



**KTH Architecture and  
the Built Environment**

# **Life Cycle Impacts of Road Infrastructure**

## ***Assessment of energy use and greenhouse gas emissions***

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**Licentiate Thesis in Infrastructure**

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## Abstract

Road infrastructure is essential in the development of human society, but has both negative and positive impacts. Large amounts of money and natural resources are spent each year on its construction, operation and maintenance. Obviously, there is potentially significant environmental impact associated with these activities. Thus the need for integration of life cycle environmental impacts of road infrastructure into transport planning is currently being widely recognised on international and national level. However certain issues, such as energy use and greenhouse gas (GHG) emissions from the construction, maintenance and operation of road infrastructure, are rarely considered during the current transport planning process in Sweden and most other countries.

This thesis examined energy use and GHG emissions for the whole life cycle (construction, operation, maintenance and end-of-life) of road infrastructure, with the aim of improving transport planning on both strategic and project level. Life Cycle Assessment (LCA) was applied to two selected case studies: LCA of a road tunnel and LCA of three methods for asphalt recycling and reuse: hot in-plant, hot in-place and reuse as unbound material. The impact categories selected for analysis were Cumulative Energy Demand (CED) and Global Warming Potential (GWP). Other methods used in the research included interviews and a literature review.

The results of the first case study indicated that the operational phase of the tunnel contributed the highest share of CED and GWP throughout the tunnel's life cycle. Construction of concrete tunnels had much higher CED and GWP per lane-metre than construction of rock tunnels. The results of the second case study showed that hot in-place recycling of asphalt gave slightly more net savings of GWP and CED than hot in-plant recycling. Asphalt reuse was less environmentally beneficial than either of these alternatives, resulting in no net savings of GWP and minor net savings of CED. Main sources of data uncertainty identified in the two case-studies included prediction of future electricity mix and inventory data for asphalt concrete.

This thesis contributes to methodological development which will be useful to future infrastructure LCAs in terms of inventory data collection. It presents estimated amounts of energy use and GHG emissions associated with road infrastructure, on the example of road tunnel and asphalt recycling. Operation of road infrastructure and production of construction materials are identified as the main priorities for decreasing GHG emissions and energy use during the life cycle of road infrastructure. It was concluded that the potential exists for significant decreases in GHG emissions and energy use associated with the road transport system if the entire life cycle of road infrastructure is taken into consideration from the very start of the policy-making process.

**Key words:** Cumulative Energy Demand (CED), Global Warming Potential (GWP), Life Cycle Assessment (LCA), road infrastructure, strategic planning.

## Sammanfattning (Summary in Swedish)

Väginfrastruktur har stor påverkan på samhällets utveckling, i både negativ och positiv bemärkelse. Stora mängder pengar och naturresurser används varje år till byggnation, drift och underhåll av väginfrastruktur. Därför uppmärksammas numera allt oftare, både nationellt och internationellt, vikten av att ta hänsyn till miljöpåverkan i ett livscykelperspektiv vid transportplanering. Det har dock visat sig att vissa frågor, som energianvändning och utsläpp av växthusgaser från byggnation, underhåll och drift av vägar än så länge sällan beaktas vid transportplanering, både i Sverige och i de flesta andra länder.

Det övergripande syftet med denna avhandling är att öka kunskapen om energianvändning och utsläpp av växthusgaser under väginfrastrukturens hela livscykel. Målet är att bidra till bättre planering av transporter på både strategisk och projektnivå. Denna avhandling är avgränsad till energianvändning och utsläpp av växthusgaser under byggnation, drift, underhåll och rivning av väginfrastruktur. Livscykelanalys (LCA) användes för analys av två fallstudier: LCA av en vägtunnel och LCA av tre metoder för återvinning/återanvändning av asfalt: varm återvinning på plats, varm återvinning i verk och återanvändning (återvinning) av asfaltgranulat som obundet lager. De miljöpåverkanskategorier som analyserades var primär energianvändning (CED) och klimatpåverkan (GWP). Andra metoder som användes i denna forskning var intervjuer och litteraturstudier.

Resultaten från den första fallstudien visade att tunnelns drift har störst påverkan på energianvändningen och utsläppen av växthusgaser under tunnelns hela livscykel. Dessutom visade resultaten att byggande av betongtunnlar har mycket högre påverkan på CED och GWP per meter körfält jämfört med bergtunnlar. Resultaten av den andra fallstudien visade att varm återvinning av asfalt på plats ger något större nettobesparing av GWP och CED än varm återvinning i verk. Jämfört med varm återvinning, är återanvändning av asfaltgranulat som obundet lager ett mindre miljövänligt alternativ, eftersom det inte ger någon nettobesparing av GWP och mindre nettobesparing av CED. Flera källor till dataosäkerhet i LCA av väginfrastruktur identifierades, t.ex. förutsägelser om den framtida elmixen och inventeringsdata för bitumen och betong.

Denna studie har bidragit till metodutveckling som kan komma till användning vid framtida LCAer av infrastruktur i form av datainsamling. Den presenterar också beräkningar av energianvändning och utsläpp av växthusgaser från väginfrastruktur, med exempel från en vägtunnel och asfaltåtervinning. Dessutom har drift av vägar och produktion av byggmaterial identifierats som nyckelfaktorer för att minska utsläpp av växthusgaser och energianvändning under väginfrastrukturens livscykel. Den övergripande slutsatsen är att det finns en betydande potential för att minska utsläpp av växthusgaser och energianvändning i vägtransportsystemet, om väginfrastrukturens hela livscykel beaktas från början i den politiska beslutsprocessen.

**Nyckelord: energianvändning, klimatpåverkan, Livscykelanalys (LCA), väginfrastruktur, strategisk planering**

## **Resumen (Summary in Spanish)**

La infraestructura vial es fundamental para el desarrollo de la sociedad humana. Sin embargo tiene efectos tanto negativos como positivos. Grandes cantidades de dinero y recursos naturales se destinan a su construcción, operación y mantenimiento cada año. Por lo tanto la necesidad de integración de los impactos del ciclo de vida de la infraestructura vial en la planificación del transporte ha sido recientemente reconocida a nivel internacional y nacional. Sin embargo, algunos temas, como el uso de energía y gases de efecto invernadero (GEI) procedentes de la construcción, mantenimiento y operación de la infraestructura vial, rara vez se consideran durante el proceso de planificación del transporte actual en Suecia y muchos otros países.

En esta tesis se ha examinado el uso de la energía y las emisiones de GEI durante el ciclo de vida (construcción, operación, mantenimiento y fin de su vida útil) de la infraestructura vial, con el objetivo de mejorar la planificación del transporte, tanto a nivel estratégico como de proyecto. La principal herramienta de análisis de sistemas ambiental utilizada es el Análisis de Ciclo de Vida (ACV), que se aplicó a dos estudios: ACV del túnel y ACV de los tres métodos para reciclado y reutilización de asfalto: reciclado en caliente in situ y en planta y la reutilización como agregado. Las categorías de impacto seleccionadas para el análisis son la Demanda Energética Acumulada (DEA) y el Potencial de Calentamiento Global (PCG). Otros métodos utilizados en la investigación incluyen entrevistas y revisión literaria.

Los resultados del primer estudio indican que la fase de explotación del túnel ha contribuido a una mayor proporción de DEA y el PCG a través del ciclo de vida del túnel. La construcción de túneles de hormigón tiene mucho más alto PCG y DEA por carril-metros que la construcción de túneles de roca. Los resultados del segundo estudio mostraron que reciclado de asfalto en caliente in situ dio un poco más ahorros netos de DEA y PCG que reciclado en caliente en planta. Reutilización de asfalto como agregado fue menos ambientalmente beneficiosa que cualquiera de estas alternativas, lo que no habría un ahorro neto de PCG y menor ahorro neto de DEA. Las principales fuentes de incertidumbre de los datos identificados en los dos estudios incluyeron la predicción de la mezcla de electricidad en el futuro y los datos para asfalto y hormigón.

Esta tesis contribuye al desarrollo metodológico de ACV de infraestructura en el futuro por el inventario de la recopilación de datos. Las cantidades de consumo de energía y las emisiones de GEI asociados con la infraestructura vial (en particular, el túnel y reciclado de asfalto) fueron también estimadas. El funcionamiento de la infraestructura vial y la producción de materiales de construcción fueron identificados como las principales prioridades para reducir las emisiones de GEI y el consumo de energía durante el ciclo de vida de la infraestructura vial. Se concluyó que existe la posibilidad de una disminución significativa en las emisiones de GEI y el consumo de energía asociado con el sistema de transporte por carretera, si la infraestructura vial se tiene en cuenta desde el inicio del proceso de formulación de políticas.

## Резюме (Summary in Ukrainian)

Дорожня інфраструктура грає важливу роль в розвитку людського суспільства, як в позитивному так і негативному значенні. Великі суми грошей і багато природних ресурсів витрачається на її будівництво, експлуатацію та обслуговування щороку. Таким чином інтеграція циклового впливу дорожньої інфраструктури протягом планування транспортної системи була широко визнана останнім часом на міжнародному та національному рівнях. Однак було відмічено, що деякі питання, такі як використання енергії і викиди парникових газів (ПГ) під час будівництва, утримання та експлуатації дорожньої інфраструктури, рідко розглядаються протягом нинішнього процесу планування транспортної системи як в Швеції так і в більшості інших країн.

Основна мета цієї роботи полягає в розширенні знань про використання енергії та викидів парникових газів протягом усього життєвого циклу дорожньої інфраструктури, з метою поліпшення транспортного планування на стратегічному та проектному рівнях. Ця робота сфокусована на використанні енергії та викидів парникових газів (ПГ) на етапах будівництва, експлуатації, технічного обслуговування та кінці строку служби дорожньої інфраструктури. Основний метод, який використовується для цього дослідження є оцінка життєвого циклу (ОЖЦ). Цей інструмент був виконаний для аналізу двох окремих систем: ОЖЦ автодорожнього тунелю і ОЖЦ трьох способів для переробки старого асфальтобетону. Категорії впливу які були відібрані для аналізу є: Кумулятивний попит на енергоресурси (КПЕ) і Потенціал глобального потепління (ППП). Інші методи які були використані в цьому дослідженні, є інтерв'ю та огляд літератури.

