from the Swedish Transport Agency), Swedish official statistics (Transport Analysis, 2016a; b; c; d), and previous studies assessing the climate impact of Swedish aviation (Kamb et al., 2016) and GHG emissions of Swedish shipping (Styhre and Winnes, 2016). Ecoinvent version 3.2 (Ecoinvent, n.d) was the main source of process data.

The data inventory for the LCA in Paper III was delimited by the scope of the LICCER model. The LICCER model requires the user to insert project specific data on infrastructure (for example length and width of roads) and traffic (for example traffic volume) in the different road corridors. Based on this data, the LICCER model quantifies material and energy use in all life cycle stages using a set of default data (for example concrete volume per square meter bridge). Different approaches were used to find and estimate project specific data: (1) compile data from the feasibility study (Englund and Dahlin, 2006), (2) make estimations based on qualitative descriptions and scenarios in the feasibility study (Englund and Dahlin, 2006), and (3) make estimations based on previous road construction projects with similar road width and traffic density (Karlsson and Carlson, 2010).

3.1.4. Impact assessment

The environmental impact categories included in Papers I-III are climate change and cumulative energy demand (CED). Climate change was calculated as global warming potential (GWP) over 100 years as in the impact assessment method ReCiPe Midpoint (H) (Goedkoop et al., 2013). CED, including primary renewable and non-renewable energy, was calculated based on the method published by Ecoinvent 2.0 (Jungbluth and Frischknecht, 2010) and expanded by PRé Consultants for the energy resources available in the SimaPro database (PRé Consultants, 2016).

The process data sets from the STA (Swedish Transport Administration, 2017c) include already characterised data. Although the STA strives to use data that are consistent with system boundaries and allocation principles in the standard EN 15804 (Toller and Norberg, 2016), there may be some variation in data quality due to lack of information or transparency in the published data. Feedstock energy was included for plastics, asphalt, and bitumen.

3.1.5. Interpretation

Interpretation of results from Papers I-II involved identifying the transport modes, forms of infrastructure, activities, material and construction activities that contributed most to the annual climate impact and energy use, and thereby provide results that could be used as decision-support when planning for emission and energy reduction measures. Uncertainties were addressed at a ‘broad-brush level’ by discussing the influence of uncertain parameters on the outcome of the study.

Interpretation of results from the LCA in Paper III involved identifying the life cycle stages and materials that contributed most to life cycle climate impact and energy use of each road corridor and identifying critical parameters. This information was used as a basis for discussion on data availability and usability of results in decision-making. Results from the case study were not used in the planning process of the specific construction project.

3.2. Literature review to support method development

To answer the research questions in Papers I-II, it was necessary to determine a method that could be used to assess annual impacts of the system while allowing for identification of hotspots. A literature review was conducted to see what methods have been applied to assess annual impacts of transport systems in previous studies and if these methods could be applied in Papers I-II. The literature reviews in Papers I-II answered the question: *What methods have been used previously to assess annual life cycle impacts of transport systems at a network level?*

The literature review included papers from peer-reviewed journals, conference papers, and reports written in Swedish and English that had been published before June 2017. Paper I included studies assessing impacts of transport infrastructure at a network level. Studies of other systems (like buildings and energy system) and studies not assessing environmental impacts of systems (like studies using material flow analysis) were not included. The literature review in Paper II included the same studies as Paper I, with the addition of studies assessing impacts of international freight and passenger transport.

3.3. Stakeholder involvement in model development

Stakeholders were involved in the development of the LICCER model to help ensure that results generated by the LICCER model are relevant for decisions concerning choice of road corridor. To discuss strengths and weaknesses of the LICCER model as supporting tool in choice of road corridor, national road authorities, as well as researchers and consultants working with environmental assessments of road infrastructure in Sweden, Norway, and the Netherlands, were invited to a workshop held in Stockholm, Sweden in September 2013. Twelve participants (not including developers of the LICCER model) attended the workshop, most of them from Swedish consultancies and universities.

The workshop included three parts: (1) an interactive exercise where the workshop participants were guided through the steps required to perform an LCA using the LICCER model, (2) a questionnaire (Potting et al., 2013b) on data availability, model usability, and usefulness of model outputs, and (3) a plenary discussion on the same topics as the questionnaire. Notes from the workshop and answers from the questionnaires were analysed with content analysis (Kvale, 1996). Answers were grouped according to the main issues data availability, model usability, and usefulness of model outputs (Potting et al., 2013b).

