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# Annual climate impact and primary energy use of Swedish transport infrastructure

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By 2045, Sweden is to have zero net emissions of greenhouse gases. To reach this goal, stakeholders involved in planning and construction of Swedish transport infrastructure aim to half their climate impact by 2030. Planning for emission reduction measures require network level studies showing environmental impacts of the infrastructure network. Previous studies do not allow assessment of current hotspots in the infrastructure network, which limits their relevance for decision-support in this question. The aim of this paper is to assess the current annual climate impact and primary energy use of Swedish transport infrastructure by using a methodological approach based on life cycle assessment. The scope includes new construction and management (operation, maintenance, and reinvestment) of existing roads, railways, airports, ports, and fairway channels. The annual climate impact was estimated to 2.8 million tonnes carbon dioxide equivalents and the annual primary energy use was estimated to 27 terawatt hours. Mainly road and rail infrastructure contributed to these impacts. Environmental hotspots of the infrastructure network were management of the infrastructure stock (particularly reinvestment of road and rail infrastructure) and material production (particularly production of asphalt, steel, and concrete). If climate targets are to be met, these areas are particularly important to address. Additional 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 for road construction and management would further increase the understanding of impacts related to Swedish transport infrastructure at the network level.

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## 1. Introduction

The Swedish parliament has adopted the goal that by 2045, Sweden is to have zero net emissions of greenhouse gases (GHG) into the atmosphere (Government Offices of Sweden, 2018). As an intermediate target, GHG emissions of Swedish domestic transport (excluding domestic aviation) is to be reduced by 70% in 2030 compared to 2010 (Government Offices of Sweden, 2018).

Previous studies have concluded that transport infrastructure can account for a significant share of transport related impacts (Chester and Horvath, 2009; Jonsson, 2005; 2007; Rahman et al., 2014). Consequently, they have argued that planning for emission reduction measures should consider not only emissions from traffic but also other emissions throughout the life cycle of transport systems, such as those related to construction, operation, maintenance, and reinvestment of transport infrastructure.

Stakeholders involved in planning and construction of Swedish transport infrastructure recognise the need for a life cycle perspective when implementing measures to reduce their climate impact, to avoid shifting environmental burdens to other countries (Fossilfritt Sverige, 2018). To reach the goal of zero net emissions by 2045, the Swedish Transport Administration (STA) aim to reduce the life cycle climate impact of constructing, operating, and maintaining transport infrastructure by 30% to 2025 and by 50% to 2030 compared to 2015 (The Swedish Transport Administration, 2019). The Swedish construction industry also aim to reduce their life cycle GHG emissions by 50% to 2030 compared to 2015 (Fossilfritt Sverige, 2018).

Life cycle assessment (LCA) can be used at different levels of decision-making (the project level and the network level) to plan for emission and energy reduction measures in transport infrastructure (Butt et al., 2015).

LCA at the project level quantifies life cycle environmental impacts of specific construction projects to provide decision-support to design and material selection, for instance (Butt et al., 2015). Several project level LCAs have assessed the climate impact and energy use of transport infrastructure such as tunnels (Huang et al., 2015; Miliutenko et al., 2012a), bridges (Du et al., 2014; Hammervold et al., 2013), and roads (Barandica et al., 2013). Life cycle inventories have also been made for ports (Stripple et al., 2016) and fairway channels (Winnes et al., 2016).

LCA at the network level focuses instead on the transport system as a whole quantifying life cycle environmental impacts of several construction projects, for example a national transport plan (Butt et al., 2015). Network level studies have been conducted for different forms of infrastructure in many countries, including the Netherlands (Keijzer et al., 2015), the US (Chester and Horvath, 2009; Loijos et al., 2013), Sweden (Jonsson, 2005; 2007; Toller et al., 2013; Toller et al., 2011a), Norway (Huang et al., 2015), Singapore (Rahman et al., 2014), Japan (Aihara et al., 2007), and China (Guo et al., 2017).

To plan for emission reduction measures that can help in reaching national climate targets, and to follow up the development over time, it is insufficient to conduct project level LCAs since these cannot provide information on the overall effects of emission reduction measures at a national level. Rather, network level studies showing what types of infrastructure, activities, and construction materials contribute most to impacts at a national level are required. However, no network level studies were found that quantify annual impacts of activities, different forms of infrastructure, and materials in the infrastructure network in a way that can be used for planning and prioritising measures to reach national environmental targets. One reason why previous network level studies cannot be used for that purpose is the methodology used to quantify annual impacts.

In LCA, impacts are often annualised by dividing the full life cycle impacts of constructing the infrastructure stock by an assumed lifetime of the infrastructure (Jonsson, 2005; 2007; Keijzer et al., 2015; Rahman et al., 2014). However, because these impacts represent past infrastructure construction they do not influence the possibilities to reduce life cycle impacts of today's infrastructure system. This approach is therefore of limited relevance when prioritising measures to reach environmental targets.

Annual impacts of transport infrastructure (Aihara et al., 2007) and other constructions including transport infrastructure (Toller et al., 2011a) have also been calculated by using already annualised data in an environmentally extended input-output analysis (IOA). However, because such data is aggregated with a low level of detail, this method does not enable identification of activities, forms of infrastructure, and materials that contribute most to impacts. Therefore, its use as a base for decision-support is also limited when planning for emission reduction measures. For example, in Sweden, construction and maintenance of transport infrastructure cannot easily be separated from other types of construction work included in the building and real estate management sector, although attempts have been made (Toller et al., 2013).

Another approach to calculate annual impacts is using LCA to quantify impacts of present activities in the transport system. This approach can be used to assess what activities, forms of infrastructure, and materials that currently contribute most to impacts at the network level and is therefore relevant when planning for emission and energy reduction measures. However, previous network level studies using this approach have assessed annual impacts of limited parts of the infrastructure network, such as concrete pavements (Loijos et al., 2013), tunnels (Huang et al., 2015), and highways (Guo et al., 2017), and do not provide an overview of different forms of infrastructure and activities at a national level. The approach was combined with an IOA in Toller et al. (2013) in order to distinguish the annual impacts of Swedish road and rail infrastructure from the building and real estate management sector based on data available at the time. However, that data had low temporal and geographical relevance and the study cannot be used to identify what activities and materials currently contribute most to impacts of Swedish transport infrastructure.

The aim of this paper is to assess the current annual climate impact and primary energy use related to new construction, operation, maintenance, and reinvestment of Swedish transport infrastructure by using a methodological approach that allows identification of environmental hotspots.

In order to enhance the decision basis for transport infrastructure planning and enable a systematic follow up we approach the following questions:

- What is the total climate impact and primary energy use of Swedish transport infrastructure and what is the contribution of different forms of infrastructure?
- What is the contribution of new construction and operation, maintenance, and reinvestment of the existing infrastructure stock to the climate impact and primary energy use of Swedish transport infrastructure?
- What is the contribution of material production and on-site activities to the climate impact and primary energy use of Swedish transport infrastructure?
- What standard measures, materials, and on-site activities currently contribute most to the climate impact and primary energy use of Swedish transport infrastructure?

# 2. Method and scope

## *2.1 Methodological approach*

The climate impact and primary energy use of Swedish transport infrastructure was calculated based on:

- Data quantifying the present infrastructure network and material and energy use for different activities
- Process data describing GHG emissions and energy use of material and energy production
- Impact assessment methods linking emissions and energy use to specific impact categories

The LCA software SimaPro, version 8 (PRé Consultants, 2016a) was used to model the infrastructure system and to visualise results. The study is based on attributional LCA (Curran et al., 2005) since it aims to describe the system as it can be observed. While the modelling approach relies on data and methods from LCA, the temporal system boundaries partly differ from that of typical infrastructure LCA, because the study focuses on infrastructure a specific year rather than on a specific object with a defined service life.

## *2.2 Scope*

Swedish transport infrastructure is owned and managed by different actors, including the Swedish Transport Administration (STA), county councils, municipalities, private actors, and companies. Because the paper aims to provide a complete overview of the transport infrastructure network, it includes all forms of road and rail infrastructure (regardless of owner and manager), airports with scheduled and non-scheduled traffic (excluding helicopter airports and airports owned by flying clubs and private actors), and ports (excluding marinas) and fairway channels (Table 1).

**Table 1. Forms of infrastructure included in the study**

| Road | Rail | Air | Sea |
|---|---|---|---|
| State-owned roads<br>Municipal roads<br>Private roads[1] | State-owned railways<br>Non-state-owned railways<br>Tramways<br>The metro<br>Industrial tracks | Airports with scheduled and non-scheduled traffic | Ports<br>Fairway channels |

1. Private roads are defined as roads owned by other actors than the state or the municipalities. Private roads can be either closed or open to the public.

Since the paper aims to assess *current annual* GHG emissions and energy use, the following activities are included (Figure 1):

- New construction
- Operation, maintenance, and reinvestment of the present infrastructure stock

For the same reason, the following activities, which would typically be included in LCA, are *not* included (Figure 1):

- Past construction of the infrastructure stock

- Future operation, maintenance, and reinvestment of new construction

By 'current impacts', we here mean impacts from the infrastructure network a typical year around 2015. Generally, impacts of new construction were calculated based on the arithmetic mean of construction projects completed during the time period 2010-2015, while impacts of operation, maintenance, and reinvestment were calculated based on the infrastructure stock in 2015. Some exceptions were made due to data availability (see section 3). Since the rate of new construction varies annually, basing the assessment on data from one year only may not be representative of the typical construction rate. However, the infrastructure stock and its maintenance and operation do not change significantly from one year to another.

For each activity included, annual GHG emissions as well as primary energy use of material and energy production are accounted for from raw material extraction to use at the construction site.

Infrastructure demolition is rare and was therefore not included. It can however be assumed that energy use for demolition is negligible compared to energy use for new construction (Toller and Larsson, 2017).

Material transportation was included for excavated rock and soil (from storage to site of use) and for road salt (from production site to site of use) since these materials are used in large quantities and have low GHG emissions during manufacturing. These transports can therefore be assumed to contribute significantly to impacts. Material transport was also included for asphalt (from production site to site of use) since this was part of the process data used for asphalt (see section 3.3). For all other materials, transportation was excluded, since it was assumed to account for a small proportion of the total primary energy use and GHG emissions of construction projects (Toller and Norberg, 2016).