Результати першого дослідження показали, що найвища частка споживання енергії та викидів ПГ протягом всього життєвого циклу тунелю припадає на експлуатацію тунелю. Було також зазначено, що будівництво бетонних тунелів витрачає більше енергії та викидів ПГ в порівнянні з тунелями в скелі. Результати другого дослідження показали, що гаряча переробка асфальтобетону на місці має трохи більше збережень КПЕ і ППП ніж гаряча переробка на підприємствах. У порівнянні з гарячою переробкою асфальтобетону, повторне використання асфальту в ролі кам'яних матеріалів є менш екологічно вигідною альтернативою, що не призводить до значних збережень ППП і КПЕ. Також було відзначено декілька джерел невизначеності даних для ОЖД транспортної інфраструктури (наприклад, передбачення майбутньої структури електрики, інвентаризаційні дані для бітуму та ін.)

Це дослідження сприяло методологічній розробці для майбутніх ОЖД з точки зору збору інвентаризаційних даних. Також були оцінені обсяги споживання енергії та викидів ПГ, пов'язаних з дорожньою інфраструктурою. Крім того, експлуатація дорожньої інфраструктури та виготовлення будівельних матеріалів були визначені як основні пріоритети для зменшення викидів ПГ та використання енергії протягом життєвого циклу дорожньої інфраструктури. Таким чином, був зроблений висновок, що дорожньо-транспортна система має потенціал для зниження значних викидів ПГ та використання енергії, у разі якщо дорожня інфраструктура приймається до уваги з самого початку процесу прийняття політичних рішень.

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## **List of papers**

This thesis is based in the following papers, which are referred to in the text by their Roman numerals:

### **Paper I**

Miliutenko, S. (2009). Assessment of energy use and greenhouse gas emissions generated by transport infrastructure, literature review. *TRITA-INFRA-FMS 2009:8*, KTH (Environmental Strategies Research), Stockholm.

### **Paper II**

Miliutenko, S., Åkerman, J. and Björklund, A. (2012). Energy use and greenhouse gas emissions during the life cycle stages of a road tunnel - the Swedish case Norra Länken. *EJTIR 12* (ISO 14040), 39-62.

### **Paper III**

Miliutenko, S., Björklund, A. and Carlsson A. (2012). Opportunities for environmentally improved asphalt recycling: The example of Sweden. Manuscript, submitted to Journal of Cleaner Production

### **Contribution of the author:**

Sofiia Miliutenko was responsible for data collection, modelling and writing the main structure of Papers I-III.

## List of abbreviations

CDW	Construction and Demolition Waste
CED	Cumulative Energy Demand (measured in MJ-eq)
EEA	Embodied energy analysis
EIA	Environmental Impact Assessment
ES	Emergy synthesis
ESA	Environmental Systems Analysis
EU	European Union
EXA	Exergy analysis
GHG	Greenhouse Gas
GWP	Global Warming Potential (measured in CO <sub>2</sub> -eq)
IOA	Input-output analysis
ISO	International Organization for Standardization
IVL	Swedish Environmental Research Institute
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
NCC	Nordic Construction Company
NVF	Nordic Road Association
RAP	Reclaimed Asphalt Pavement
SEA	Strategic Environmental Assessment
SFA	Substance Flow Analysis
SKL	Swedish Association of Local Authorities and Regions
STA	Swedish Transport Administration
VTI	Swedish National Road and Transport Research Institute

# 1 Introduction

## 1.1 Background

Road infrastructure plays a vital role in the development of human society, in both negative and positive ways. It has developed enormously since the beginning of the 20<sup>th</sup> century (SNA, 2002). By 2010, the Swedish road network comprised about 584 500 km, which is approximately 15 times the circumference of the Earth, and it continues to grow (Oscarsson, 2010; SNA, 2002). On average, about 5 000 km of new roads are constructed in Sweden every year (recalculated from Oscarsson (2010)). The country spends approximately 7 000-10 000 million SEK every year on the operation and maintenance of state road infrastructure (Trafikverket, 2010). Moreover, it was estimated that approximately 10 TWh of energy are used for construction and maintenance of road infrastructure in Sweden (recalculated from Toller et al. (2011)).

However, despite such an important share of environmental impact and financial expense being associated with road infrastructure, certain issues, such as energy use and greenhouse gas (GHG) emissions from the construction, maintenance and operation of road infrastructure, are rarely considered during the current transport planning process in Sweden and most other countries.

For instance, the American scientist Chester (2009) stated that “current decision-making relies only on analysis at the tailpipe, ignoring vehicle production, infrastructure provision, and fuel production required for support”. Moreover, a recent study on analysis of transport infrastructure planning in Sweden concluded that impacts from construction of infrastructure were only partially included in the environmental assessment during the planning process of a new traffic route, the Stockholm Bypass (Finnveden and Åkerman, 2011). Those authors pointed out that such an important aspect as production of materials for the new tunnel construction was not included in the assessment. This led to an underestimation of GHG emissions and consequently an incomplete picture during the choice of possible alternatives (ibid). Federici (2009) also noted that “published LCA studies on road and rail systems very seldom account for infrastructures in detail, but mainly focus on the manufacturing of vehicles and their fuel use”.

So, if infrastructure constitutes a significant part of the total environmental impact of transportation, there is a severe risk of transport planning decisions being sub-optimised from an environmental point of view. In particular, in light of the challenges posed by climate change, it is urgent to develop low-carbon transportation systems in which “carbon emissions are lower than the infrastructure alternatives available for providing a specific transportation service” (Claro, 2010).

However, even though it has not yet been observed fully in practice, the importance of including life cycle impacts of infrastructure during transport planning has recently been widely recognised on international and national level, as shown below for the examples of the EU and Sweden.

According to a recently published EU White Paper on competitive and resource-efficient transport infrastructure, EU-funded transport infrastructure should “take into account energy efficiency needs and climate change challenges (i.e. climate resilience of the overall infrastructure, refuelling/recharging stations for clean vehicles, choice of construction material etc.”, in order to reduce GHG emissions to around 20% below the 2008 level by 2030 (COM, 2011). The same document states that transport infrastructure should be “planned in a way that maximizes positive impact on economic growth and minimizes negative impact on the environment”.

As far as the national level in Sweden is concerned, the Swedish Transport Administration (STA) aims to contribute to the achievement of several Swedish Environmental Quality Objectives (Vägverket, 2007). One of these is “Reduced Climate Impact”. A major step in the work of achieving this quality objective is to reduce energy use during the construction and operation of transport infrastructure (ibid). Thus the Swedish Transport Administration has a goal for increased use of Life Cycle Assessment (LCA) in its planning processes. This goal states that “everything built must be as durable as possible, with long term cost effectiveness as the goal, taking into consideration construction, operation and maintenance” .....“LCA analyses will be everyday occurrences” (Vägverket, 2001).

In summary, there is an urgent need for better understanding of energy use and GHG emissions associated with road infrastructure. In order to minimise those impacts, more information is needed about how they can be measured, to what extent they can be decreased and the processes and activities that should be targeted.

## **1.2 Overall aim and scope of the thesis**

The overall aim of this thesis was to provide further knowledge about energy use and GHG emissions for the whole life cycle of road infrastructure, in order to improve transport planning on both strategic and project levels.

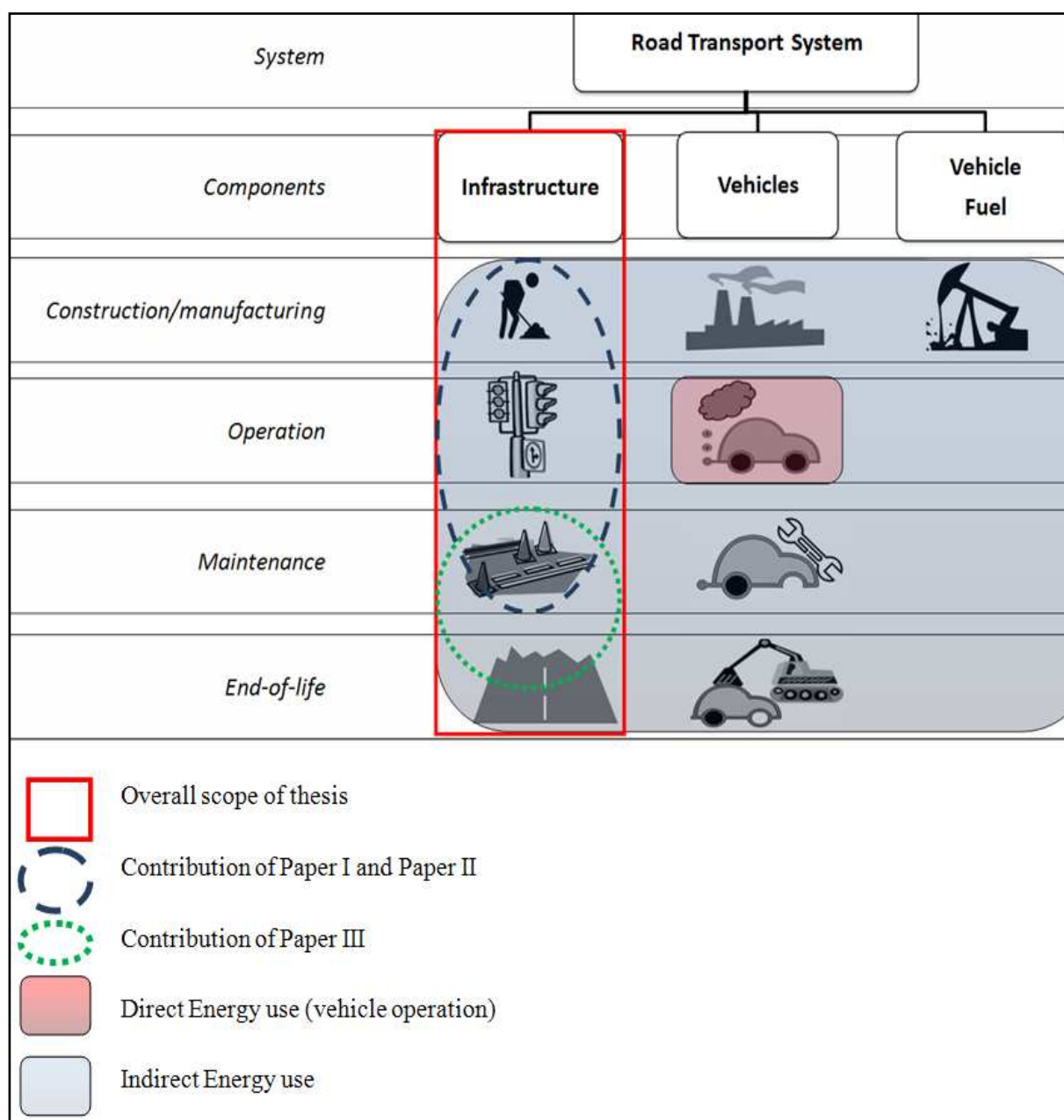
At the strategic level (i.e. during policy-making or programme/plan development on future transport investments and measures within a transport corridor (Eriksson and Lingestål., 2002)), better knowledge would permit more informed choices between different alternatives for transport system development, including the ‘zero’ alternative – no new construction. On project level (i.e. during the feasibility study, design and construction phases of a specific project (Eriksson and Lingestål., 2002)), improved knowledge could help identify processes that contribute a significant share of the total environmental impact (so called ‘hotspots’) during the life cycle of road infrastructure and how they could be minimised.