3.4. Case study

Case study is a research method to examine specific objects of analysis, for example persons, places, and events, in order to answer specific research questions (Gillham, 2000). In Paper III, the case study analysed a specific road construction project to identify the parameters that have the largest influence on life cycle climate impact and energy use. The results served as a basis for discussing what parameters are most important to consider in early planning. The case study was also the basis for discussions at the workshop held with stakeholders (see section 3.3).

The selected case study was the reconstruction of road 55 between Yxtatorpet and Malmköping in Sweden. This case study was chosen for several reasons: 1) because of relatively good data availability, 2) possibilities to compare results to a previous study using JOULESAVE to assess life cycle energy use of this construction project, and 3) a possibility to test several features of the LICCER model (bridge, plain road, extended road).

4. Results and analysis

This section answers the research questions of this thesis based on results from the papers. Research question 1 is answered by Paper I, research question 2 is answered by Paper II, and research question 3 is answered by Paper III.

4.1. Swedish transport infrastructure at a network level: annual climate impact and energy use

Paper I estimated the annual climate impact and primary energy use of Swedish transport infrastructure an average year around 2015. The scope included construction, operation, maintenance, and reinvestment of road, rail, air, and sea transport infrastructure. Figure 1 shows some results from Paper I.

The total annual climate impact was estimated to 3 million tonnes CO_2 equivalents and the annual primary energy use was estimated to 27 TWh. Road infrastructure accounted for the largest proportion of impacts – around 70% of the climate impact and around 80% of the primary energy use.

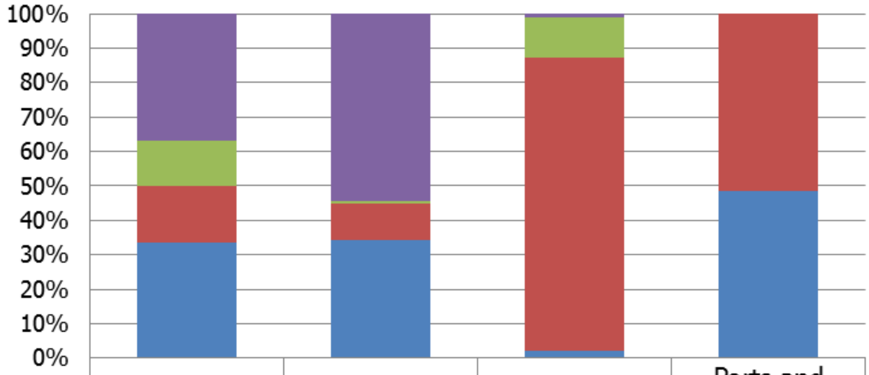
Paper I included all forms of transport infrastructure, regardless of owner. The study showed that state-owned road infrastructure accounted for about half of the climate impact and primary energy use of road infrastructure. The municipal road network is about half as long as the state-owned and also had about half as high climate impact and primary energy use. The private road network had, despite mainly consisting of smaller gravel roads, a significant contribution to the climate impact of road infrastructure, largely due to the deforestation taking place in construction of forest roads. The study also showed that the state-owned rail network, which is longer than the non-state-owned network, accounted for most impacts of rail infrastructure.

Analysing the contribution of different activities to the impacts of Swedish transport infrastructure, Paper I found that management of the infrastructure stock (operation, maintenance, and reinvestment) accounted for 70% of the annual climate impact and 80% of the annual primary energy use. What activities that contributed most to impacts of each mode varied. Whereas operation dominated impacts of airports and ports and fairway channels, new construction, and reinvestment were the dominating causes of impacts of road and rail infrastructure. In total material production accounted for 50% of the climate impact and 70% of the energy use, but had a more significant contribution to impacts than on-site activities[3] for several forms of infrastructure and activities.

Paper I also analysed the proportion of climate impact and energy use due to different components, materials, and construction activities. It was found that surface roads and railroad tracks (including the sub- and superstructure) contributed most to impacts, whereas tunnels, bridges, and ancillary components had a smaller importance for the overall results. The materials that dominated impacts were asphalt, concrete, and steel. Together these materials accounted for 70% of the climate impact of road construction and 75% of the climate impact of rail construction. Impacts of construction activities were mainly due to diesel used for construction machines.