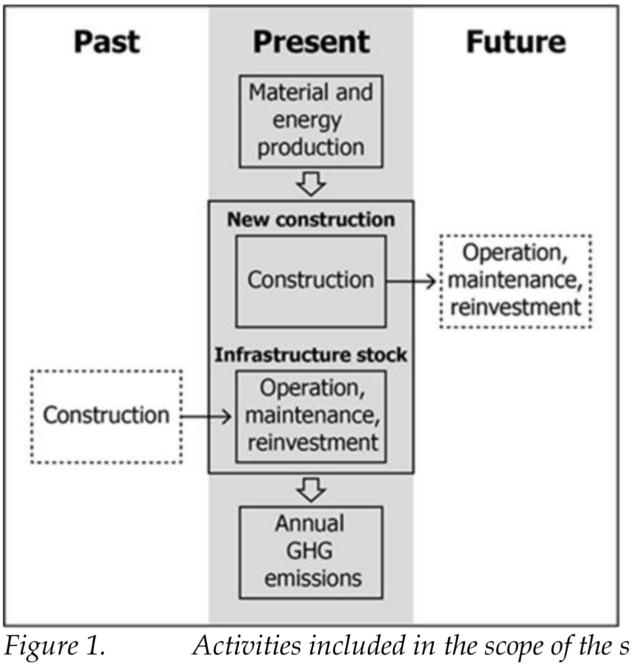


*Figure 1. Activities included in the scope of the study*

In this paper, the overall term 'management' is used to describe the activities operation, maintenance, and reinvestment. There is no common definition of these activities in the literature. In this paper, the following distinctions are used:

- Operation: measures enabling and supporting transport, for example road lighting. Table 2 includes a full list of operation activities included in this paper.
- Maintenance: short term measures necessary for the transport system to perform its intended function. In this paper, this includes fixing smaller pavement damages on roads and airports as well as milling of railway tracks.
- Reinvestment: a form of preventive maintenance, involving larger projects intended to restore the infrastructure to its original state by replacing a construction component (for example the bounded base layer and tunnel lining) with the same, or a similar, type of construction component.

**Table 2. Activities included in operation of road and rail infrastructure, airports, and ports and fairway channels**

| Form of infrastructure | Operation activities |
|---|---|
| Road | Road lighting<br>Winter maintenance (salting, sanding, ploughing)[1]<br>Tunnel operation (ventilation, lighting, pumping water) |
| Rail | Electricity supply for rail infrastructure<br>Operation of station buildings |
| Airport | Operation of terminals, workshops, and hangars<br>Operation of ground-support equipment<br>De-icing of runways |
| Ports and fairway channels | Operation of buildings in the port area<br>Operation of vehicles and working vessels<br>Loading and un-loading of cargo<br>Leakage of petrol from oil tankers<br>Piloting of ships<br>Ice breaking<br>Lightening of fairway channels |

1. According to the definitions of the activities operation, maintenance, and reinvestment above, winter maintenance is included under operation (despite including the word 'maintenance'). This is also consistent with the categories used in the model Klimatkalkyl (Swedish Transport Administration, 2016c).

### *2.3 Impact assessment methods*

The study includes the environmental impact categories climate change and cumulative energy demand (CED). Climate change (expressed in CO2 equivalents) was measured as global warming potential (GWP) over 100 years, using the impact assessment method ReCiPe Midpoint (H) (Goedkoop et al., 2013). CED (expressed in MJ) represents direct and indirect energy use including primary renewable and non-renewable energy. CED 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, 2016b).

The process data sets from the STA (see section 3.3) include already characterised data, expressed in kilogram CO2 equivalents and MJ. The STA strives to use representative process data sets that are consistent with system boundaries and allocation principles in the European standard for environmental declarations of construction works EN 15804 (Swedish Standards Institute, 2013) as background generic data (Toller and Norberg, 2016). However, there may be some variation in data quality due to lack of information available or lack of transparency in published data, which is a source of uncertainty. Feedstock energy is included for plastics, asphalt, and bitumen.

# 3. Data inventory

The scope of this study includes all forms of transport infrastructure at a network level. Because different actors compile different types of data on Swedish transport infrastructure, inventory data was compiled from different sources covering different time periods. Average life cycle inventory data was used since the paper is based on attributional LCA.

The general approach was to quantify GHG emissions and primary energy use based on the following forms of data:

1. A quantified description of the infrastructure system (such as kilometres of single-track railway in new construction)
2. Data on material and energy use for different activities and forms of infrastructure (such as tonne concrete required to construct one of kilometre single-track railway)
3. Process data quantifying GHG emissions and primary energy use of material and energy production (such as kg $CO_2$ equivalents per tonne concrete)

The Appendix provides the resulting quantity of infrastructure in new construction and in the existing infrastructure stock, the resulting material and energy use for activities, and references to process data used.

## *3.1 Quantified description of the infrastructure system*

The quantified description of the infrastructure system includes the quantity of different forms of infrastructure added by new construction during one year and those present in the existing infrastructure stock.

Road and rail infrastructure was divided into so-called 'standard measures' as in the model Klimatkalkyl, version 4.0 (Swedish Transport Administration, 2016a). Klimatkalkyl, developed by the STA, provides default material and energy use templates for the most common standard measures in construction, operation, maintenance, and reinvestment of Swedish road and rail infrastructure (Toller and Larsson, 2017). The data in the model is based on data collected from previous construction projects and is representative of Swedish transport infrastructure.

Airports were divided into the standard measures buildings (hangars and terminals) and paved surfaces (apron, runway, and taxiway). Ports and fairway channels were not divided into standard measures, since material and energy use in construction and management was provided directly with no connection to specific construction projects.

The number of different standard measures in new construction of road and rail infrastructure as well as airports was based on construction projects completed 2010-2015. Data sources used to compile a list of construction projects is found in Table 3. For most forms of infrastructure (state-owned road and rail infrastructure[5], non-state owned railways, tramways, and airports), construction projects conducted in the time period could be readily compiled from annual reports, newspaper articles, and systems for economic accounting. However, this could not be done for municipal and private road infrastructure, in which case the annual increase in road length was based on the arithmetic mean of annual difference in road length between 2007 and 2015 and on the annual increase in forest roads. No new construction projects took place in the metro during the specified time period. A simplified assessment was made for industrial tracks and new construction was not included.

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[5] State-owned road and rail infrastructure was categorised into 'small investment projects' (defined by the STA as projects with an investment cost of less than 50 MSEK) and 'large investment projects' (defined by the STA as projects with an investment cost of more than 50 MSEK).

**Table 3. Data sources used to compile a list of new construction projects for different forms of infrastructure.**

| Form of infrastructure | Data source |
|---|---|
| State-owned road and rail (large investment projects) | STA's annual reports 2010-2015 |
| State-owned road and rail (small investment projects) | Excerpt from the STA's system of economic accounting 2011-2015 |
| Non-state-owned railway | Infrastructure holder (Stockholm County Council, n.d.-a) |
| Municipal and private road infrastructure (excluding forest roads) | Statistics on road length 2007-2015 (received from the STA) |
| Private roads – forest roads | Skogforsk et al. (2017) |
| Tramways | Newspaper articles (Folkbladet, 2009); infrastructure holders (Stockholm County Council, n.d.-b; Västtrafik, 2012); other sources (Ramböll, 2008; Spårvagnsstäderna, n.d.) |
| Airports | Newspaper articles (Bergner, 2015; Comstedt, 2015; Mauritzon, 2013; Swedish Radio, 2010; SVT, 2011); infrastructure holders (Arvidsjaur Municipality, 2015; Gällivare municipality, 2011; Halmstad City Airport, 2014; Halmstad municipality, 2016; Kalmar Öland Airport, 2015; Skavsta Airport, 2011; Swedavia, 2013; 2014; n.d.; Örebro Municipality, 2013) |

To divide the new construction projects into standard measures, different approaches were used depending on the data availability for different forms of infrastructure (Table 4).

**Table 4. Data sources used to find type and quantity of standard measures in new construction projects and in the infrastructure stock for the different forms of infrastructure.**

| Form of infrastructure | New construction projects | The infrastructure stock |
|---|---|---|
| State-owned road | Large investments: Project descriptions and previous climate calculations received from the STA<br><br>Small investments: Based on investment costs of small investment measures, received from the STA, and previous construction projects | Infrastructure holders: NRDB[1] via Lastkajen (Swedish Transport Administration, 2016b) (plain roads); Swedish Transport Administration (2014) (tunnels); dataset received from the STA (bridges) |
| State-owned rail | Same approach as for state-owned road infrastructure | Infrastructure holders: statistics received from the STA via Lastkajen (Swedish Transport Administration, 2016b); datasets received from Jernhusen (station buildings) and the STA (platforms) |
| Municipal and private road infrastructure | Estimations based on number of standard measures in the stock | Infrastructure holder: NRDB[1] via Lastkajen Swedish Transport Administration (2016b) |
| Non-state-owned railway | Project descriptions, see Table 3 | Infrastructure holder (data received from Stockholm County Council); statistics (Transport Analysis, 2016a) |
| Tramways | Project descriptions, see Table 3 | |
| Metro | | |
| Airports | Annual reports and newspaper articles, see Table 3 | Estimations based on data from infrastructure holder (Swedavia, 2011) |
| Industrial tracks | | Dataset received from the Swedish Transport Agency |

1. National Road Database

For some forms of infrastructure (large state-owned road and rail investments, non-state owned railways, tramways, and airports), standard measures included in new construction projects were, with the exception of deforestation and soil stabilisation[6], readily available via project descriptions, previous climate calculations, newspaper articles, and annual reports. For other forms of infrastructure, alternative approaches were used.

For municipal and private road infrastructure, the statistics on change in road length did not provide information on type of roads constructed. To estimate type and number of standard measures in new construction, it was assumed that the proportion of different standard measures constructed were the same as the proportion of standard measures in the infrastructure stock. For example, 4% of the municipal road network is gravel roads. Therefore, it was assumed that 4% of the road length constructed was gravel roads.