The specific research questions examined in the thesis were:

- ❖ **HOW** can energy use and GHG emissions of road infrastructure be assessed?
- ❖ **WHAT** are the energy use and GHG emissions during the life cycle of road infrastructure?
- ❖ **WHICH** elements and phases during the life cycle of road infrastructure have the largest energy use and GHG emissions?

The scope of the thesis was restricted to primary energy use (measured as Cumulative Energy Demand (CED)), and GHG emissions (measured as Global Warming Potential (GWP)) during the stages of construction, operation, maintenance and end-of-life of road infrastructure, which is one of the main components of the road transport system (Figure 1).

The complete life cycle of each stage was covered, from extraction of raw materials to emissions after waste disposal. Impacts of vehicles and vehicle fuel use during operation on roads were not included.



**Figure 1. Components of the transport system covered by the thesis**

As indicated in Figure 1, Papers I-III covered different parts of the overall scope of the thesis.

Specific objectives of **Papers I-III** were as follows:

- Paper I: *‘Assessment of energy use and greenhouse gas emissions generated by transport infrastructure, literature review’*

The overall aim of Paper I was to analyse existing environmental assessment tools, methods and results found in measuring energy use and GHG emissions in the whole life cycle of transportation infrastructure, with the focus on construction, operation and maintenance phases of road and railroad infrastructure. Although the literature scrutinised in Paper I was wider in scope, the results and analysis discussed in this thesis only relate to road infrastructure.

- Paper II: *‘Energy use and greenhouse gas emissions during the life cycle stages of a road tunnel - the Swedish case Norra Länken’*

The overall aim of Paper II was to improve our understanding of the life cycle energy use and GHG emissions of one important part of road infrastructure – a road tunnel.

- Paper III: *‘Opportunities for environmentally improved asphalt recycling: The example of Sweden’*

The aim of Paper III was to identify and evaluate the potential for improving treatment of reclaimed asphalt pavement in Sweden, from a life cycle environmental perspective.

### **1.3 Outline of the thesis**

This cover essay provides a summary of Papers I-III, which are appended at the end of the thesis. The background, overall aim of the thesis and specific objectives of the appended papers have been described in Chapter 1. Chapter 2 provides a scientific context based on the literature review in Paper I, together with recent updates in this field. Chapter 3 describes the main methodology used in each paper. Chapter 4 summarises the results of Papers II and III, while Chapter 5 discusses data uncertainty and variability identified in the case studies. Chapter 6 summarises the contribution of each paper to the overall aim of the thesis, discusses limitations of the chosen methodology and policy implications of the research, and provides proposals for future research.

## 2 Scientific context (Paper I and recent updates)

This chapter provides definitions of road infrastructure and indirect energy use. It also summarises the main studies performed in the area of assessment of life cycle energy use and GHG emissions from transport infrastructure (based on Paper I and recent updates).

### 2.1 Infrastructure as part of indirect energy use in transport systems

When discussing the impacts of transport systems, it is useful to make a distinction between direct and indirect impacts. As defined by Jonsson (2005), vehicle operation is regarded as **direct energy use of the transport system**. Road infrastructure and its different life cycle stages are regarded as one of the components of **indirect energy use**, together with manufacturing, maintenance and end-of life of vehicles and fuel/electricity production (see Figure 1). The term **infrastructure** used in this study refers to the following items: roads, tunnels, bridges, and other supporting components (signs, lighting installations, road furniture etc.).

The life cycle of road infrastructure as defined in this study includes the following four main stages: construction, operation, maintenance and end-of-life. Each of these stages can be further subdivided into extraction/production of materials, processes on-site and waste disposal (Paper II). Extraction/production of construction materials is sometimes considered as a separate stage of the life cycle of road infrastructure (for instance by Claro (2010)). However in this thesis, extraction/production and transportation of materials, as well as waste disposal, are included in each of the four individual life cycle stages of road infrastructure.

Processes on-site for each life cycle stage of infrastructure include the following main activities:

- **Construction** stage refers to ground preparation, construction of main constituent parts of the road infrastructure, production and installation of other items (signs, wires, pipes, road furniture etc.).
- **Operation** stage refers to supporting functions that facilitate possibilities to use the infrastructure (Claro, 2010; Jonsson, 2007). These include the following activities: lighting, cleaning, accident control, sand spreading, salting, snow clearance, street-sweeping, maintenance of road markings, vegetation clearing and others (Jonsson, 2007).
- **Maintenance** stage refers to works that are required due to corrosion, erosion and displacement (Jonsson, 2007). These include the following main activities: surface coating, manufacturing, maintenance and operation of working machines, painting road markings and additional filling material (Jonsson, 2007).
- **End-of-life** (demolition and final disposal) of infrastructure consists of the following activities: mechanical dismantling, transport and subsequent management of demolition waste (Jonsson, 2007). Since infrastructure is rarely completely demolished, this stage is rarely included in the analysis of life cycle assessments (Mroueh et al., 2000).

## 2.2 Assessment of life cycle energy use and GHG emissions from transport infrastructure

As described in Paper I and Muench (2010), a number of studies have been performed on the assessment of environmental impacts of transport infrastructure (e.g. Mroueh et al., (2000); Stripple, (2001); Birgisdottir, (2006) Jonsson, (2007); Karlsson et al., (2010) and others).

The papers analysed in the literature review (Paper I) included the following tools for assessing environmental impacts of transport systems: EIA (environmental impact assessment), SEA (strategic environmental assessment), LCA (life cycle assessment), SFA (substance flow analysis), MFA (mass flow accounting), IOA (input-output analysis), EEA (embodied energy analysis), EXA (exergy analysis) and emergy synthesis (ES) (Federici et al., 2008). All these tools have a common name – Environmental Systems Analysis. As defined by Wageningen University (2012): “Environmental Systems Analysis is a quantitative and multidisciplinary research field aimed at analyzing, interpreting, simulating and communicating complex environmental problems from different perspectives.” However, there is no single common definition of ESA (Moberg, 2006).

According to Duchin and Hertwich (2003), ESA tools can be subdivided into three groups: 1) material flows, energy flows and environmental accounting; 2) Life Cycle Analysis (the product level) and 3) Input-Output Economics (the Meso-level). Such tools were also categorised by Wrisberg et al. (2002) into procedural (e.g. EIA and SEA) and analytical (e.g. SFA, MFA, IOA, LCA, EEA, EXA, ES). As defined by Moberg (2006), procedural tools improve the procedures leading to decision-making, while analytical tools provide information that may be used for communication, systems optimisation and comparison of different alternatives. Procedural tools can include a number of analytical tools (Moberg, 2006).

Different tools (as well as methodologies) are used for various levels of assessment, considering different objects of study, different environmental or social issues, etc. (Finnveden and Moberg, 2005). Consequently, in general they cannot replace each other. However, very often they can complement each other. Thus, in order to make a thorough study of a specific topic, the use of several methodologies in combination is recommended (ibid).

Among the papers reviewed in Paper I, it was observed that Chester and Horvath (2009) used a combination of IOA and LCA in order to evaluate environmental impacts of passenger transportation systems. Federici and colleagues used a combination of MFA, EEA, EXA, ES, as well as an LCA approach in their studies (Federici et al., 2008; Federici et al., 2009). The most commonly used analytical tool for assessment of the environmental impacts of transport infrastructure is LCA (Jonsson, 2007; Schlaupitz, 2008; Stripple and Erlandsson, 2004).

Stripple and Erlandsson (2004) subdivided LCA of transport systems according to level of analysis:

- **Network level** (transport service), referring to the annual transportation consumed per capita or per geographical area

- **Corridor level** (transport operation), referring to tonnage and km, or person and km of transported goods or passengers
- **Project level** (transport object), referring to km or road, bridge, tunnel and carrying capacity (Stripple and Erlandsson, 2004).

The studies included in Paper I considered either the project or corridor level of analysis (Miliutenko, 2009; Toller et al., 2011).

Examples of the first group of studies (project level) include Schlaupitz (2008), Stripple and Erlandsson (2004), Karlsson (2010), Meil (2006), ECRPD (2009) and others. It is possible to calculate from the data presented by Schlaupitz (2008) that about 6480 kWh of primary energy are used over a 100-year period for the construction, operation and maintenance phases for 1 metre of a two-lane plain road (without tunnels and bridges). According to Stripple and Erlandsson (2004), the total energy use during construction, maintenance and operation phases for 1 metre of road (with an unspecified percentage of tunnels and bridges) over a 40-year period is about 6940 kWh.

Examples of the second group of studies (corridor level) include Chester et al. (2009), Federici et al. (2003), Schlaupitz (2008) and Jonsson (2007). Based on recalculations of data in Chester and Horvath (2009), it can be concluded that indirect energy use accounts for about 23-32% of the total life cycle energy demand for road transport, 40-69% for rail transport and 7-29% for air transport. In contrast, Jonsson (2007) concluded that indirect energy use for road transportation accounts for about 45% of total life cycle energy demand. Federici et al. (2003) showed that the railway system has a larger demand for energy and material input per ton-km for construction and maintenance than road infrastructure.