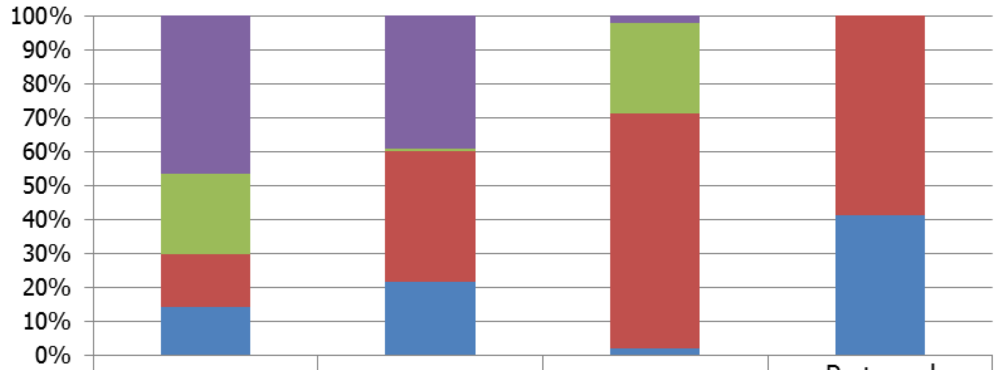
[3] On-site activities were defined as activities taking place on the construction site (like earthworks and deforestation) or on the existing infrastructure (like road lighting and heating of buildings)

Climate impact of new construction and the infrastructure stock



	Road	Rail	Airport	Ports and fairways
Reinvestment (ktonne CO2 eq.)	678	343	1	0
Maintenace (ktonne CO2 eq.)	245	5	9	0
Operation (ktonne CO2 eq.)	302	65	62	112
Construction (ktonne CO2 eq.)	615	217	2	105

Primary energy use of new construction and the infrastructure stock



	Road	Rail	Airport	Ports and fairways
Reinvestment (GWh)	10194	1180	18	0
Maintenace (GWh)	5146	20	228	0
Operation (GWh)	3379	1159	590	566
Construction (GWh)	3155	656	19	396

FIGURE 1 ANNUAL CLIMATE IMPACT (KTONNE CO_2 EQUIVALENTS) AND PRIMARY ENERGY USE (GWH) OF SWEDISH TRANSPORT INFRASTRUCTURE. NOTE THAT FOR SEA TRANSPORT INFRASTRUCTURE, MATERIAL AND ENERGY INPUT FOR MAINTENANCE AND REINVESTMENT IS INCLUDED IN THE ACTIVITY NEW CONSTRUCTION DUE TO THE INVENTORY DATA USED (SEE PAPER I).

4.2. The Swedish transport system at a network level: annual climate impact and energy use

Whereas Paper I assessed the annual climate impact and primary energy use of Swedish transport infrastructure, Paper II provided a complete overview of the Swedish transport system at a network level, assessing climate impacts and primary energy use of infrastructure as well as vehicles and fuel. The transport system was defined as the system used for Swedish inhabitants' national and international travel and for the import of goods to Sweden. However, because of approximations made (see section 3.1.2), results from Paper II also show the annual climate impact and energy use of Swedish road and rail infrastructure compared to vehicles operating on this infrastructure. Figure 2 shows some of the results from Paper II.

The annual climate impact of the Swedish transport system was estimated to 44 million tonnes CO_2 equivalents and the annual primary energy use was estimated to 178 TWh. Road transport and aviation together accounted for close to 90% of the climate impact and primary energy use. Paper II found that, even though direct climate impact and energy use dominated total impacts of the Swedish transport system, indirect climate impact and energy use were significant, especially for road and rail transport. In total, indirect impacts accounted for around 30% of the climate impact and primary energy use. Infrastructure (results from Paper I) accounted for 6% of the climate impact and 14% of the energy use.

Paper II analysed what activities contributed most to the indirect climate impact and primary energy use of the different transport modes. The impacts of road transport were dominated by vehicle manufacturing (mainly manufacturing of passenger cars) and fuel production. About half of the climate impact of fuel production was due to biofuels. In rail transport on the other hand, vehicles contributed only little to indirect impacts. Rather, indirect impacts were due to infrastructure construction and reinvestment and the production of energy used for operation of trains. Impacts of energy production were mainly due to electricity production because diesel use is relatively limited in Swedish rail transport. Fuel production dominated indirect impacts also from aviation and shipping, especially due to kerosene and fuel oil used for international transport.