Due to the large quantity of small road and rail investment projects[7], the quantity of standard measures was estimated using a simplified approach based on investment costs at the STA 2011-2015 and not based on specific information on each project. Categories of measures in the STA's system of economic accounting were assumed to correspond to standard measures in

[6] For assumptions on soil stabilisation, see the Appendix (Table A1 and Table A2)
[7] In total more than 3 000 between 2011 and 2015

Klimatkalkyl. The quantity of different standard measures was estimated by dividing the total cost of projects in a category (MSEK/year) by an estimated construction cost for that standard measure (MSEK/km). Construction costs were estimated based on the cost of previous construction projects. For categories with no corresponding standard measure in Klimatkalkyl, impacts were determined by multiplying the investment cost (MSEK/year) by impacts per SEK ($CO_2$/SEK and TWh/SEK, respectively) for the projects with a corresponding standard measure in Klimatkalkyl.

In this paper, forest is seen as a carbon sink permanently removed during construction. The quantity of deforestation in new construction of roads and railways was not stated in the project descriptions. Therefore, assumptions were made to estimate the quantity of deforestation in new construction. The volume of standing biomass removed in a project was estimated by multiplying the project's surface area (including extra width on each side of the road or railway track)[8], the proportion of forestland in the county (Swedish University of Agricultural Sciences, 2016), and the volume of biomass per surface area forestland (Swedish Transport Administration, 2016c). This assumption does not include deforestation due to construction of traffic junctions and roundabouts; however, it can be assumed this is negligible compared to the length of roads. Deforestation was included for all construction projects that were not located in urban areas and that were constructed on forestland. Climate impacts of other forms of land use, for example construction on agriculture land, have not been included since such data is not currently available in Klimatkalkyl.

The appendix provides the resulting number of standard measures in new construction of road infrastructure (Table A1), rail infrastructure (Table A2), and airports (Table A3).

The quantified description of the transport infrastructure also included number of different standard measures in the infrastructure stock. Standard measures in the rail infrastructure stock were provided from infrastructure holders and from the Swedish Transport Agency. For road infrastructure, quantity of different types of bridges and tunnels on the state-owned road network was provided from the STA. However, infrastructure holders did not have information on length of different types of roads (expressed in the form of standard measures in Klimatkalkyl). Therefore, the roads in the infrastructure stock were divided into standard measures based on the road width (Table A4), for example, it was assumed that all roads with a width between 1.0 and 5.0 metres correspond to the standard measure "1 lane road" in Klimatkalkyl. The airside area at airports was estimated by assuming that the airside occupies 25% of an airport's total surface area (calculated based on data from Swedavia, 2011).

Table 5 summarises the data inventory of standard measures in Swedish transport infrastructure and key figures used in calculations. The Appendix provides additional details on the resulting inventory of standard measures in the road infrastructure stock (Table A5, Table A6) and in the rail infrastructure stock (Table A7).

[8] It was assumed that 10 meters are cleared on each side of the road and that 20 meters are cleared on each side of the railway track (Stripple, 2001; Swedish Transport Administration, 2016c).

**Table 5. Form and number of standard measures in new construction and the infrastructure stock, based on the data inventory in this paper. For more details, see Appendix.**

| Form of infrastructure | Annual new construction | Infrastructure stock |
|---|---|---|
| Road, state-owned (km) | 271 | 98 500 |
| Road, municipal (km) | 94 | 42 900 |
| Road, private (excluding forest roads) (km) | 1 924 | 226 000 |
| Road, forest roads (km) | 1 700 | 210 000 |
| Walking and cycling paths (km) | 190 | 18 720 |
| Road, bridges ($m^2$) | 34 640 | 4 655 880 |
| Road, tunnels (km) | 2 | 49 |
| Railway (track km) | 94 | 15 420 |
| Tramway (track km) | 6 | 280 |
| Metro (track km) | n/a | 280 |
| Rail, bridges (track km) | 2.5 | 172 |
| Rail, tunnels (track km) | 10 | 287 |
| Industrial tracks (track km) | n/a | 14 550 |
| Airports, surface area, paved (hectare) | 1.51 | 15 000 |

### *3.2 Material and energy use for infrastructure construction and management*

Material and energy use for infrastructure construction and management was estimated in different ways depending on form of infrastructure and activity.

For all forms of road and rail infrastructure, material and energy use for construction and management was based on data from Klimatkalkyl version 4.0 (Swedish Transport Administration, 2016c) complemented with data on measured energy use in operation of infrastructure. Measured energy use (Table 6) was included for road lighting (Swedish Association of Local Authorities and Regions, 2012), operation of railway infrastructure (Transport Analysis, 2016a), and operation of railway stations along the state-owned railways (dataset received from Jernhusen). Industrial tracks were assumed to require the same energy use as operation of state-owned railways, since they are of about the same length.

Material and energy use for reinvestment were calculated theoretically based on the life length of different standard measures. In Klimatkalkyl, material and energy use for reinvestment is estimated by dividing the material and energy use for each construction component (for example railway sleepers) in a standard measure (for example single-track railway) with a specified service life (Toller and Norberg, 2016). No reinvestments were included for the construction components rock and soil fill and excavation.

Klimatkalkyl was also used to assess material and energy use for construction and management of paved surfaces at airports. Material and energy use for operation of airports (Table A8) was estimated by extrapolating measured data from Arlanda airport (Swedavia, 2016) to all Swedish airports based on the number of passengers at the airports and number of landing and take-off cycles in 2015 (Transport Analysis, 2016b). Material and energy use for reinvestment in airports was based on actual reinvestment projects in 2015 (Table A9).

Material and energy use for new construction, maintenance, and reinvestment at Swedish ports (Table A10) was extrapolated from measured material and energy use in construction projects at the Port of Gothenburg in 2013 (Sarbring, 2014), based on the handled volume of cargo at Swedish ports in 2013 (Transport Analysis, 2016c). This resource use could not be allocated between different activities, and was therefore included under ‘construction’. Data from Sarbring (2014) was complemented with data from Winnes et al. (2016) on energy use for construction and maintenance dredging and lighting of fairway channels. Energy use for operation of ports (Table A11) was estimated by extrapolating measured data from the port of Gothenburg (Port of Gothenburg, 2016) to all Swedish ports based on the quantity of cargo handled at Swedish ports in 2015 (Transport Analysis, 2016c).

**Table 6. Energy use for operation of Swedish transport infrastructure during one year.**

| Operational activity | Total annual energy use |
|---|---|
| Road lighting (TWh) | 1.5 |
| Operation of railways (GWh) | 277 |
| Operation of tramways (GWh) | 4 |
| Operation of metro (GWh) | 58 |
| Operation of station buildings (GWh) | 60 |
| Operation of industrial tracks (GWh) | 277 |
| Operation of airports (GWh) | 313 |
| Operation of ports and fairway channels (GWh) | 113 |

### *3.3 Process data for material and energy production*

Process data describing GHG emissions and primary energy use of material and energy production was mainly gathered from the STA (Swedish Transport Administration, 2017) and is generally assumed representative of material, electricity, and fuel used in Sweden (Toller and Norberg, 2016). For materials not found at the STA, process data was gathered from Ecoinvent 3.2 (Wernet et al., 2016). Table A12 lists the source of process data used for different materials.

In Ecoinvent 3.2, the system model "allocation and cut off by classification" as implemented in SimaPro was used since no credits from material recycling at end-of-life are included in this study (in accordance with the standard EN 15804 [Swedish Standards Institute, 2013]). This system model is based on the approach that primary material production is always allocated to the primary user of a material and the primary material producer does not receive any credit for the provision of recyclable materials (Wernet et al., 2016).

## 4. Results and analysis

### *4.1 Total climate impact and primary energy use*

The annual climate impact of construction and management of Swedish road, rail, air, and sea transport infrastructure was estimated to 2.8 million tonnes $CO_2$ equivalents. The corresponding primary energy use was estimated to 27 TWh.

Road and rail infrastructure dominated the climate impact and primary energy use. Airports, ports, and fairway channels had a relatively small importance for the overall result. Road infrastructure accounted for 66% of the climate impact and 82% of the primary energy use (Figure 2). Rail infrastructure, airports, and ports and fairway channels accounted for 23%, 3%, and 8% of the climate impact and 11%, 3%, and 4% of the primary energy use, respectively (Figure 2). The dominance of road and rail infrastructure to impacts was expected considering the relatively large supporting infrastructure in road and rail transport.

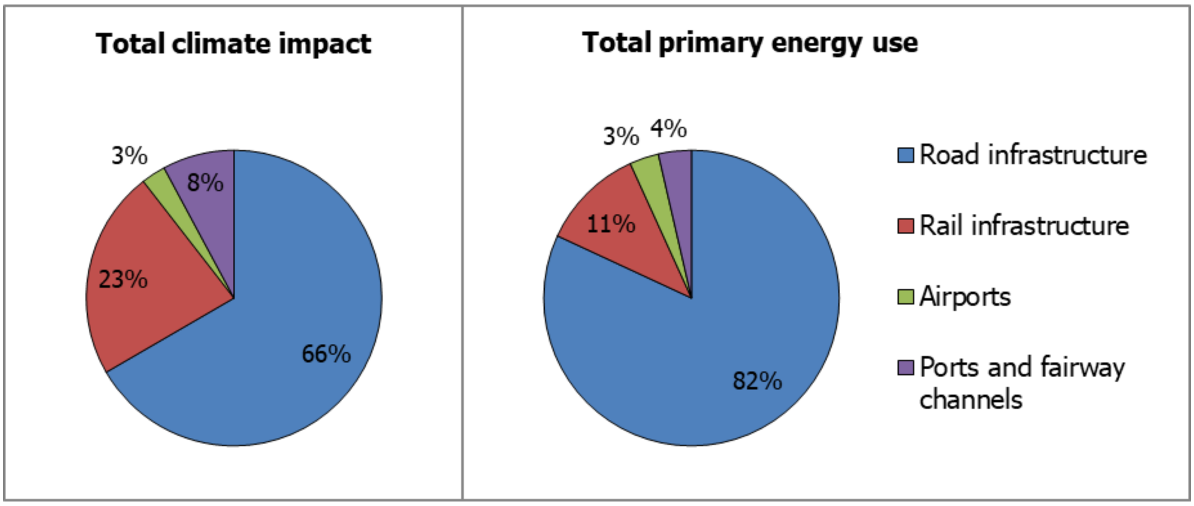



*Figure 2. Contribution of road infrastructure, rail infrastructure, airports, and ports and fairway channels to the current annual climate impact and primary energy use of Swedish transport infrastructure*

The impacts of road and rail infrastructure can be further divided on different ownerships. State-owned road infrastructure accounted for about 40% of the climate impact and 50% of the primary energy use of road infrastructure (Figure 3). The municipal road network, which is about half as long as the state-owned road network, also had about half as high climate impact and primary energy use. Despite consisting of mainly smaller gravel roads, the private road network accounted for about a third of the total climate impact. This is because it is significantly longer than the state-owned and municipal road networks together and because of the deforestation taking place in construction of forest roads. The biogenic carbon emissions from deforestation are not due to use of energy resources, therefore the relative contribution of private roads to the primary energy use is lower.