Current interest in the life cycle environmental performance of road infrastructure has also resulted in the development of several rating systems, such as Environmental Product Declarations (EPDs), CEEQUAL (Civil Engineering Environmental Quality Assessment and Award Scheme), DGNB (German Seal of Approval for Sustainable Construction) and LEED (Leadership in Energy and Environmental Design) in USA (Muench, 2010). Researchers have also developed a number of practical tools that evaluate the use of different materials for road or bridge construction using a life cycle perspective. Examples of these tools are 'Road-res' (Birgisdottir et al., 2006), 'Palate' (Horvath, 2003), WRAP tools (WRAP, 2010) and Bridge LCA (Hammervold et al., 2009).

The conclusion drawn from the literature review in Paper I was that it is almost impossible to compare quantitatively the results of different studies and tools, due to the fact that different types of data and phases of infrastructure are evaluated. However, most of the studies reviewed concluded that the indirect phases of the road transport system contribute a significant share of total energy use and GHG emissions. This indicates a need for more information on the life cycle environmental performance of road transport infrastructure.

### **3 Methodology**

This chapter gives theoretical overview of the main methods used in this thesis: Life Cycle Assessment, case studies, interviews and literature review.

#### **3.1 Background: research methods used in the thesis**

As described in section 2.2, a number of environmental system analysis tools have been used to evaluate the environmental impacts of transport systems. The reason for this is that transport planning is a complex issue that leads to various environmental, social and economic impacts and benefits involving many different stakeholders. Thus in order to consider all those aspects when choosing between alternatives for transport development, there is a need for a holistic approach that combines “ecological, economic, technological and policy perspectives” (Wageningen University, 2012). Consequently, ESA tools were developed for this purpose. These tools can be used for learning purposes, communication or decision-making (Moberg, 2006).

As concluded from Paper I, LCA is the most common tool used for assessing energy use and GHG emissions for road infrastructure (section 2.2). Since one of the objectives of this thesis was to analyse energy use and GHG emissions in the whole life cycle of road infrastructure, LCA was the main tool used throughout the research process. This tool was applied for the analysis of two selected case studies (Paper II and Paper III). The methods used for data analysis and collection were literature review and interviews (including several field visits). Theoretical concepts of the chosen methodologies are explained in the following sections.

#### **3.2 Life Cycle Assessment (LCA)**

LCA is a systems analysis tool that takes into account potential environmental impacts of a product or service throughout the whole life cycle from raw material acquisition to transport, production and use, as well as the impact in the end-of-life phase as waste (ISO 14040, 1997). As discussed in section 2.2, LCA is an analytical tool. According to the definition by UNECE, “LCA may be applied within the whole process of decision-making: identification of issues and impacts, analysis context and baseline, contributing to development of alternatives, assessment of impacts, comparing the options” (UNECE, 2007).

LCA methodology consists of four main stages: 1) defining of the goal and scope of the study and determining the boundaries; 2) inventory analysis that involves data collection and calculation of the environmental burdens associated with the functional unit and each of the life cycle stages; 3) impact assessment; and 4) interpretation of the results (ISO, 2006).

One of the most important stages in the LCA procedure is defining the functional unit, which is a reference unit that quantifies the performance of the system (Weidema et al., 2004). The functional unit in Paper II was determined by the object of assessment – the tunnel structure assessed. This corresponds to the project level of analysis, as defined in section 2.2 (Strippel and Erlandsson, 2004). The functional unit chosen in Paper III was 1 ton of RAP (Reclaimed

Asphalt Pavement or asphalt ‘waste’), which means that the study was performed from the waste management perspective rather than the road construction perspective.

Another important aspect associated with LCA is the allocation problem that arises during the process of inventory analysis, when the product or process investigated shares a common activity with other products not analysed in the study. This leads to a need to allocate the share of the environmental burdens to the product or process studied (Ekvall and Finnveden, 2001). There are several methods that can be used for handling allocation problems. It is well known that the choice of allocation procedure can significantly influence the final results (Guinée and Heijungs, 2007). Thus, as recommended by ISO 14041, allocation should be avoided, wherever possible, through more detailed collection of inventory data or system expansion (Ekvall and Finnveden, 2001). When it is not possible to avoid allocation, it is recommended that this problem be solved by either reflecting the physical relationships between the environmental burdens and the functions (for instance mass or energy content) or by reflecting other relationships between the environmental burdens and the functions (for instance economic allocation) (Ekvall and Finnveden, 2001; Guinée and Heijungs, 2007). A different type of allocation problem arises in open-loop recycling, when material from one product life cycle is recycled into another (Ekvall and Finnveden, 2001). In cases where recycling does not cause a change in the inherent properties of the material, ISO 14041 recommends calculating avoided environmental burdens as if the material had been recycled back into the same product (ibid).

Allocation problems mentioned above were encountered in each LCA study (Paper II and Paper III). For instance, allocation problems regarding reuse of blasted rock in tunnel construction (Paper II) and open-loop asphalt recycling (Paper III) were handled by calculating avoided burdens. Paper III also discusses the allocation problem when calculating the share of environmental impact for bitumen.

Two types of LCA can be distinguished: 1) Attributional, sometimes also called descriptive or accounting; and 2) Consequential, sometimes also called change-oriented (Finnveden et al., 2009). The processes included in an attributional LCA are those that contribute significantly to the product or service studied, while the processes included in a consequential LCA are those that could be affected by the decisions to be supported in the study (Rebitzer et al., 2004). One of the differences between these two types of LCA is the choice between average and marginal data. Marginal data reflecting the effects of small changes should be used in consequential LCA, while average data reflecting the actual physical flows should be used in attributional LCA (Finnveden et al., 2009).

Attributional LCA with the choice of average data was used as the main method in Paper II and Paper III. This method was chosen due to the fact that it allows identification of major contributing processes to a system in the current situation (Paper II). However, the choice of marginal data for electricity was also tested in Paper II.

### **3.3 Case study**

Two case studies were examined: LCA of a road tunnel (Paper II) and LCA of three methods for asphalt recycling and reuse (Paper III). The term ‘case study’ is commonly used in LCA to describe what is being analysed. However, it is seldom problematised why a specific case is analysed and what purpose it may serve, in addition to presenting a set of results for that particular case.

Flyvberg (2006) described the case study as “a detailed examination of a single example”. According to Yin (2009), a case study can also be defined as “an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context”. The case should be a complex functioning unit, be investigated in its natural context with a multitude of methods and be contemporary. Case studies can be performed in both social and natural sciences (Johansson, 2005). Flyvberg (2006) states that “case studies are useful for both generating and testing [a] hypothesis, but are not limited to these research activities alone.”

The case study in Paper II is a site-specific LCA of processes related to the life cycle of the road tunnel Norra Länken that is being constructed in Stockholm. The case study in Paper III is a comparison of three methods for asphalt recycling and reuse in Sweden, reflecting the average case on a national level.

The purpose of the particular case studies in Papers II and III was to provide data which can be generalised and used in other studies (as explained in Paper II). Another purpose of using these case studies was to contribute to development of methodology for further LCAs of transport infrastructure.

In conclusion, these case studies were intended to be useful owing to the knowledge obtained during the learning process which generates a better understanding of environmental impacts of road infrastructure. The findings from these two case studies can be validated by third-party reviewers and comparisons with similar studies conducted by other researchers.

### **3.4 Interviews**

Interviews were an important method of data collection used in different stages of this research (Papers II and III). The interview method of research involves a meeting with the key stakeholders in which a researcher asks a series of questions. According to Kvale (2006), an interview can be defined as a meeting where the reporter obtains information from a person, as a meeting with another person to achieve a specific goal, or as a conversation with a purpose. Interviews can be subdivided into structured, semi-structured or open, and into qualitative or quantitative. As defined by Alvesson (2003), qualitative interviews are relatively loosely structured and open to what the interviewee feels is relevant and important to talk about, given the interest of the research project. Advocates of interviews typically argue that this approach is beneficial in terms of getting information on experiences, knowledge, ideas and impressions (Alvesson, 2003). Schostak (2005) noted that “interviewing is very often seen as an ordinary tool for data collection, while in reality it is a complex

process that cannot be separated from the dynamic of the project or from the multiple and changing contexts of everyday life.”

The interviews conducted for the research reported in Papers II and III were often semi-structured and semi-qualitative. The main aim of these interviews was data collection for the case studies. They were also performed in the beginning of the projects, as a means of determining the scope of the research question.

The interviews were usually performed with the key stakeholders identified at the beginning of the project. This was followed by ‘snowball’ sampling, where each respondent identified at the beginning of the study was asked for references to other individuals who could be potential interviewees (Norman and Russell, 2006).

Stakeholders on the national, local and project level of asphalt recycling were sought. These included contractors, property owners and research institutes. A questionnaire was sent out in advance of each interview. Both quantitative data and qualitative aspects were asked for in Paper III, but only quantitative data in Paper II. Example included estimates (in tons) of the approximate stock of asphalt (Paper III), materials used or energy consumed during tunnel construction, operation, maintenance (Paper II), the frequency of recycling (Paper II and Paper III), and the interviewee’s experience of obstacles to the process of asphalt recycling (Paper III).

The interviews were sometimes also combined with field visits, e.g. to the tunnel construction site (Paper II) and asphalt recycling sites (Paper III).

### **3.5 Literature review**

The literature was reviewed throughout the whole process of research (in Papers I, II and III). Paper I reviewed the literature on existing environmental assessment tools, methods and results found in measuring energy use and GHG emissions in the whole life cycle of transportation infrastructure. The documents included were scientific journal articles, reports, books, electronic sources and doctoral theses specialising in environmental assessment and transport systems. No studies older than 1997 were included. The studies reviewed were performed in the following countries: Sweden, USA, Italy, Norway, UK, Finland, Netherlands, Australia, Denmark and Germany.