Indirect aspects contributed more to primary energy use than to climate impact of road transport and aviation. Paper II found two main reasons for this. First, feedstock energy was included for materials containing fossil fuels, such as rubber tires and asphalt. For that reason, road infrastructure and road vehicle maintenance contributed more to indirect energy use than to indirect climate impact of road transport. Second, high altitude effects were included for aviation. For that reason, indirect aspects had higher contribution to the total energy use than to the total climate impact.

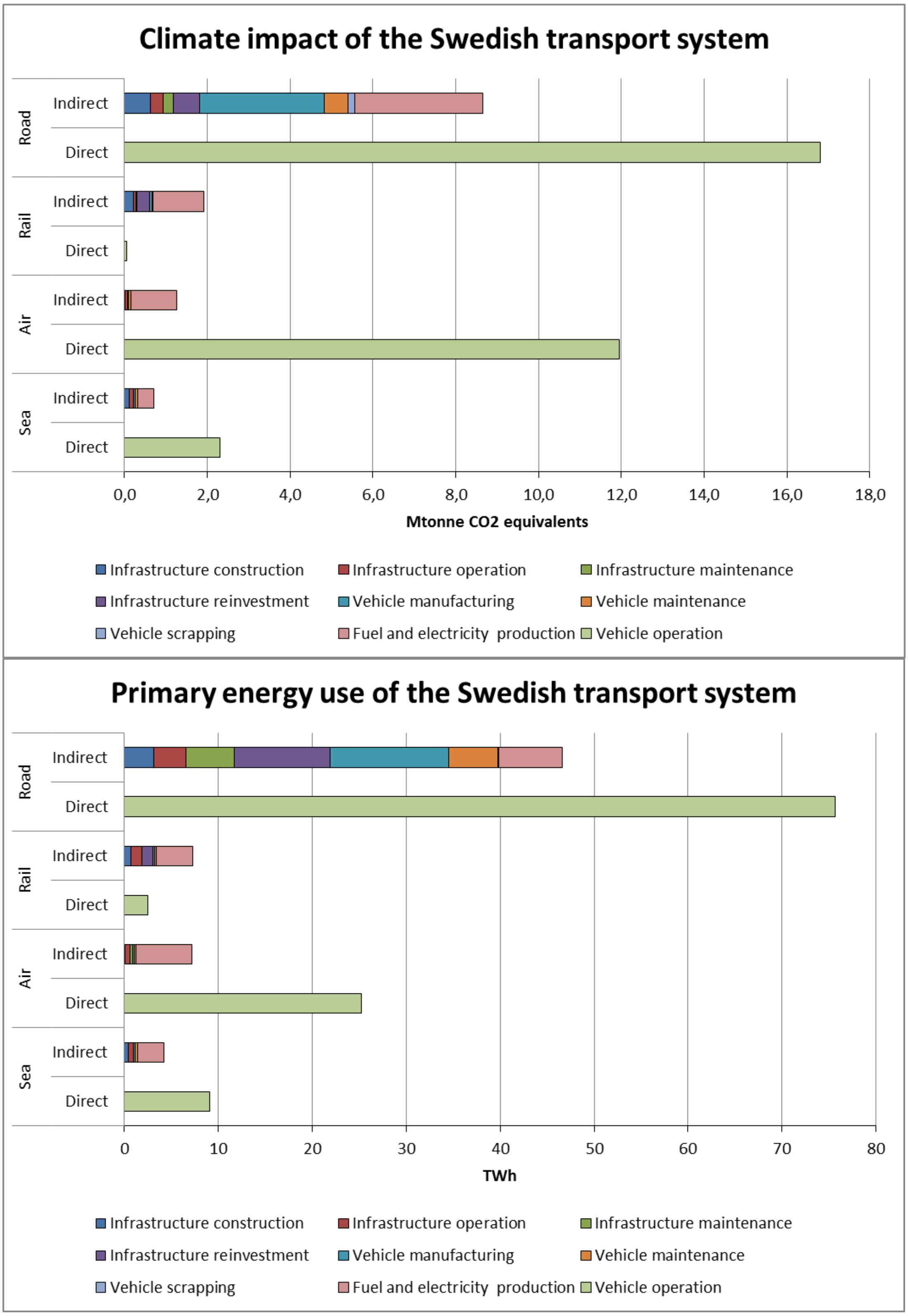


FIGURE 2 DIRECT AND INDIRECT CLIMATE IMPACT (MTONNE CO_2 EQUIVALENTS) AND PRIMARY ENERGY USE (TWH) OF THE SWEDISH TRANSPORT SYSTEM