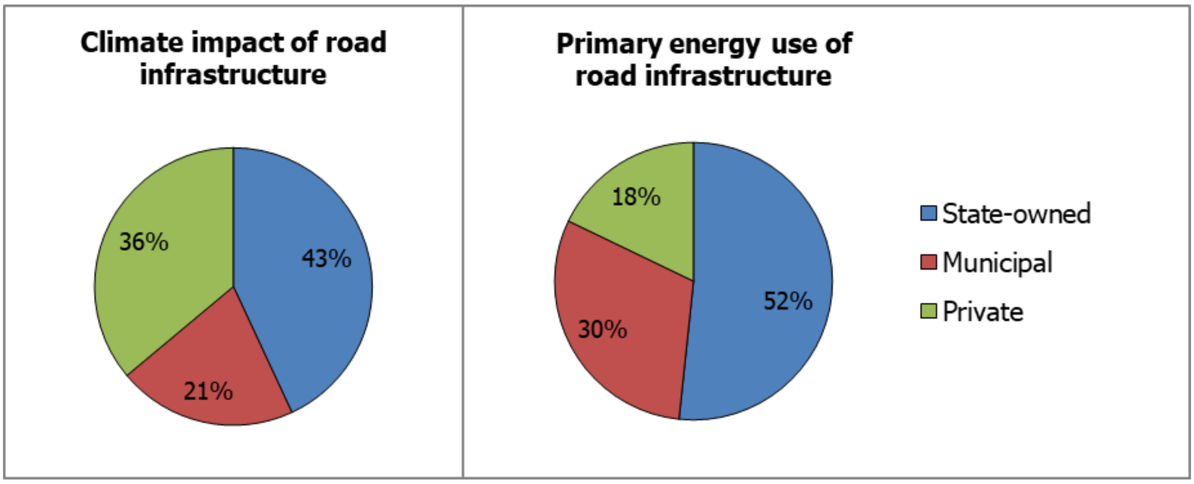



*Figure 3. Contribution of state-owned, municipal, and private road infrastructure to the annual climate impact and primary energy use of Swedish road infrastructure*

The state-owned rail network, which is longer than other parts of the rail infrastructure, accounted for around 60% of the climate impact and primary energy use of rail infrastructure (Figure 4). Industrial tracks accounted for about one third of the impacts. However, this result may be overestimated since it was assumed that management of industrial tracks requires the same resources as state-owned tracks, when in fact they may require less resources.

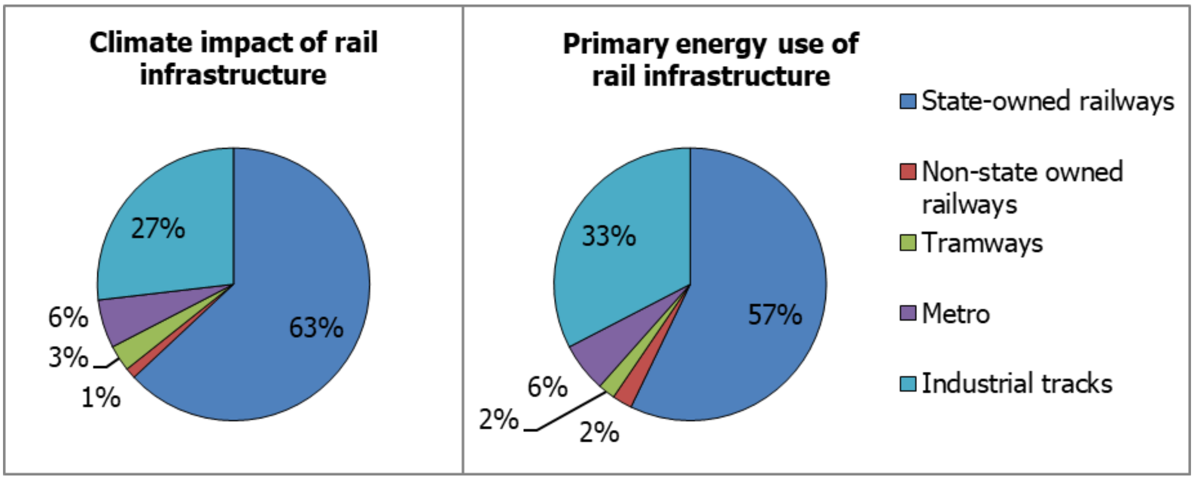
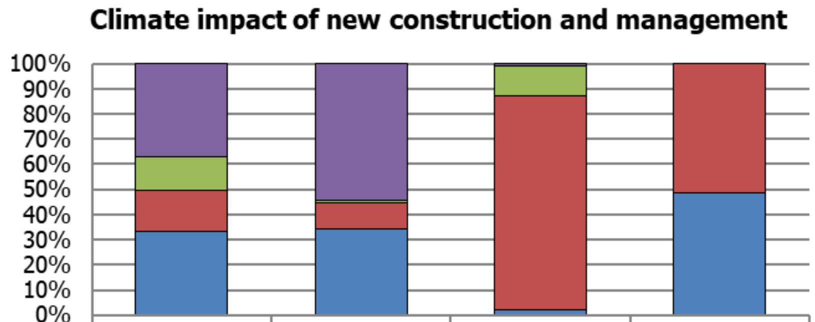


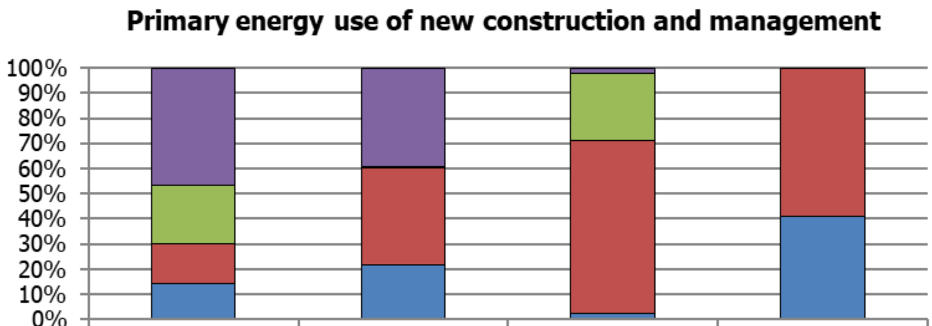

*Figure 4. Contribution of state-owned railways, non-state owned railways, tramways, metro, and industrial tracks to the annual climate impact and primary energy use of Swedish rail infrastructure*

### *4.2 Impacts of new construction and the infrastructure stock*

In total, management of the infrastructure stock accounted for about 70% of the annual climate impact and 80% of the annual primary energy use. Figure 5 shows the contribution of new construction and management of the infrastructure stock to the annual impacts. For road infrastructure, management of transport infrastructure accounts for about 67% of the climate impact and 86% of the energy use. Infrastructure management is also significant for rail infrastructure, accounting for about 65% of the climate impact and 78% of the energy use. Especially road and rail reinvestment contributes to these impacts. For rail infrastructure, maintenance contributed very little to impacts because only rail milling is accounted for in this activity. The share of climate impacts from new construction is higher for private roads due to the influence of deforestation. Operation dominates the climate impact of airports, ports, and fairways (note that the activity construction of ports and fairways also includes material and energy use for maintenance and reinvestment, see section 3.2).




| | 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 |
| Total (ktonne CO2) | 1841 | 631 | 74 | 217 |




| | 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 |
| Total (GWh) | 21873 | 3016 | 854 | 963 |

*Figure 5. Annual climate impact (ktonne $CO_2$ equivalents) and primary energy use (GWh) of new construction and management (operation, maintenance, reinvestment) of the infrastructure stock. * Note that the activity construction of ports and fairways also includes material and energy use for maintenance and reinvestment (see section 3.2).*

### *4.3 Impacts of on-site activities and material production*

In total, material production accounted for 50% of the climate impact and 70% of the primary energy use. Although material production dominated the total climate impact and primary energy use of infrastructure, on-site activities[9] are non-negligible and dominate the impacts of infrastructure operation and rail infrastructure maintenance (Figure 6). The reason why on-site activities dominate the climate impact of road construction is the previously mentioned deforestation related to the forest roads. For example, analysing state-owned road infrastructure alone, material production account for close to 60% of the construction-related climate impact. Material production is especially important in reinvestment (Figure 6), due to the limited

[9] On-site activities are here defined as activities taking place on the construction site (like earthworks and deforestation) or on the existing infrastructure stock (like road lighting and heating of buildings).

construction work involved (no rock and soil excavation for example). Ports and fairway channels also have high impacts from on-site activities due to construction and maintenance dredging.