The literature review in Paper II was conducted with the aim of collection of inventory data for tunnel LCA, which involved reviewing scientific articles, books, technical reports and the websites of construction companies. The literature review in Paper III was performed in order to gather information about the current state of asphalt recycling methodologies in Sweden and abroad, as well as to collect inventory data for LCA of the asphalt recycling methodologies chosen for study. The literature considered in Paper III included peer-reviewed articles, reports published by the Swedish Transport Administration (STA), Nordic Road Association (NVF), contractors (NCC, Skanska), research institutes and the official websites of STA and the Swedish Association of Local Authorities and Regions (SKL).

## 4 Results (Paper II and Paper III)

This chapter summarises the results of the case studies presented in Papers II and III: LCA of a road tunnel and LCA of asphalt recycling methodologies.

### 4.1 Life Cycle Assessment of a road tunnel (Paper II)

This study sought to improve understanding of the life cycle energy use and GHG emissions of transport infrastructure, using the example of the Norra Länken road tunnel that is being built in Stockholm.

The study was performed in two parts: Part 1) detailed data inventory for the construction phase of rock tunnels; and Part 2) screening assessment for the whole tunnel infrastructure, including both concrete and rock tunnels, through all life cycle phases: construction, maintenance and operation. The end-of life phase was excluded from the analysis.

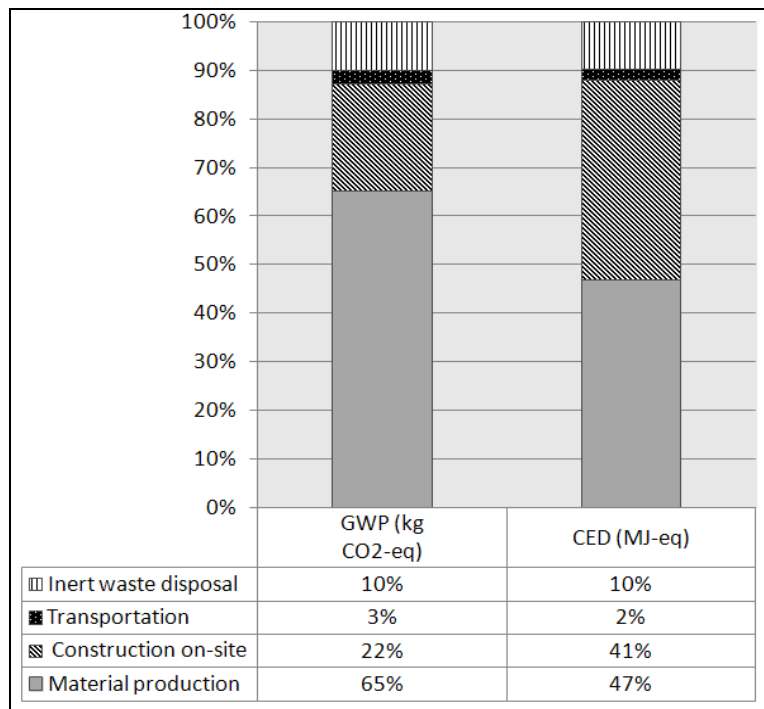
For the detailed data inventory of construction of a rock tunnel in Part 1, preliminary Bills of Quantities were used. These contain preliminary engineer estimates for all activities and materials to be used, and are compiled by contractors, mainly in order to chart the financial costs.

The functional unit in Part 1 corresponded to the rock tunnels in Norra Länken, covering only the construction phase. In Part 2, the functional unit was the rock and concrete tunnels in Norra Länken, covering construction, operation and maintenance (see Table 1). The results were normalised to the common functional unit- one metre of one lane, when comparing environmental impacts during rock tunnel construction and concrete tunnel construction.

*Table 1. Length and type of the tunnel sections of Norra Länken examined in this study (Vägverket, 2009)*

Tunnel type	km	1-lane	2-lane	3-lane
Total rock (considered in Part 1 of the study)	7.5	39%	38%	24%
Total concrete (where 0.65 km is a mixed concrete and rock tunnel)	2.5	64%	16%	20%
Total rock+concrete (considered in Part 2 of the study)	10	45%	32%	23%

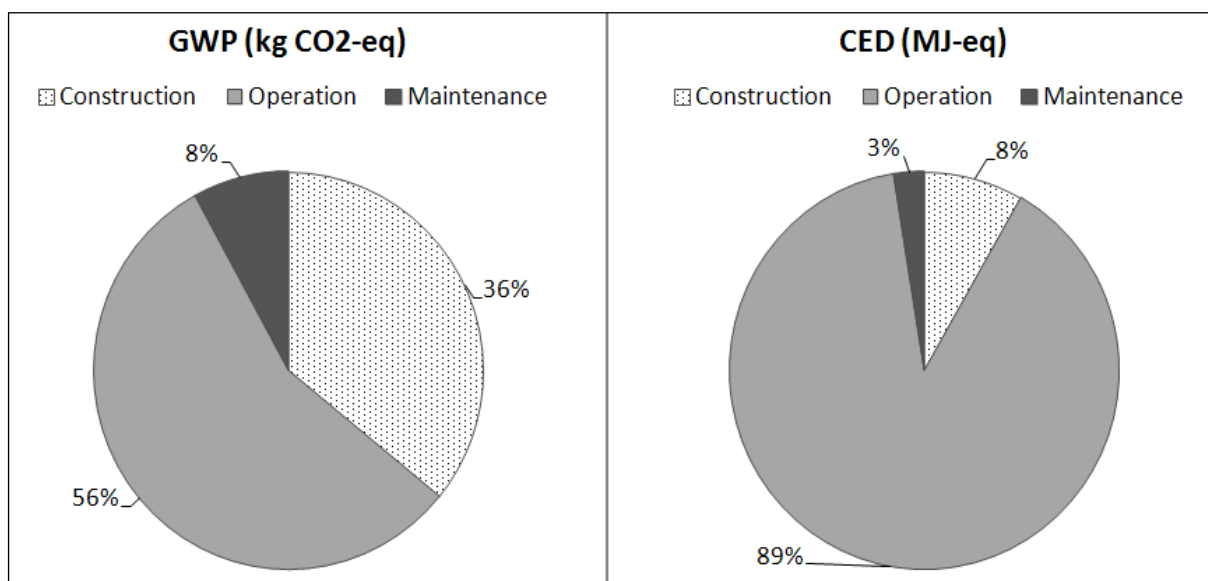
The detailed analysis in Part 1 showed that production of materials (i.e. concrete and asphalt) made the largest contribution to Cumulative Energy Demand (CED) and Global Warming Potential (GWP) during the construction phase of a rock tunnel (Figure 2).



**Figure 2. Share of GWP (CO<sub>2</sub>-eq) emissions and CED (MJ-eq) during rock tunnel construction**

The screening LCA in Part 2 indicated that construction of concrete tunnels had much higher CED and GWP per lane-metre than construction of rock tunnels. Moreover, the operational phase (mainly lighting, ventilation) of the tunnel was found to have the highest share of energy use and GHG emissions throughout the tunnel's life cycle. The total estimated GWP from construction, maintenance and end-of-life of the Norra Länken tunnel amounts to about 431 000 ton CO<sub>2</sub>-eq.

Comparing the different phases throughout the life cycle of the tunnel in a 100-year perspective, the operational phase had the highest share of CED and GWP, and the maintenance phase the lowest. Operation and maintenance accounted for roughly 1.6 and 0.2 times the GWP of construction, respectively (Figure 3).



**Figure 3. Share of CED and GWP during the main life cycle stages of Norra Länken**

The conclusion was that GHG emissions and energy use related to the tunnel life cycle should be taken into consideration from the very start of the policy-making process. An alternative approach to construction of new tunnels might be to instead use existing transport infrastructure in a more efficient way, e.g. by using congestion charging and adjusting parking charges to better reflect the true cost of scarce land. The case for such alternative strategies, which already entail emission reductions due to reduced traffic volumes, may be further strengthened by the additional reduction caused by decreasing the need for new infrastructure such as tunnels.



*Figure 4. Photo of the tunnel Norra Länken construction site*

#### **4.2 Life Cycle Assessment of asphalt recycling (Paper III)**

The aim of this study was to identify and evaluate the potential for improving treatment of reclaimed asphalt pavement in Sweden, from a life cycle environmental perspective.

The literature review and interviewing of the key stakeholders provided data and information about the current situation of asphalt recycling in Sweden and helped to explore possible obstacles and identify opportunities for improving current practices. The results showed that asphalt recycling practices are different for all three groups of owners: The State, represented by the Swedish Transport Administration (STA), municipalities and industry.

Life Cycle Assessment (LCA) methodology was used to identify processes within asphalt recycling methodologies that contribute a significant share of the total environmental impact (hotspots) and to compare the life cycle environmental performance of the main methodologies used for asphalt recycling and reuse in Sweden: hot in-plant, hot in-place and reuse as unbound material. Two impact categories were selected for this analysis: Global Warming Potential (GWP) and Cumulative Energy Demand (CED).

Since treatment of RAP is the main function of the technologies compared, asphalt recycling and reuse were analysed from a waste management point of view. In other words, the resource

use and impacts that are avoided when asphalt is reused or recycled were subtracted from each alternative, so that the single net function of each alternative was treatment of 1 ton of RAP.

The results showed that hot in-place recycling gave slightly more GWP and CED savings than hot in-plant recycling. There were no savings of GWP and small savings of CED during asphalt reuse.

Based on the inventory data chosen for Paper III, total net savings for hot asphalt recycling in-plant and in-place were more or less the same: about 0.02 ton CO<sub>2</sub>-eq/ton of RAP and 3 GJ-eq/ton of RAP. Total net savings of CED for asphalt reuse into unbound material were about 0.14 GJ-eq/ton of RAP. No net savings were observed for CO<sub>2</sub>-eq (Figure 5 and Figure 6).