4.3. Life cycle assessment in choice of road corridor: inventory data needed

Paper III examined how LCA can be used to support the choice of road corridor, considering the practical prerequisite of data availability and usefulness of results in the decision-making process. It was concluded that (1) collection of project specific data should focus on parameters that differentiate the road corridors, that can be influenced in early planning, and that are not directly related to the road length and (2) LCA based models used in early planning should include nation specific generic data approved by the national road authority.

Paper III found that parameters that differentiate the road corridors and the parameters that can be influenced by choice of road corridor are not necessarily environmental hotspots of the system. For example, in the case study, earthworks had low climate impact and energy use compared to the traffic on the road, but it was one of the parameters that planners could influence by choice of road corridor and the main parameter that differentiated the road corridors. Additionally, earthworks are not necessarily related to the road length. For example, in the case study, the shortest construction alternative required more rock excavation than the others.

In contrast, climate impact and energy use of traffic and pavement, two hotspots of the system, could be influenced mainly by altering the road length. Impacts of the pavement layer are influenced by decisions not taken until the design stage, such as choice of specific pavement materials. Parameters influencing the choice of pavement materials are therefore of smaller relevance in choice of road corridor. Here, Paper III identified a possibility to further improve the LICCER model by including the possibility to specify different traffic scenarios for the different road corridors. This does not influence the results of the case study in Paper III; however, traffic density and annual traffic increase could vary between road corridors in other construction projects.

Because data is scarce in early planning, generic data is a necessity to calculate life cycle climate impact and energy use of road corridors. A general request at the workshop that was held with stakeholders (see section 3.3) was the access to default generic data that is national specific and preferably approved by the national road authority. In Sweden, such data is now provided by the STA through the model Klimatkalkyl (Toller and Larsson, 2017). By including the possibility to replace default generic data with project specific data, stakeholders considered the LICCER model to remain simple but flexible.

Although generic data for different construction types could solve some problems with data availability, uncertainties may be introduced and there is a risk that the model would become too simple to differentiate between road corridors. Especially for earthworks, generic default data should be used with caution. Earthwork is a parameter with large variation so site-specific data are therefore preferred in order to get reliable results for decision support in early planning.

5. Concluding discussion

The aim of this thesis was to contribute with knowledge on climate impact and primary energy use of transport systems for decision-support in early planning. Section 5.1 compares results from Papers I-II with statistics and previous network level studies on GHG emissions and energy use of the Swedish transport system. Section 5.2 discusses data requirements and data uncertainties at project and network level. Section 5.3 provides examples on how results from Papers I-III can be used to support decision-making.

5.1. Comparison with previous studies at network level

Several previous studies have quantified direct and indirect GHG emissions and energy use of transport systems and transport infrastructure at a network level. Also official statistics according to the production and consumption perspectives presents annual transport related emissions. These perspectives complement each other. They answer different questions about transport related impacts and thereby describe different parts of the transport system. Because of that, they also give different quantitative estimates of transport related impacts.

The methodological approach applied in Papers I-II had not been used previously to assess annual climate impact and primary energy use of the Swedish transport system at a network level. The papers thereby provided a picture of Swedish transport related impacts that had not been available previously. In Papers I-II, results were compared with results from previous network level studies and statistics using other methodological approaches. This comparison illustrates how, and why, different approaches lead to different quantitative estimates of transport related impacts.

For example, Paper II showed that the climate impact of the Swedish transport system is around 44 Mtonne CO_2 equivalents per year – not much lower than Sweden's total production based GHG emissions that were 62 Mtonne CO_2 equivalents in 2015 (including international transport) (Swedish Environmental Protection Agency, 2018). About 40% of the production based emissions – 26 Mtonne CO_2 equivalents – were due to national and international transport.