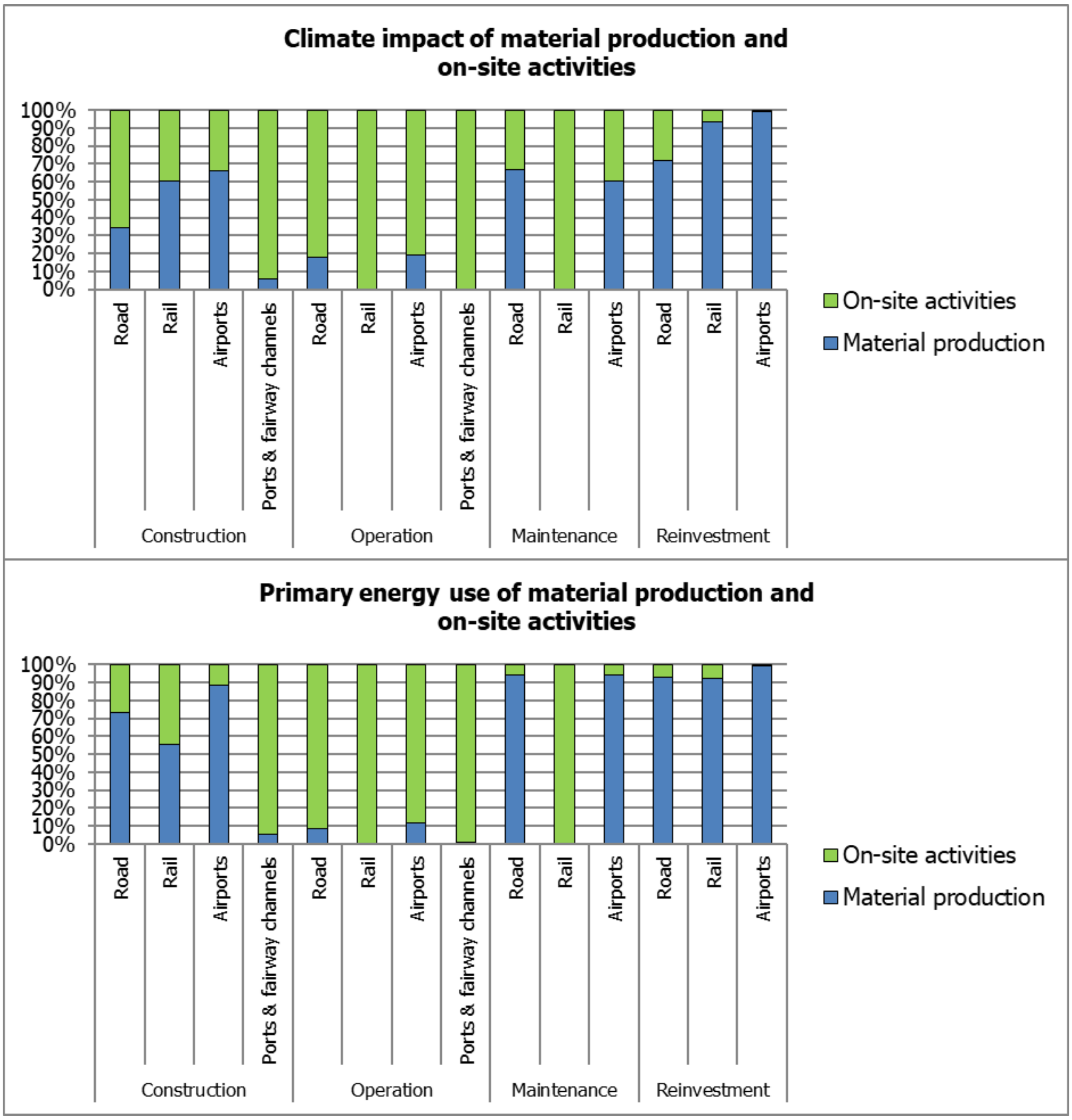



*Figure 6. Contribution of on-site activities and material production to the annual climate impact and primary energy use of construction and management (operation, maintenance, and reinvestment) of Swedish road, rail, air, and sea transport infrastructure.*

### *4.4 Impacts of different standard measures, materials, and on-site activities*

Figure 7 and Figure 8 shows the contribution of different standard measures to the climate impact of state-owned road infrastructure[10] as well as rail infrastructure. Surface roads and railroad tracks (including the sub- and superstructure) together accounted for more than half of the climate impact and primary energy use of road and rail construction and reinvestment. Overall, tunnels and bridges had a smaller contribution, even though tunnels dominated the impacts of tramway construction. Although tunnels and bridges have higher material and energy use per lane and track kilometre, the combined length of tunnels and bridges is relatively low in the Swedish infrastructure network. In the metro, stations and platforms dominate the impacts. For road and rail infrastructure, the proportion of standard measures' contribution to energy use is the same as for their climate impact.

It should be noted that the smaller road investment measures at the STA accounted for half of the climate impact and primary energy use of new construction of state- owned road infrastructure, mainly due to construction of two-lane roads. The contribution of these smaller investment measures is uncertain since compiled data on the standard measures included in these projects is not available. Excluding these smaller investment measures increases the influence of tunnels and bridges (since only surface roads were included in the small investment projects based on the method used to estimate number of standard measures in these projects); however, surface roads still dominates. The smaller rail investment measures had less significance (5% of the climate impact and primary energy use of construction of state-owned rail infrastructure).

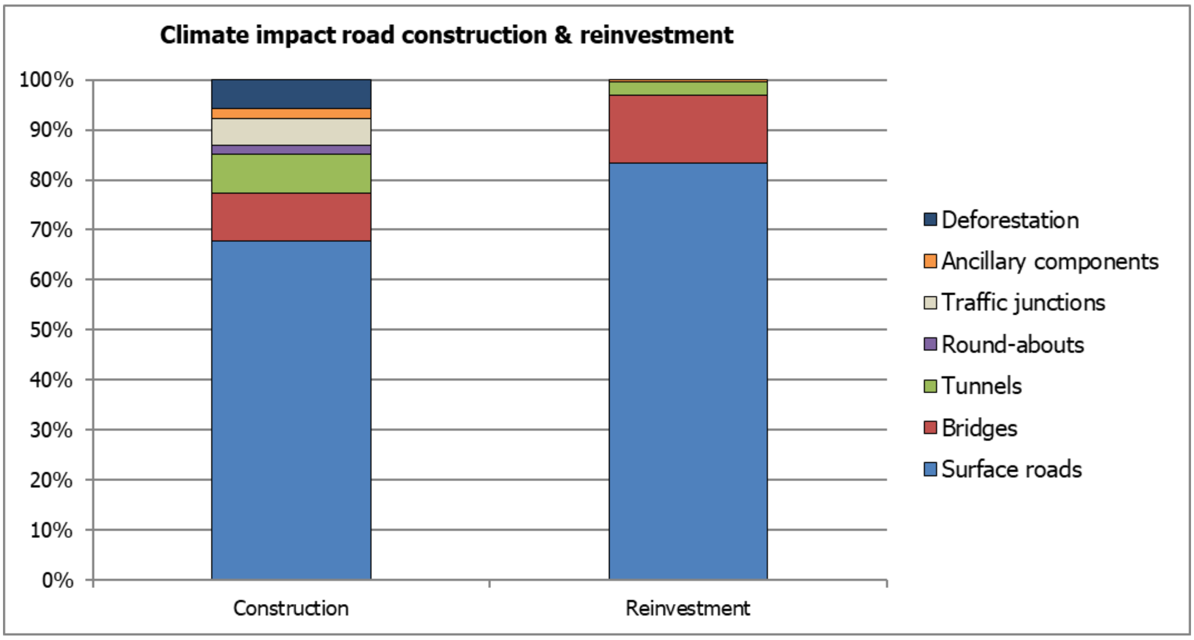



*Figure 7. Contribution of different standard measures to the annual climate impact of construction and reinvestment of state-owned road infrastructure.*

[10] The climate impact of private and municipal roads is not depicted because surface road was the only standard measure included for these forms of infrastructure.

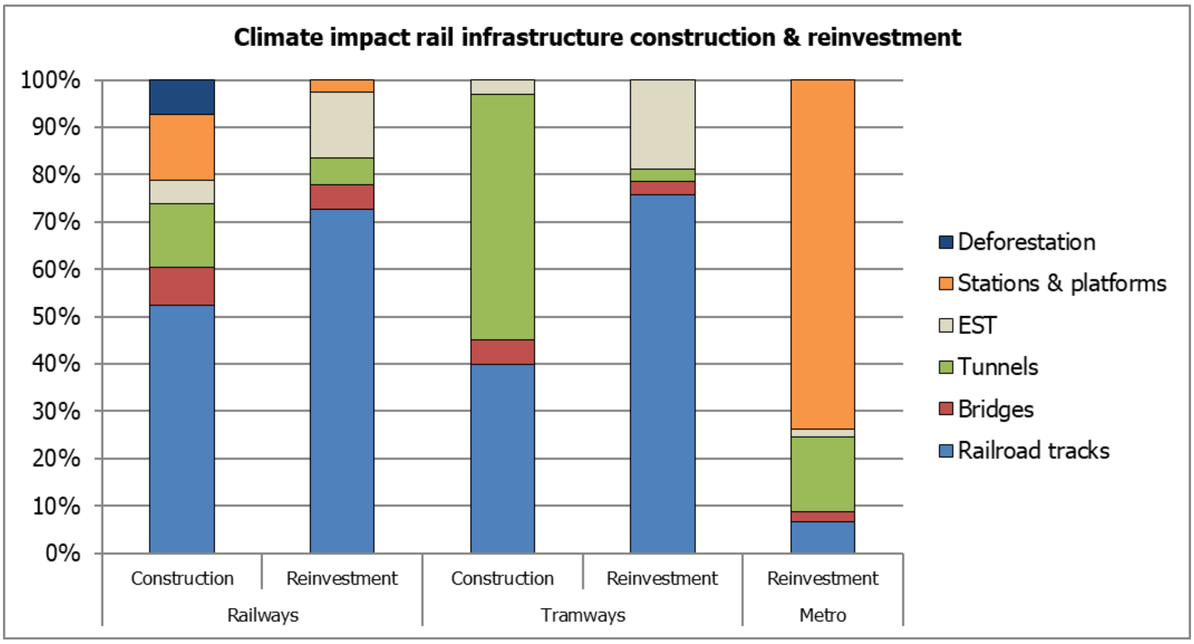



*Figure 8. Contribution of different standard measures to the annual climate impact of construction and reinvestment of railways, tramways, and metro. No new construction in the metro took place during the time period. EST = electrification, signalling, and telecommunications system.*

A few materials dominated the impacts of material production: asphalt, concrete, and steel (Figure 9). Together these materials accounted for about 70% of the climate impact of road construction. Steel and concrete accounted for about 75% of the climate impact of rail construction. Asphalt has a significantly larger proportion of energy use due to the feedstock energy included in this material. In reinvestment of road infrastructure and airports, climate impact and energy use of material production are almost exclusively due to asphalt production. In reinvestment of rail infrastructure, impacts of material production are mainly due to steel and concrete production.