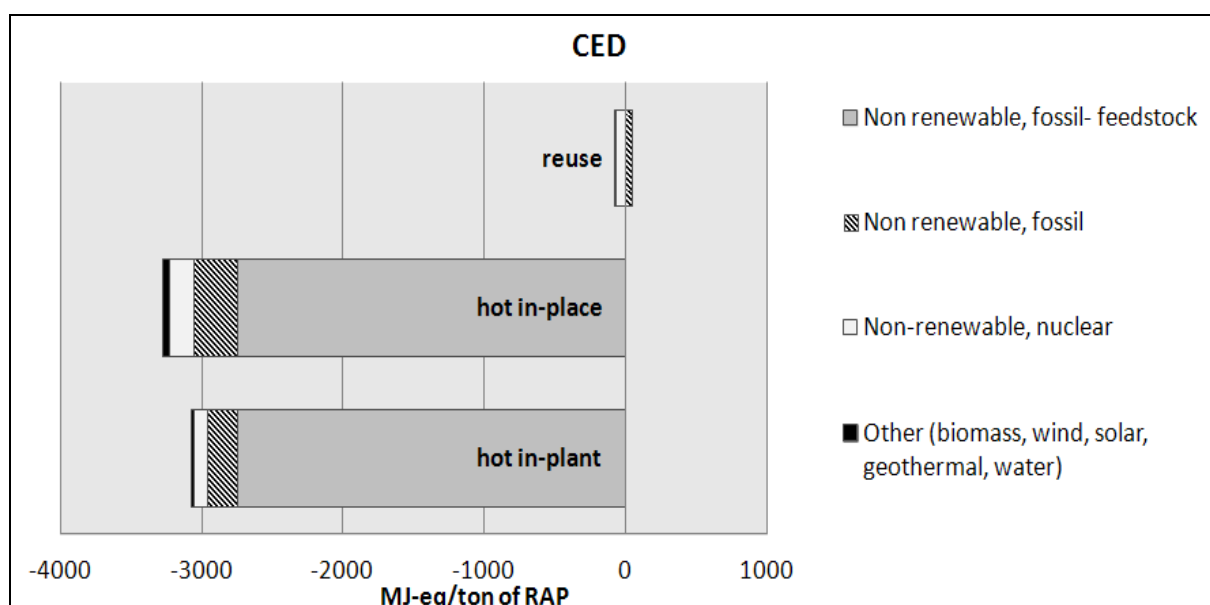


Figure 5. Comparison of Cumulative Energy Demand (CED) savings for asphalt recycling and reuse

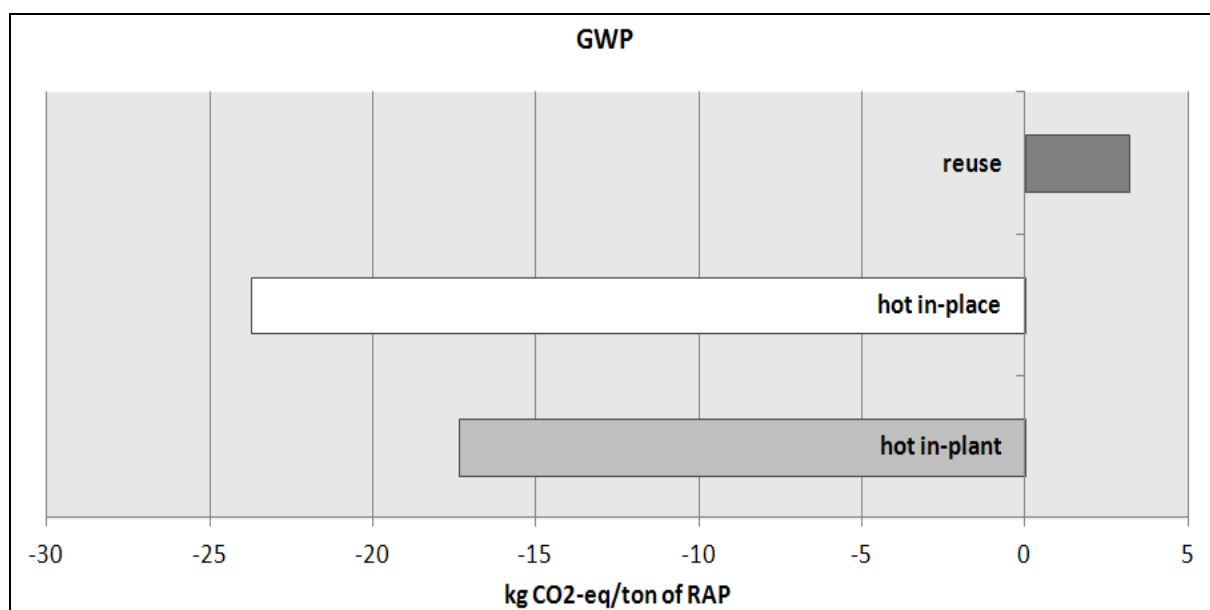


Figure 6. Comparison of Global Warming Potential savings for asphalt recycling and reuse

It was concluded that asphalt recycling is environmentally preferable to asphalt reuse. However each method of asphalt recycling can provide different benefits, so possibilities exist for improving the environmental performance of the processes involved. These possibilities were subdivided into logistic, technical and organisational. They are as following:

- Logistics
  - need for improved transport regulations for transportation of RAP
- Technical
  - decrease fuel consumption for asphalt heating by covering asphalt piles
  - prolong service life of recycled asphalt with the help of RAP rejuvenation
- Organisational
  - in order to help smaller municipalities, the contractors or road authorities could take greater responsibility for asphalt recycling activities
  - clear distinctions should be made in the definitions of 'recycle' vs. 'reuse' and 'bitumen' vs. 'asphalt' (in both the Swedish and English languages).



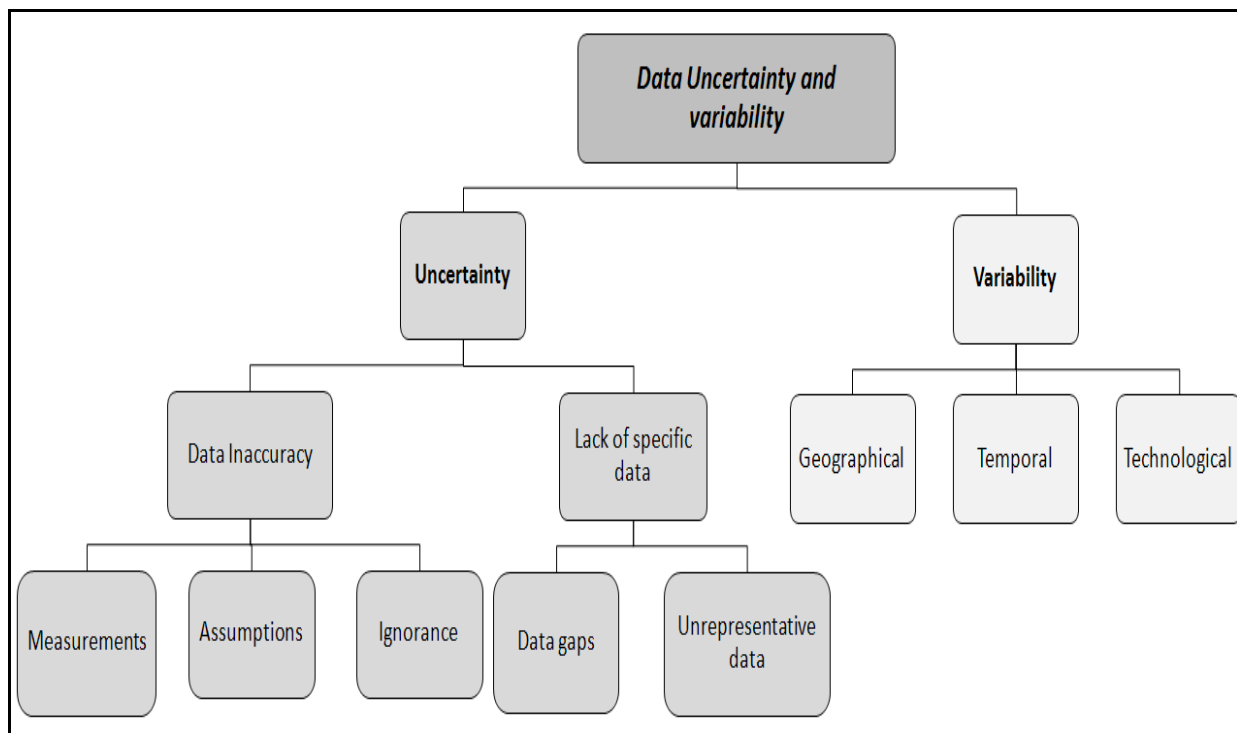
**Figure 7. Photo of asphalt recycling techniques (from left to right): hot in-place, hot in-plant**

## 5 Data uncertainty and variability

This chapter provides general information about data uncertainty and variability in LCA, followed by a section on data uncertainty and variability that were handled in Papers II and III.

### 5.1 Types and sources of data uncertainty and variability in LCA

Different types and sources of data uncertainty and variability have been identified by several researchers (for example Huijbregts et al. (2001), Björklund (2002), Lloyd and Ries (2007), Heijungs and Huijbregts (2004) etc.). First of all, it is important to differentiate between data uncertainty and variability. Even though these two terms have different sources, they are often confused. Uncertainty is when the value of a parameter is not exactly known, but the effect of this can be reduced by further research (Heijungs and Huijbregts, 2004). Variability, on the other hand, cannot be reduced by additional research, as it corresponds to inherent differences between individuals, places, time, processes, etc. (Heijungs and Huijbregts, 2004). Hertwich and colleagues (2000) emphasised that the distinction between data uncertainty and variability is important, because due to the confusion in these terms decision-makers are sometimes more concerned about parameter uncertainty than variability. It has been pointed out that it is impossible to distinguish which type of uncertainty and variability is the most important, since this depends on the specific case study (Huijbregts et al., 2003; Lloyd and Ries, 2007). According to Huijbregts et al. (2001), uncertainty can be further subdivided into data inaccuracy and lack of specific data, and variability can be geographical, temporal and technological (see Figure 8).



*Figure 8. Main sources of uncertainty and variability (after Huijbregts et al. (2001) and Lloyd and Ries (2007))*

Four types of statistical quantitative approaches to incorporate uncertainties and variability in LCA have been identified by Heijungs and Huijbregts (2004). These are:

- Parameter variability/scenario/sensitivity analyses (testing of different data sets),
- Sampling methods (Monte Carlo analysis),
- Analytical methods (based on mathematical expressions)
- Non-traditional methods (fuzzy sets, Bayesian methods, non-parametric statistics etc.).