Paper II discussed reasons for this difference. One reason is that indirect GHG emissions have been included and thereby emissions of materials and components manufactured outside of Sweden. Another reason is that different approaches have been used to assess impacts of international aviation. Whereas Paper II includes emissions from the whole flight (from Sweden to the final destination), statistics according to the production perspective include emissions from fuels bunkered for the flight to the first layover. Additionally, Paper II includes the high-altitude effects of aviation.

According to the consumption perspective, Swedish GHG emissions were about 105 Mtonne CO_2 equivalents in 2015, with about one fifth of these emissions – 21 Mtonne CO_2 equivalents – due to households' consumption of transport services (Swedish Environmental Protection Agency, 2017c). Unlike the production perspective, the consumption perspective includes also emissions from manufacturing outside of Sweden. However, those emissions are allocated differently than in Paper II. For example, emissions due to freight transport are allocated to the different commodities transported and thus not included in the category households' consumption of transport services. Additionally, infrastructure construction and management is not allocated to the transport services, but to the post 'public investments'. Paper I estimated that Swedish transport infrastructure contribute with 3 Mtonne CO_2 equivalents per year, corresponding to 8% of the climate impact of public investments in 2015.

The examples above show that different methods largely lead to different conclusions on transport related impacts. Another example of this can be found in Paper I. In contrast to previous studies (Chester and Horvath, 2009; Guo et al., 2017; Huang et al., 2015; Jonsson, 2005; 2007; Keijzer et al., 2015), Paper I found that road construction has lower impacts than management of the infrastructure stock. One reason for this, discussed in Paper I, is the construction rate on which calculations are based. If the assessment of annual impacts includes construction of the infrastructure stock, and the present rate of new construction is lower than it has been previously, the influence of new construction could be overestimated. Including past production of the infrastructure stock may provide results that are less suitable as decision support when planning emission reduction measures to reach national environmental targets since emissions are no longer possible to influence.

Paper I also provided an example of different methods resulting in consistent quantitative results. The climate impact of Swedish transport infrastructure (according to Paper I) is consistent with findings by Toller et al. (2011) that used EEIOA data to assess impacts of Swedish transport infrastructure. However, the method used by Toller et al. (2011) to allocate emissions between different construction activities is uncertain and it is difficult to speculate on reasons for the two methods providing consistent results.

Although the two methods provided consistent results, they are not applicable to the same decision-contexts. Results from Toller et al. (2011) do not have a resolution that enables identification of environmental hotspots of Swedish transport infrastructure. However, the method is valuable for comparisons and for environmental indicator purposes. Input-output studies may also be used as a “quick check” of the development towards a target and can thereby complement bottom-up studies like in Paper I.

5.2. Data requirements and data uncertainty at project and network levels

The previous section discussed different methods to assess annual impacts. These methods are all uncertain in different ways. This section focuses on data requirements and data uncertainties when applying LCA in early planning at the project level and when using the methods in Papers I-II to assess annual impacts at the network level. Depending on level of decision-making – project or network level – there are different reasons for data gaps and data uncertainties.

Network level studies are complex with broad data inventories. To support decision-making on reaching national environmental targets, like in Papers I-II, data is collected on an already existing transport system (however, network level studies may also be conducted for transport plans, such as the national transport plan made by the STA). Individual infrastructure holders and traffic operators may have detailed information on transport volumes and material use for different activities, however; compiling this data for the whole transport network may be too time-consuming. Hence the challenge in the data inventory is to find aggregated data (for example total energy use for rail operation) at a level required to complete the assessment. If such data is not available, other approaches must be used to estimate material and energy use, which was described in Papers I-II.

In Papers I-II, aggregated data was found mainly for infrastructure operation, domestic vehicle operation, and international aviation and shipping because of available statistics and previous studies in these areas. Finding data on annual construction rate of non-state-owned road and rail infrastructure, small investment measures at the STA, and on transport work conducted in international road freight transport was particularly difficult.

Project levels studies also face challenges in the data inventory; however, for different reasons. Project level studies in early planning require data on a specific construction project that has not yet been undertaken, as well as assumptions on future infrastructure management and traffic operation on the road. In Paper III, it was demonstrated how inventory data could be collected from the feasibility study or estimated based on scenarios and qualitative descriptions in the feasibility study. However, as was discussed in Paper III, even parameters with good data availability (i.e. those that were available in the feasibility study) are uncertain. For example, Karlsson et al. (2017) showed that the actual volume of excavated rock during construction of the road in the case study was 62% lower than what was estimated in the feasibility study.