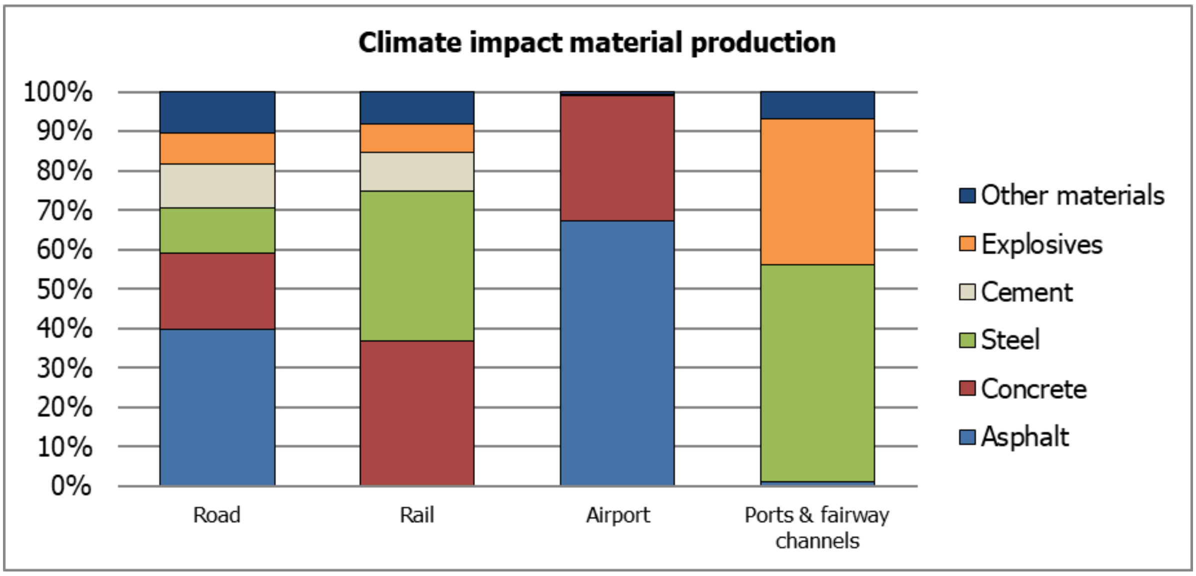



*Figure 9. Contribution of different construction materials to the annual climate impact of material production in construction of Swedish road, rail, air, and sea transport infrastructure.*

In total, impacts of on-site activities are mainly caused by diesel combustion in construction machines used in new construction, maintenance, and reinvestment, however, for individual forms of infrastructure there are exceptions. For example, in construction of private roads deforestation dominates impacts of on-site activities and for ports construction and maintenance dredging accounts for the largest share of emissions and energy use. In road operation, impacts from on-site activities are mainly due to road lighting; however, diesel use for snow removal is an important contributor to impacts of state-owned roads, accounting for about 40% of on-site impacts in operation of state-owned roads. At ports and airports, fuel for ground service vehicles and electricity and heating for buildings were the main contributors to on-site activities.

## 5. Discussion

This paper assessed the current annual climate impact and primary energy use of Swedish transport infrastructure at a network level. It thus provides decision support that may help stakeholders involved in planning of infrastructure to identify appropriate measures for emission and energy reduction. The paper used a methodological approach based on LCA to quantify annual impacts of the current infrastructure network, with a level of detail that enables identification of hotspots. This perspective complements other approaches to assess annual impacts and life cycle impacts of transport networks as well as individual construction projects.

### *5.1 Comparison to previous studies*

The annual climate impact of Swedish transport infrastructure was estimated to 2.8 million tonnes $CO_2$ equivalents and the annual primary energy use was estimated to 27 TWh. These impacts are lower than the impacts of Swedish domestic transport (17 million tonne $CO_2$ equivalents and 95 TWh in 2015) (Swedish Energy Agency, 2016; Swedish Environmental Protection Agency, 2017), but not insignificant.

The estimated climate impact regarding construction, maintenance, and reinvestment can be compared with findings of Toller et al. (2011a) who found, using input-output data, that the GHG emissions from the Swedish building and real estate management sector was 1.9 million tonne $CO_2$ equivalents when buildings and management of buildings were excluded. However, the method used by Toller et al. (2011a) to allocate emissions between different parts of the sector is uncertain. Although being valuable for comparisons and for environmental indicator purposes, those results do not have a resolution that enables identification of hotspots, reduction measures, and policies for transport infrastructure.

Using a simplified bottom-up approach, Toller et al. (2013) estimated annual GHG emissions of construction, maintenance, and reinvestment of Swedish road and rail infrastructure to about 2.7-2.8 million tonne $CO_2$ equivalents (Toller et al., 2011b). This figure is higher than reported in this study (when infrastructure operation is subtracted from the total emissions). It can however be assumed that the figure in Toller et al. (2011b) is overestimated since impacts of road construction were based on data from Jonsson (2005) who reports relatively high energy use in road construction compared to other studies (Toller et al., 2013).

### *5.2 Environmental hotspots and improvement measures*

One hotspot identified was the management of the infrastructure stock that had a higher contribution than new construction to the total impacts. This can be expected in a case like Sweden with a well-developed infrastructure stock and relatively little new construction. However, in contrast to this study, previous network level studies have found that new construction has higher impacts than management of the infrastructure stock (Chester and Horvath, 2009; Guo et al., 2017; Huang et al., 2015; Jonsson, 2005; 2007; Keijzer et al., 2015). One explanation for this discrepancy is the construction rate on which calculations are based. The difference can be due to both different methodologies and a real decline in new construction.

When the assessment of annual impacts includes past construction of the infrastructure stock, the impacts of new construction could be overestimated if the current rate of new construction is lower than it has been previously. Using Sweden as an example, Jonsson (2005; 2007) accounts for annual construction of 2 450 kilometres of state-owned roads. The annual construction rate is significantly lower in this paper – 270 kilometres of state-owned roads per year. The reason for this difference is that Jonsson (2005; 2007) estimated annual construction rate by dividing the length of the infrastructure stock (98 000 km of state-owned roads) by a life length of 40 years, whereas we in this paper account for the arithmetic mean of construction projects completed 2010-2015. In other cases, new construction can dominate over management if the infrastructure network is under rapid development (Guo et al., 2017).

The relative importance of infrastructure management also depends on the assumed life length of infrastructure. In this paper, the impacts of infrastructure management depend on the assumed lifetime of construction components used by STA in Klimatkalkyl. Material and energy use for reinvestment of road and rail infrastructure is based on the assumption that reinvestments are made when the life length has expired in order to maintain the intended standard in the road and rail network. It is not certain that reinvestments are actually made to that extent, and in that case the calculated impacts would be overestimated in a short-time perspective. In a longer time perspective however, non-sufficient reinvestments might instead increase the impacts of reinvestments since larger and less optimal reinvestment measures might then be needed to maintain transport capacity.

Another important hotspot identified was material production. Because material production accounts for a significant proportion of the climate impact and energy use of infrastructure construction and management, planning for emission reduction measures should consider possibilities to reduce the impact of material production. Focusing solely on on-site activities would overlook possibilities to reduce the climate impact and primary energy use of transport infrastructure.

Impacts of material production may be reduced by setting environmental requirements in public procurement (Garbarino et al., 2016). In Sweden, the STA has recently implemented climate requirements on use of concrete, cement, and reinforcement steel, to encourage use of materials with lower GHG emissions. These requirements are consistent with results from this study showing the significant impact of these materials. However, results from this paper also indicate the importance of setting climate requirements on asphalt. Based on the data inventory in this study, the STA uses around 60% of the asphalt and around 70% of the concrete used for transport infrastructure in Sweden. Thus they could be an important stakeholder in reducing climate impacts of these construction materials for Swedish transport infrastructure. Also in other European countries, public procurement has the potential to influence the market and reduce environmental impacts in the public sector (Garbarino et al., 2016).

Even though material production accounted for the largest proportion of impacts from road and rail infrastructure, on-site activities due to construction work and deforestation are non-negligible. Reducing emissions from on-site activities in construction of forest roads may be difficult, since their purpose is to enable transports through forest. For other forms of road and rail infrastructure, measures for decreasing the impact of on-site activities should be considered. Such measures include minimised deforestation but also optimised management of excavation masses.

### *5.3 Uncertainties and further studies*

The climate impact of on-site activities is also influenced by the forms of biogenic carbon included in the study. Currently, Klimatkalkyl accounts for biogenic carbon in standing biomass only. This underestimates the on-site climate impact for all forms of infrastructure. If the soil carbon stock is included, on-site activities could be more significant than estimated in this paper.

A requirement for applying the methodological approach in this paper is the use of previous project level studies as a source of inventory data. For example, in this paper the calculation model Klimatkalkyl was used as a source of data on material and energy use for infrastructure. However, whereas these studies provide necessary inventory data, they also introduce uncertainties when project specific data is extrapolated to the whole infrastructure network. If the data in these studies is an average of data from several construction projects, possible errors in different projects may cancel each other out. However, there is also a risk that the average is too high or too low, in which case it may have significant consequences.