Another way of incorporating data uncertainty and variability is a semi-quantitative approach called a Pedigree matrix, which reports data quality in terms of the history or origin of data and is useful in identifying possibilities for data quality improvement (Weidema and Wesnaes, 1996). Irrespective of the approach chosen, it is important to emphasise that estimation of uncertainties is a source of uncertainty itself (Björklund, 2002).

During the literature review presented in Paper I, it was found that the studies included on transport infrastructure discussed uncertainty and variability, but only a few actually analysed these quantitatively. For instance, Chester and Horvath (2009) used a Pedigree matrix for analysing data on geographical and temporal considerations of emissions, component lifetimes, vehicle models and passenger kilometres travelled and performed a sensitivity analysis of the functional unit chosen (passenger occupancy). Federici et al. (2009) performed a sensitivity analysis with regard to the amount of raw material for each input flow; the values of matter, energy or emergy intensities; occupancy factors in the different transportation modes and/or European countries; and turnover years assumed in calculations of infrastructure and vehicles. Jonsson (2007) discussed the variability of trucks and the natural variability in climate and other environmental factors affecting operation of transport infrastructure. Schlaupitz (2008) discussed the importance of assumptions regarding future electricity mix; future development of material production; the climate impact of seizing land for loss of carbon storage in soil; assumptions of technological development after 2030; and the variability in material quantities used for construction of transportation infrastructure (Schlaupitz, 2008).

Kendall et al. (2009) pointed out that prediction of future events and conditions adds uncertainty to the infrastructure LCAs and that there is large variability regarding inventory data on certain construction materials, such as cement used for concrete production and bitumen used for asphalt production. They concluded that in order to characterise the robustness of results, targeted scenario and sensitivity analysis should be performed with regard to the uncertain parameters.

## **5.2 Data uncertainty and variability in Paper II and Paper III**

The approach chosen for incorporating uncertainty in the case studies (Papers II and III) was sensitivity analysis. This is an approach for tackling data uncertainty when a “few different data sets and/or models and/or choices are investigated as to their consequences for the model results” (Heijungs and Huijbregts, 2004).

For instance, sensitivity analysis in Paper II showed that the results differed greatly depending on the carbon intensity of electricity assumed. When the impact of different electricity mixes was tested, the results for GWP from operation varied by a factor of 40 (Figure 9). In scenarios 2 and 4, in which electricity for the operational phase was represented by the forecast average future electricity mix or a low-carbon electricity mix, the operational phase contributed a much lower share of the total life cycle GWP of the tunnel.

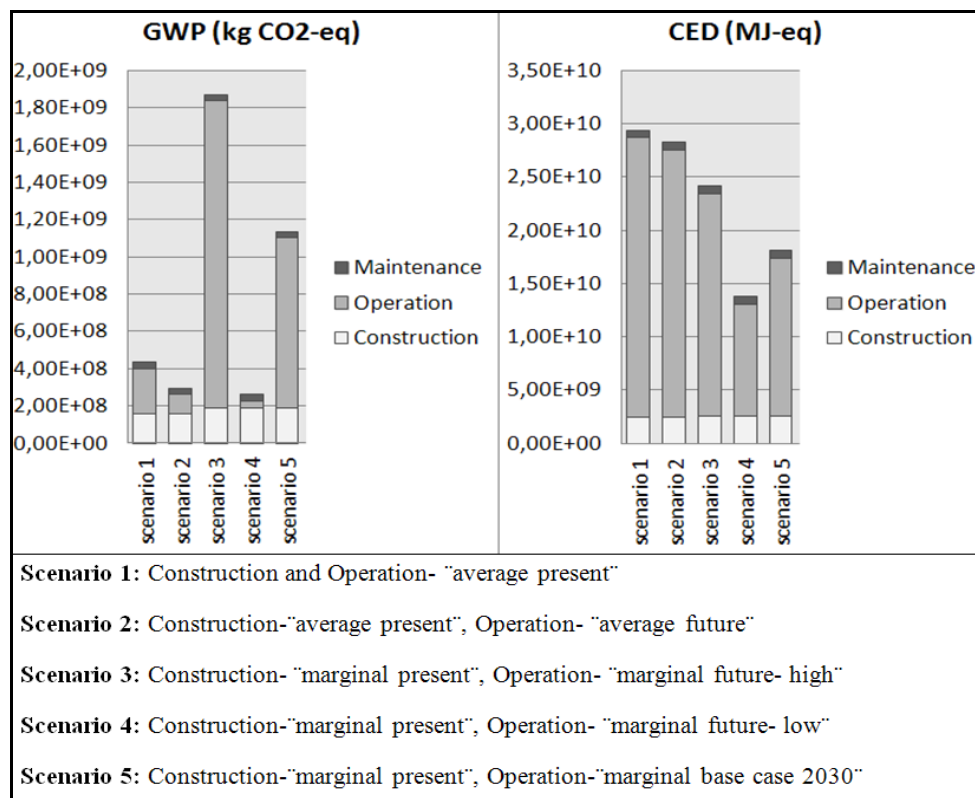


Figure 9. Sensitivity analysis of choice of electricity mix (Paper II)

A sensitivity analysis of the data sets in Paper III showed that the results were very sensitive to the choice of inventory data for asphalt concrete (Figure 10).

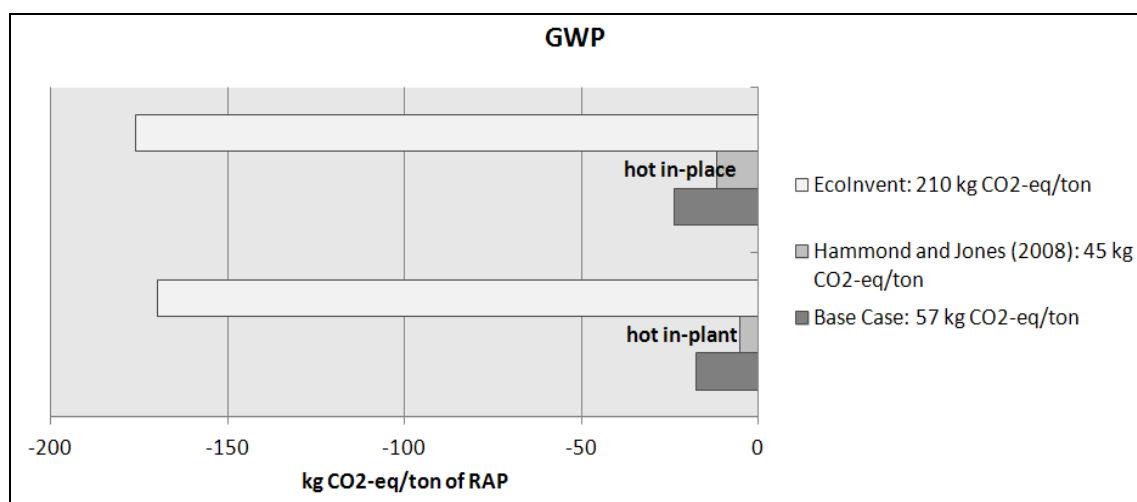


Figure 10. Sensitivity analysis of choice of background inventory data for asphalt concrete on the results of Global Warming Potential (Paper III)

Thus, it should be emphasised that due to such data uncertainty and variability, the conclusions from Paper II and Paper III should be based on identified hotspots and comparative magnitudes rather than uncertain numerical results.

## 6 Discussion and conclusions

This chapter summarises the main conclusions of the research, discusses whether the overall aim of this thesis was achieved, and reflects on the contribution of each paper. It also points out some advantages and disadvantages of the main methodology used in the research (LCA).

### 6.1 Was the overall aim of the thesis achieved?

The overall aim of this thesis was to provide further knowledge about energy use and GHG emissions for the whole life cycle of road infrastructure, in order to improve transport planning on both strategic and project levels. As explained in section 1.2, in order to achieve this aim, the thesis sought to answer three main questions: **How** can energy use and GHG emissions of road infrastructure be assessed? **What** are the energy use and GHG emissions during the life cycle of road infrastructure? **Which** elements and phases during the life cycle of road infrastructure have the largest energy use and GHG emissions?

The contribution of each paper in providing answers to these questions is discussed below.

#### 6.1.1 HOW?

*How can energy use and GHG emissions of road infrastructure be assessed?*

Paper I contributed by finding the main tools and methods used in the literature for assessing energy use and GHG emissions for the whole life cycle of road infrastructure (see Figure 1). Paper I concluded that the main methods and tools for assessing energy use and GHG emissions for road infrastructure can be procedural (SEA, EIA) and analytical (SFA, MFA, IOA, LCA, EEA, EXA, ES). As far as the levels of decision-making are concerned, SEA is used at the strategic level, while EIA is used at the project and design level, during the choice of site-specific alternatives for road infrastructure construction or design phase. Analytical tools can be applied at any level of decision-making. Moreover, they can be included as part of procedural tools.

An important observation arising from the literature review in Paper I was the lack of consistent approach in performing infrastructure LCAs. Since each LCA study aimed at answering different research questions related to specific elements of road infrastructure, different system boundaries were analysed and different types of data considered. Thus it was difficult to compare quantitatively the results from various studies. Consequently, a need for a more consistent choice of functional units and more transparent reporting of inventory data for infrastructure LCAs was identified.

Papers II and III contributed to the methodological development of LCA in the context of road infrastructure, which was identified in Paper I as the most commonly used tool for assessments in this field. These papers presented useful data (such as quantities of materials and other resources used during tunnel life cycle phases and asphalt recycling processes), which can serve as inventory data for other LCA studies.

Moreover, Paper II identified Preliminary Bills of Quantities as being a useful source of data collection for this type of case study (section 4.1). Bills of Quantities provide site-specific

data for many construction projects, not only in the sphere of road infrastructure, but also for railways and buildings. Some of those data consist of information about transportation distances (expressed in ton\*km) or the quantity of materials (expressed in ton, kg or m<sup>3</sup>) during each stage of the construction process. Other data require additional recalculation in order to be useful in LCA modelling, for instance length of pipes (expressed in m), quantity of bolts (expressed in pieces) and others.