Due to these challenges, both network and project level studies in early planning must rely on previous studies conducted in later planning stages as a source of inventory data on material and energy use. For example, in Papers I-II the model Klimatkalkyl and the life cycle inventory database Ecoinvent were used as sources of inventory data. Paper III identified the need for nation specific generic data to implement LCA in choice of road corridor. Also network level studies as in Paper I require such nation specific data to provide representative results. Assessments like in Paper II, including international transport, rely to a larger extent on average European and global data.

Although previous studies are valuable as sources of inventory data, they also introduce uncertainties. As discussed in Paper III, default data may not be representative of the actual construction project and variation in data is large. It was therefore concluded in Paper III that generic data should not be used for site-specific activities that differentiate road corridors, such as earthworks. Paper III suggested that methods to assess earthwork volumes, such as geological information systems (GIS), are integrated with LCA models. While this could provide more precise inventory data, the volumes of blasted rock may still be uncertain, due to lack of knowledge on precise road location within the road corridor, for example (Karlsson et al., 2017).

Another source of uncertainty is when project specific data is extrapolated to the whole transport system at a network level. If the default value is an average of data from several construction projects, possible errors in different projects may cancel each other out when applied at the network level. However, if the average is too high or too low, applying default data may have significant consequences for the outcome of the study. Such variation in data may also have significant consequences for project level studies even if the default value represents an average since it may still be far from the case in the specific construction project.

An example of this uncertainty from Paper I is the use of asphalt in reinvestment. The asphalt quantities resulting from the data inventory in Paper I were about two times higher than the produced volume of asphalt in Sweden (Miliutenko et al., 2012b). One reason for this, discussed in Paper I, is that material use in reinvestment was overestimated when applying Klimatkalkyl to the whole road network.

In addition to the volume of asphalts used, Paper I concluded that the following aspects are particularly uncertain due to the lack of aggregated data and their importance for the results: quantity of deforestation in new construction of forest roads, and type measures in small investment measures at the STA. Also the emission factor of bitumen was identified as an uncertainty due to insufficient information available on production of bitumen used on the Swedish market. These examples all give rise to new questions that can be answered by further research (see section 6).

In Paper II, it was found there was a lack of aggregated data enabling assessment of direct and indirect impacts of international road freight transport. The estimations made likely lead to significantly underestimating impacts of road freight transport. This is because Swedish registered lorries are used mainly for domestic freight transport, while import and export is mainly conducted by foreign registered lorries. An alternative way to handle this problem could have been to estimate the transport work required using for example the method used by Cadarso et al. (2010) to estimate the CO_2 emissions of importing goods to Spain. Comparing the results from Paper II with results from studies on Swedish freight transport using other methods, may lead to further understanding of the impacts.

The uncertainties mentioned here affects how results can be used in a decision-making situation. Also, how results are to be used affects what should be done about these uncertainties. Paper III analysed the importance of uncertainties for decision-making, concluding that uncertainties are mainly important to consider for those parameters that differentiate the road corridors, can be influenced by decisions in early planning, and are not directly related to the road length. Also in Papers I-II, uncertainties influence how results can be used for decision-making. Usability of results in different contexts could be improved by reducing the uncertainty in parameters that are significant for assessment of specific planning measures. For example, improved knowledge on specific quantity of asphalt in airport maintenance may not be pertinent for decisions related to planning of transport systems. However, a better estimate of impacts related to industrial tracks may be necessary to assess the consequences of shifting transport modes from road to rail and sea.

5.3. How results from this thesis can be used in practice

The papers included in this thesis provide decision support in different contexts. Papers I-II provide decision support on the question: *How can impacts of transport systems be reduced to reach national climate targets?* It was argued that decision-support for that question should focus on current annual activities (rather than what has been done in the past when building up the stock) and should allow for assessment of hotspots. Results from Papers I-II can be used in different ways in the planning of emission reduction measures.