An increased knowledge of annual construction rate would contribute to a more precise quantified description of Swedish transport infrastructure. Further studies on deforestation and small investment measures would also improve the understanding of impacts related to Swedish transport infrastructure. For example, in this paper, deforestation contributed significantly to the climate impact; however, whether this reflects the actual quantity of felled biomass in construction requires further investigation. Similarly, the small investment measures at the STA had a significant influence on impacts of road construction. Further studies could indicate, for example, how the small investment measures best can be matched to standard measures in Klimatkalkyl and what proportion of investment costs are attributed to resource use. Many of the smaller construction projects are likely less resource intensive than the larger projects and therefore, a larger proportion of the cost is likely related to planning.

Other uncertainties are related to material use and process data. Although the study is based on material quantities representative of Swedish infrastructure, there are discrepancies between estimated material quantities and previously estimated material flows. The material quantities resulting from the data inventory differ from previously estimated material flows in Sweden. For example, estimated volumes of concrete used in construction and management of Swedish transport infrastructure (The Royal Swedish Academy of Engineering Sciences, 2015) are twice as high as in this study. This difference corresponds to construction of 6 km concrete tunnel and could therefore be due to underestimating construction and reinvestment of concrete heavy infrastructure such as tunnels and bridges. Another example is asphalt where the resulting use of asphalt quantities is almost two times higher than the produced volume of asphalt in Sweden (Miliutenko et al., 2012b). Since around 80% of the asphalt in this study is used in maintenance and reinvestment of road infrastructure, a possible explanation for this discrepancy is that material use in these activities is overestimated, as was discussed previously.

Another uncertainty related to pavement is the emission factor used for bitumen. The emission factors used in this study have been proposed to be representative of Sweden, except for bitumen due to insufficient information available on production of bitumen used on the Swedish market. Erlandsson et al. (2016) have suggested an emission factor that is higher than the one used by the STA. Using this emission factor would increase the impacts of asphalt and the importance of road infrastructure compared to other forms of transport infrastructure. Further studies on the use and impact of asphalt in Swedish construction would further increase the understanding of impacts of Swedish transport infrastructure at a network level.

The purpose of this study is not to provide precise figures as much as indicating the relative importance of different forms of transport infrastructure, activities, standard measures, and construction materials. The research is based on currently available data on construction projects and the Swedish infrastructure stock and data estimated by the STA to be representative of construction and management of Swedish transport infrastructure. Data that is more detailed is available from individual infrastructure holders, but for the purpose of a broad data inventory, the level of detail is sufficient to show relative impacts. More research would fill data gaps identified in this study.

*5.4 Generalisation of results*

The methodology applied in this paper is suited for application in all countries to plan for emission reduction measures at a network level, however, the activities and materials that currently contribute most to impacts depend on specific characteristics of the actual transport systems. For example, in regions with a rapidly developing transport infrastructure, environmental impacts may originate mainly from new construction (Guo et al., 2017). In case of challenging construction conditions, long tunnel sections may be more common (Huang et al., 2015), increasing the influence of concrete and steel to impacts of material production. In addition, the form of pavement influences the relative impact of different forms of material, for example, in case of concrete roads which is uncommon in Sweden, or use of recycled materials. Another aspect is the influence of forest roads, which contributed significantly to climate impact of Swedish transport infrastructure, but may be less relevant in other countries.

## 6. Conclusion

In this study, we assessed the annual climate impact and primary energy use of Swedish transport infrastructure at a network level. We used a life cycle assessment approach that allows for assessment of current impacts and identification of environmental hotspots. This approach may help stakeholders in transport infrastructure to plan for emission reduction measures.

The total climate impact was found to be around 2.8 million tonnes $CO_2$ equivalents and the annual energy use was around 27 TWh. Road and rail infrastructure had the most significant contribution to these impacts. Based on the identification of hotspots, the paper suggests measures that should be considered when planning for reduced climate impact and energy use of Swedish transport infrastructure.

It is suggested that efforts towards energy efficiency and reduced GHG emissions should consider not only new construction, but also management of the existing infrastructure stock as the latter was found to contribute most to the impacts. This paper identified road and rail reinvestment as two particularly important hotspots to focus on in such work. For most activities, material production contributed more to impacts than on-site activities. Opportunities to reduce impacts of material production, especially asphalt, concrete, and steel, should therefore not be overlooked, since focusing solely on on-site activities would not suffice to reach required levels of emission reduction. However, also emissions of construction machinery can be reduced by optimised management of excavation masses and reduced diesel consumption.

The study has indicated areas for future research that would further increase the understanding of Swedish transport infrastructure at the network level. These are the 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.

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# Appendix

**Table A1. New construction of road infrastructure during 1 year (arithmetic mean over the period 2010–2015): resulting inventory of standard measures (plain roads, tunnels, bridges, traffic junctions, roundabouts, wildlife fence, noise protection, soil stabilisation, and deforestation). Length of plain roads do not include roads constructed in tunnels and on bridges, since the standard measures for tunnels and bridges in Klimatkalkyl 4.0 include also construction of the road.**

| Standard measure | Unit | Form of road infrastructure | | |
|---|---|---|---|---|
| | | **State-owned** | **Municipal** | **Private** |
| Motorway 4 lanes, 21.5 m wide | km | 1 | | |
| Motorway 4 lanes, 18.5 m wide[1] | km | 23 | | |
| 2+2 road | km | 6 | 4 | |
| 2+1 road, 14.0 m wide | km | 8 | 0.3 | |
| 2+1 road, 12.5 m wide[1] | km | 3 | | |
| 2 lane road, 9 m wide[1] | km | 8 | | |
| 2 lane road, 8 m wide[1] | km | 210 | 20 | 4 |
| 2 lane road, 6.5 m wide | km | 3 | 80 | 20 |
| 1 lane road, 5 m wide | km | 9 | 6 | 160 |
| Gravel road | km | | 4 | 3 440 |
| Walking and cycling path | km | 190 | | |
| Widening of road, 1 m | km | 3 | | |
| Widening of road, 2 m[1] | km | 1 | | |
| Widening of road, 4 m[1] | km | 5 | | |
| Widening of road, 5 m | km | 3 | | |
| Widening of road, 6 m[1] | km | 10 | | |
| Widening of road, 9 m[1] | km | 2 | | |
| Widening of road, 10 m[1] | km | 2 | | |
| Extra pavement | $m^2$ | 326 600 | | |
| Cable barrier | m | 31 100 | | |
| Rock tunnel, 1 lane | m | 490 | | |
| Rock tunnel, 2 lanes | m | 490 | | |
| Rock tunnel, 3 lanes | m | 300 | | |
| Rock tunnel, 4 lanes | m | 70 | | |
| Concrete tunnel, 1 lane | m | 270 | | |
| Concrete tunnel, 2 lanes | m | 80 | | |
| Concrete tunnel, 3 lanes | m | 80 | | |

| | | | | |
|---|---|---|---|---|
| Concrete tunnel, 4 lanes | m | 60 | | |
| Concrete beam bridge | $m^2$ | 990 | | |
| Short span concrete bridge | $m^2$ | 520 | | |
| Composite bridge | $m^2$ | 7 600 | | |
| Bridge, type not specified | $m^2$ | 25 400 | | |
| Bridge, for walking and cycling | $m^2$ | 130 | | |
| Bridge barrier | km | 4 | | |
| Roundabout, normal | number | 6 | | |
| Roundabout, small | number | 40 | | |
| Junction, large | number | 7 | | |
| Junction, medium | number | 3 | | |
| Wildlife fence | km | 80 | | |
| Noise protection | km | 5 | | |
| Deforestation | $m^3$ sub | 20 430 | | 252 200 |
| Soil stabilisation, LC columns[2] | m | 1 788 900 | 494 000 | 763 180 |

1. Material and energy use for construction of these standard measures was estimated by scaling material and energy use for construction of other standard measures.
2. It was assumed that soil stabilisation is required in all road construction projects. It was assumed that 10% of a project's surface area is stabilised with 5 metres of lime-cement (LC) columns per $m^2$ stabilised soil (Stripple, 2001).

**Table A2. New construction of rail infrastructure during 1 year (arithmetic mean over the period 2010–2015): resulting inventory of standard measures (substructure, superstructure, electrification system, signalling system, telecommunication system, tunnels, bridges, station buildings, platforms, soil stabilisation, and deforestation).**

| Standard measure | Unit | Form of rail infrastructure | | |
|---|---|---|---|---|
| | | **State-owned railways** | **Non-state-owned railways** | **Tramways** |
| Substructure, single-track[1] | track km | 70 | | 0.4 |
| Substructure, double-track[1] | track km | 6 | 2 | 3 |
| Superstructure, single-track | track km | 80 | 0.01 | 0.4 |
| Superstructure, double-track | track km | 7 | 2 | 3 |
| Electrification system, single-track[2] | track km | 110 | 0.01 | 0.4 |
| Electrification system, double- track[2] | track km | 10 | 2 | 3 |
| Signalling system, single-track[2] | track km | 110 | 0.01 | 0.4 |
| Signalling system, double-track[2] | track km | 10 | 2 | 3 |
| Telecommunications system, single- | track km | 110 | 0.01 | 0.4 |

| | | | | |
|---|---|---|---|---|
| track[2] | | | | |
| Telecommunications system, double-track[2] | track km | 10 | 2 | 3 |
| Rock tunnel, single- track | track km | 6 | | |
| Rock tunnel, double-track | track km | 0.8 | | 0.1 |
| Concrete tunnel, single-track | track km | | | |
| Concrete tunnel, double-track | track km | | | 0.2 |
| Service tunnel | track km | 3 | | |
| Concrete beam bridge, single-track | track km | 1 | | |
| Concrete beam bridge, double-track | track km | | | 0.06 |
| Short span concrete bridge, single-track | track km | 0.3 | | |
| Short span concrete bridge, double-track | track km | 0.3 | 0.1 | |
| Composite bridge, single-track | track km | 0.6 | 0.01 | |
| Composite bridge, double-track | track km | 0.1 | | |
| Station building, above ground | $m^2$ | 1 090 | | |
| Platform[3] | $m^2$ | 13 980 | | |
| Soil stabilisation, LC columns[4] | m | 102 410 | 5 280 | 6 600 |
| Soil stabilisation, concrete piles[4] | m | 39 570 | 2 040 | 2 550 |
| Deforestation | $m^3$ solid under bark | 19 370 | 640 | |

1. The substructure is shorter than the superstructure since the standard measures for tunnels and bridges in Klimatkalkyl 4.0 includes the substructure in the tunnel and on the bridge.
2. The length of electrification, signalling, and telecommunication systems were assumed to be the length of the rail superstructure (unless stated otherwise in the project descriptions).
3. For projects that included platform construction at a station, it was assumed that the platform area constructed was equal to the platform area on that station in 2016 based on data received from the STA.
4. It was assumed that soil stabilisation is required in all rail construction projects. It was assumed that the project requires 1 320 metres of LC columns and 510 metres of concrete piles per track kilometre (Stripple and Uppenberg, 2010).