To my knowledge, no previous environmental assessment of transport infrastructure has used Preliminary Bills of Quantities for data collection. However, other studies mention the usefulness of data collected from the preliminary Bill of Quantities for LCA of buildings (Crawford and Treloar, 2005; Li et al., 2010).

It can be argued that the data in the Preliminary Bill of Quantities for a project could be underestimated, as they consist of preliminary engineer estimates (Paper II). Thus in order to check this, the data from the Preliminary Bill of Quantities were compared with updated real data on the example of blasted rock from the construction phase of the Norra Länken road tunnel. This comparison showed that differences were quite small (1-15% depending on site). Since the Norra Länken tunnel was still under construction when the LCA study was performed, it was difficult to compare the same data on the example of other types of materials.

Another important aspect to consider is that certain data from the Preliminary Bill of Quantities required additional recalculation in order to be useful in LCA modelling, which was time-consuming. However, it was observed that with a little extra effort by the contractors, the preliminary Bill of Quantities could be slightly modified in terms of data reporting, in order to make it more feasible for practitioners to collect inventory data for LCA. Moreover, it should be noted that there is a need to improve data reporting regarding waste treatment on-site (which is currently not included in the Preliminary Bill of Quantities).

### **6.1.2 WHAT?**

*What are the energy use and GHG emissions during the life cycle of road infrastructure?*

A review of earlier estimates of the share of indirect energy use and GHG emissions from the total transport system (as defined in section 2.1) was one of the aims of Paper I. It was found that the share of indirect energy use (including life cycle of infrastructure, manufacturing and maintenance of vehicles and fuel production) can be significant: from 23-32% (Chester and Horvath, 2009) to 45% (Jonsson, 2007) of the total impact of road transport systems.

Paper II analysed the amount of energy use and GHG emissions throughout the life cycle of one of the most energy-intensive elements of road transport infrastructure, a road tunnel. The results for the base case of the study showed that the total GHG emissions and energy use during the life cycle (construction, operation and maintenance) of the Norra Länken tunnel amount to approximately 29 000 TJ-eq and 431 000 ton CO<sub>2</sub>-eq, which is equivalent to about 2% of GWP impact from domestic transports in Sweden (Swedish EPA, 2011). However, it was found that the final results can vary greatly depending on the electricity mix chosen for

the operational phase of the tunnel. Regarding GWP for the operational phase of the tunnel, the results can range from less than 40 000 tons CO<sub>2</sub>-eq to about 1.6 million tons CO<sub>2</sub>-eq.

Paper III estimated that about 0.02 ton CO<sub>2</sub>-eq and 3 GJ-eq per ton of reclaimed asphalt can be avoided with the help of recycling. Based on rough calculations, if asphalt that is reused nowadays in Sweden (about 0.5 Mton) were to be recycled instead, then about 10 000 tons CO<sub>2</sub>-eq could be avoided, which is equivalent to about 0.5% of GWP impact from the Swedish waste sector (Swedish EPA, 2011). However, Paper III also showed that the final results can vary greatly depending on the inventory data chosen for transport distances and asphalt concrete.

### **6.1.3 WHICH?**

*Which elements and phases during the life cycle of road infrastructure have the largest energy use and GHG emissions?*

From the literature reviewed in Paper I, it was concluded that operation of the road made the largest contribution in terms of energy use and GHG emissions throughout its life cycle of 40 years (Strippel and Erlandsson, 2004). This is mainly due to energy consumed by road lights and traffic control (Strippel and Erlandsson, 2004). Thus as specified in Chester and Horvath (2009), infrastructure operation can be improved by reduced electricity consumption and cleaner fuels for electricity generation.

Studies that concentrated their analysis on life cycle stages of road pavement (excluding energy use during operation phase) have concluded that production of construction materials contributes the largest share of energy use and GHG emissions throughout the life cycle of road pavement, while construction activities on-site contribute the smallest share (Muench, 2010).

Paper II showed that production of construction materials (mainly concrete and asphalt) provides the largest share of CED and GWP during the phase of rock tunnel construction (excluding its operation and maintenance). From a screening LCA of the total tunnel structure, it was concluded that tunnel operation contributes the largest share of CED and GWP.

Paper III identified possibilities for decreasing the impacts from maintenance of asphalt concrete (which was identified as one of the main hotspots in Paper II) with the help of recycling. The main hotspots during asphalt recycling were: processes on-site (heating/scarifying/mixing/paving) in the case of hot in-place recycling, and production of virgin material (bitumen and aggregates) in the case of hot in-plant recycling. Transportation of reclaimed asphalt pavement was identified as the main hotspot for asphalt reuse.

## **6.2 Limitations of the LCA tool**

The LCA tool was used in Paper II and Paper III due to its ability to assess potential environmental impacts of road infrastructure in a systematic and holistic way. However, LCA

is not a perfect tool as it has certain limitations, including subjective choices and assumptions, the lack of potential impact models, the accuracy of available data, and the uncertainty in the impact results (Lo et al., 2005).

It is important to emphasise that data uncertainty and variability are present in each LCA study. Some types of data uncertainty and variability (e.g. type of electricity mix chosen or inventory data selected for a certain type of material) can be communicated with the help of sensitivity analysis, Monte Carlo analysis and other methods (as discussed in Chapter 5). However, there are certain types of data uncertainty and variability that cannot be avoided in LCA. This is not because of lack of methods to do so, but primarily because there is always uncertainty in modelling natural processes, no matter how sophisticated the model is. Secondly, the real world is full of variations, which leads to data variability (Huijbregts, 1998). There are also practical reasons: handling all types of data uncertainty and variability is too time-consuming.

Moreover, even though LCA has a standardised procedure (which is defined by ISO 14040), there is no generally accepted methodology for all studies of the same products or services. It was seen in the literature review (Paper I) that even when the same life cycle phases were considered in previous studies, they did not include the same processes. For instance, when analysing the phase of construction, Chester et al. (2009) included the processes of parking and insurance and Schlaupitz (2008) considered GHG emissions during soil removal and tree cutting (which were not considered in other studies). It was observed that each LCA study is unique with regard to the choice of system boundaries and processes considered. Consequently, such inconsistencies make it difficult to compare the studies with each other.

Thus in order to avoid these inconsistencies, there is a need for further development of LCA methodology for road infrastructure. This thesis contributed to this development through transparent reporting of data and detailed description of system boundaries. Several sources of data uncertainty and variability in this thesis were handled with the help of sensitivity analysis.

### **6.3 How can this research be useful for decision-making?**

As described in section 1.2, the knowledge generated by this research can be useful for decision-making on both strategic and project levels.

As far as the strategic level of road infrastructure planning is concerned, the results from Paper I and Paper II contribute further knowledge about the amount of energy use and GHG emissions associated with road infrastructure, which can be useful during the choice of alternatives for future transport system. Once policy-makers understand the magnitude of energy and emissions during the life cycle of road construction, they can start implementing standards and policies in order to decrease those impacts. Muench (2010) provides examples of similar processes within other sectors, such as the automobile industry (fuel efficiency standards) and power generation (clean energy portfolio requirements).

Paper II concluded that in response to demand for increased road capacity, construction of new infrastructure should be compared against other alternatives, such as economic policy instruments (i.e. congestion charging or charging systems for parking lots). Knowledge about the amount of energy use and GHG emissions during the life cycle of road infrastructure can make this comparison fairer and avoid sub-optimisation. Paper II also concluded that consideration of economic policy instruments is especially important for countries with high carbon intensity in electricity production.

The results in Papers I-III can also contribute to decision-making on project level as they allowed the main hotspots for road infrastructure life cycle in general, tunnel life cycle and asphalt recycling activities to be identified. This knowledge can help decision-makers to determine the processes and materials that should be targeted in order to minimise energy use and GHG emissions during the design, construction or maintenance of road infrastructure. For instance, operation of road infrastructure (mainly lighting) and production of construction materials (asphalt and concrete) were identified as the main priority for decreasing GHG emissions and energy use during the life cycle of road infrastructure.

Thus the potential exists for significantly decreasing GHG emissions and energy use of road transport systems, if road infrastructure is taken into consideration from the very start of the policy-making process on a strategic level.

## 6.4 Proposals for future research

There is no doubt that the current research is but one piece of a complicated transport system puzzle (as shown in Table 2).

*Table 2. Contribution of this thesis to the overall assessment of transport systems (red = issues included in the thesis, grey = suggested areas for future research)*

Issues considered  Elements of transport system	Environmental					Social	Economic
	GHG emissions	Cumulative Energy Demand	Toxicity, Eutrophication	Acidification	Others		
Road Transport:							
<i>Life cycle of road infrastructure</i>							
<i>Life cycle of vehicle</i>							
<i>Life cycle of vehicle fuel</i>							
Railroad Transport							
Air Transport							
Sea Transport							

The research presented in this thesis took into consideration only two environmental impact categories: energy use and GHG emissions. In order to obtain a more comprehensive picture of the impacts of transport infrastructure, there is a need to consider other environmental impacts, such as acidification, toxicity, eutrophication and ozone depletion. Moreover, when analysing the impacts of road infrastructure, economic and social perspectives should also be taken into consideration.

As discussed in section 1.2, this thesis examined one of the elements of indirect energy use for road transport systems, namely road infrastructure (Figure 1). In order to understand the magnitude of the impact from the whole road transport system, there is a need to include life cycle perspectives of vehicles and fuel used for operation as well.

Expanding the scope further, it should be emphasised that in order to analyse the transport system as a whole, taking into account all possible alternatives for its future development, a detailed life cycle analysis should be performed of other modes of transport: rail, air and sea. Paper I showed that some studies have been performed on assessment of the life cycle environmental impacts of railway infrastructure (considering indirect phases), but very few studies actually analyse the indirect phases of air and sea transportation.

As far as the methodological level is concerned, it was concluded here that in order to conduct an extensive analysis, a combination of various tools should be used (section 2.2). Moreover, analytical tools (LCA, MFA etc.) can be incorporated into procedural tools (SEA, EIA). Thus there is a need for further research to investigate how these tools can be incorporated and used in practice.

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