One way that results can be used is to identify emission reduction measures based on the environmental hotspots identified in Paper I-II. Based on activities that contributed most to impacts of Swedish transport infrastructure, Paper I suggested that planners (1) work systematically with emissions and energy efficiency in management of the infrastructure stock as well as in new construction, (2) consider opportunities to reduce material related impacts in planning and management of the infrastructure stock, and (3) decrease the impact of on-site activities by smart management of excavation masses and by reducing diesel consumption in construction machines. Paper II showed the importance of reducing indirect emissions as well as direct emissions and thereby reinforced conclusions and recommendations from previous studies that policy and planning of transport systems should include a life cycle perspective.

Based on these environmental hotspots, Papers I-II also discussed what actors could reduce these emissions. In Paper I, the STA was identified as an important stakeholder in reducing impacts of construction materials used in infrastructure by placing climate requirements not only on reinforcement steel and concrete, but also on asphalt. Paper II discussed the influence that Swedish actors may have over impacts of the Swedish transport system, considering that a significant proportion of these impacts were due to international transport. Even though reducing impacts of aviation and shipping requires international efforts, impacts may be affected by national policies. For example, the recently implemented tax on departing passengers may limit air travel volume.

The hotspots identified in Papers I-II reflect the transport system under current transport policy. Results can also be used to indicate how impacts could change in the future. For example, if climate targets are to be reached, direct GHG emissions of vehicle operation must be reduced significantly, which would increase the relative importance of vehicles and infrastructure. If such emission reduction measures are reached by a higher production rate of electric vehicles, indirect GHG emissions of vehicle manufacturing and maintenance may be higher than they are today. If identified need for transport is more often solved by improving the existing infrastructure, impacts of reinvestment and maintenance may increase.

Results from Papers I-II may also be used in a policy context. Based on the knowledge generated in Papers I-II, it is possible to analyse how total GHG emissions and energy use are affected by different assumptions on future policy measures. This could be achieved by for example analysing a number of what-if scenarios reflecting current trends in the transport sector. Such analyses may indicate important long-term development paths required to reach climate and energy targets.

Paper III provides prerequisites to construct LCA based models that can support decision-making in choice of road corridor by answering questions such as: '*Which road corridor has the lowest life cycle impacts?*' and '*What materials and construction activities contribute most the life cycle impacts of road corridors?'.* Paper III showed what parameters should be project specific and collected by planners for the specific project (for example volume of excavated rock and soil) and which parameters can be generic and included in the models (for example thickness of pavement layer for a specific type of road). This aids the of LCA at a planning stage where there are big opportunities to reduce life cycle impacts of the infrastructure project, but project specific inventory data is scarce.

6. Suggestions for future studies

Future studies involve both improvement of data availability and assessment of uncertainty in Papers I-II as well as methodological development in environmental assessment at project and network level.

Papers I-II indicated areas where more research would increase the understanding of climate impact and energy use of the Swedish transport system. One area was improved data availability on activities in the transport system, such as construction rate of non-state owned road and rail infrastructure and data on international freight transport. Paper II could also be complemented with data already compiled by actors in the transport system but that were not available for use in this paper (for example making use of more detailed data on port calls).

Additional suggestions in Paper I were research on impacts of small construction measures, the size of biogenic carbon emissions (in standing biomass as well as soil carbon), and the use and impacts of asphalt in road construction and management. For better estimations of material and energy use, both at project and network levels, efforts should be made to continuously improve the access to data representative of national construction conditions.

Neither Paper I nor II included a quantitative uncertainty or sensitivity analysis for analysing the effects of uncertainties in input data on the results. This may be required to fully understand the effects of uncertainties in input data on the results.

Also methodological development may improve data availability and assessments of climate impacts of transport systems. For example, using consequential or dynamic LCA may provide a complementing picture of annual impacts of transport systems. Other forms of data may be available by using other methods. If more detailed input-output data were available such data could be used to estimate environmental hotspots as well as annual impacts of transport systems. Methodological development may also be necessary to integrate different assessment tools with each other – for example integrating tools like Klimatkalkyl with methods for geological assessments.

Papers I-II did not relate impacts of the transport system to the transport work conducted. This may be needed to discuss possible future policy measures and to suggest policy measures based on the functions that the system supports.

The models in Papers I-III could be extended to include also other environmental impact categories than climate impact and primary energy use to avoid shifting burdens between different impact categories. Particularly abiotic resources may be important for long-term planning of the transport system, considering the present trend towards electrification of the road transport system. Additionally, integration of land use change may be important for assessment of transport plans.

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