**Table A3. New construction at airports during 1 year (arithmetic mean 2010-2015): resulting inventory of standard measures (hangar, apron, runway, terminal, and taxiway).**

| Standard measure | Quantity ($m^2$) |
|---|---|
| Hangar | 680 |
| Apron | 5 000 |
| Runway | 7 600 |
| Terminal | 1 230 |
| Taxiway | 2 000 |

**Table A4. Maintenance and reinvestment of road infrastructure: how the road infrastructure stock was divided into standard measures representative of the standard measures in Klimatkalkyl 4.0. The road length was received from the NRDB via Lastkajen (Swedish Transport Administration, 2016b).**

| Road type | Categorisation |
|---|---|
| Gravel road | All gravel roads regardless of width |
| 1 lane road < 4.5 m | All paved roads with a width of 1.0-5.0 metres + private roads with no specified width in the NRDB[1] |
| 2 lane road, 6.7-11.5 m | All paved roads with a width of 5.1-11.0 metres + municipal roads with no specified width in the NRDB[2] |
| 2+1 road | All paved roads with a width of 11.6-13.5 metres |
| Motorway 4 lanes | All paved roads with a width of 13.6-40 metres |
| 86% of the length of private roads | |
| 45% of the length of municipal roads | |

**Table A5. Operation and maintenance of road infrastructure: the infrastructure stock divided into standard measures representative of the standard measures in Klimatkalkyl to calculate impacts of maintenance and operation. Because Klimatkalkyl uses another approach to calculate impacts of operation and maintenance than impacts of construction and reinvestment, other standard measures are accounted for in Table A6.**

| Standard measure | Unit | Form of road infrastructure | | |
|---|---|---|---|---|
| | | **State-owned** | **Municipal** | **Private** |
| Motorway 4 lanes, urban | km | | 170 | |
| Motorway 4 lanes, countryside | km | 170 | | 10 |
| 2+1 road | km | 2 870 | 480 | 20 |
| 2 lane road, 6.7-11.5 m wide | km | 65 040 | 37 590 | 3 230 |
| 1 lane road < 4.5 | km | 11 990 | 2 340 | 20 460 |

| | | | | |
|---|---|---|---|---|
| Gravel road | km | 18 470 | 1 790 | 437 910 |
| Rock and concrete tunnel, 1 driving lane | km | 7 | | |
| Rock and concrete tunnel, 2 driving lanes | km | 23 | | |
| Rock and concrete tunnel, 3 driving lanes | km | 9 | | |
| Rock and concrete tunnel, 4 driving lanes | km | 10 | | |

**Table A6. Reinvestment of road infrastructure: the road infrastructure stock divided into standard measures representative of the standard measures in Klimatkalkyl 4.0. The length of plain roads was assumed to include also roads in roundabouts and junctions. The surface area of bridges was assumed to include also bridges in junctions. Stone and wood bridges, vault bridges, and soil composite bridges (representing 10% of the bridge area on the state-owned road network and most bridges on the private road network) were not included.**

| Standard measure | Unit | Form of road infrastructure | | |
|---|---|---|---|---|
| | | **State-owned** | **Municipal** | **Private** |
| 2+2 road | km | 170 | 170 | 10 |
| 2+1 road | km | 1 170 | 140 | 7 |
| 2 lane road, 8 m wide | km | 20 600 | 8 780 | 630 |
| 2 lane road, 6.5 m wide | km | 46 100 | 29 140 | 2 610 |
| 1 lane road | km | 11 990 | 2 340 | 20 460 |
| Gravel road | km | 18 470 | 1 790 | 437 910 |
| Walking and cycling path | km | 2 430 | 15 430 | 860 |
| Rock tunnel, 1 driving lane | km | 6 | | |
| Rock tunnel, 2 driving lanes | km | 20 | | |
| Rock tunnel, 3 driving lanes | km | 8 | | |
| Rock tunnel, 4 driving lanes | km | 9 | | |
| Concrete tunnel, 1 driving lane | km | 1 | | |
| Concrete tunnel, 2 driving lanes | km | 3 | | |
| Concrete tunnel, 3 driving lanes | km | 1 | | |
| Concrete tunnel, 4 driving lanes | km | 1 | | |
| Concrete beam bridge | $m^2$ | 1 748 370 | | |
| Short span concrete bridge | $m^2$ | 1 668 790 | | |
| Composite bridge | $m^2$ | 1 248 720 | | |

**Table A7. Reinvestment of rail infrastructure: the rail infrastructure stock divided into standard measures representing the standard measures in Klimatkalkyl 4.0.**

| Standard measure | Unit | Form of rail infrastructure | | | | |
|---|---|---|---|---|---|---|
| | | **State-owned** | **Other** | **Tramway** | **Metro** | **Industrial tracks** |
| Substructure[1] | track km | 13 800 | 1 280 | 275 | 160 | 14 550 |
| Superstructure[2] | track km | 14 130 | 1 310 | 280 | 280 | 14 550 |
| Electrification system[3] | track km | 12 040 | 160 | 280 | 280 | 7 280 |
| Signalling system[3] | track km | 12 040 | 160 | 280 | 280 | 7 280 |
| Telecommunications system[3] | track km | 12 040 | 160 | 280 | 280 | 7 280 |
| Rock tunnel | track km | 130 | 10 | 4 | 100 | |
| Concrete tunnel | track km | 30 | 3 | | 10 | |
| Concrete beam bridge | track km | 120 | 1 | | | |
| Composite bridge | track km | 30 | 10 | | | |
| Bridge, not specified[4] | track km | | | 1 | 10 | |
| Station building, above ground[5] | $m^2$ | 176 780 | | | | |
| Station building, underground, rock and soil | number | | | | 40 | |
| Platform | $m^2$ | 792 690 | | | | |

1. The substructure does not include the substructure in tunnels and on bridges, since the standard measures for bridges and tunnels in Klimatkalkyl 4.0 include substructure
2. Excluding non-trafficked tracks
3. Only included for electrified tracks
4. This standard measure, an average of the bridge standard measures in Klimatkalkyl 4.0, was used when information on bridge type was not available.
5. Includes also space used for commerce, offices, storage rooms, restaurants, etc.

**Table A8. Operation of air transport infrastructure: annual material and energy input for different activities. Fuel and electricity use for operation of buildings and vehicles includes also operation of buildings and vehicles used for management of aircraft and energy use for commerce at the airport.**

| Activity | Material and energy input | Unit | Quantity |
|---|---|---|---|
| Operation of buildings | District heating | MWh | 114 200 |
| | Oil | MWh | 1 140 |
| | Electricity | MWh | 198 060 |
| Operation of vehicles | Natural gas | $m^3$ | 960 740 |
| | Rape seed methyl ester | $m^3$ | 630 |
| | Petrol | $m^3$ | 160 |
| | Diesel | $m^3$ | 5 070 |
| Fire practice | Liquefied petroleum gas | tonne | 3 |
| | Sekundol 85 | $m^3$ | 60 |
| Deicing runways | Formate | MWh | 5 370 |
| | Sand | tonne | 2 540 |

**Table A9. Reinvestment of air transport infrastructure in 2015: resulting inventory of standard measures**

| Standard measure | Unit | Quantity | References |
|---|---|---|---|
| Runway repaved | $m^2$ | 209 460 | Kalmar Öland Airport (2015); Skavsta Airport (2015); Vilhelmina Municipality (2016) |
| Runway sealed[1] | $m^2$ | 110 000 | Windh (2015) |

It was assumed that the runway was sealed with 0.5 kg of bitumen emulsion per $m^2$ and that the emulsion contained 50% bitumen. Length and width of runway according to Transport Analysis (2016b).

***Table A10. New construction maintenance, and reinvestment of sea transport infrastructure: estimated annual material and energy input. Fuel use for vehicles slightly overlaps with fuel use for operation, since the on-site vehicles are used for different activities.***

| Material and energy input | Unit | Quantity | Included resources from the list made by Sarbring (2014) |
|---|---|---|---|
| Stainless steel | tonne | 460 | Acid proof stainless steel; stainless steel |
| Low-alloyed steel | kg | 170 | Alloy steel |
| Galvanised steel | tonne | 20 | Blank galvanised steel (harden, carbon, and stainless); E-coated steel; galvanised steel; galvanised stainless steel; harden steel; harden spring-steel; yellow galvanised steel |
| Steel, general | tonne | 80 | Crude steel; untreated steel |
| Reinforcement steel | tonne | 250 | Reinforcement steel |
| Aluminium | kg | 590 | Aluminium |
| Iron, general | tonne | 40 | Galvanised iron; iron |
| Zinc | tonne | 30 | Zink |
| Polycarbonate | tonne | 3 | Composite material |
| Neoprene elastomer | tonne | 6 | Rubber |
| Polyvinylchloride | tonne | 3 | PVC plastics |
| Polystyrene | tonne | 12 | Polystyrene |
| Polypropylene | tonne | 2 | Polypropylene |
| Polyethylene | tonne | 10 | Polyethene |
| Polyester | kg | 280 | Polyester |
| Glass reinforced plastic | tonne | 1 | Glass reinforced plastic |
| Asphalt | tonne | 1 050 | Asphalt |
| Cement | tonne | 80 | Cement |
| Concrete | tonne | 11 600 | Concrete |
| Core board | tonne | 1 | Paper |
| Wood | $m^3$ | 700 | Compreg wood; Swedish wood |
| Plywood | $m^3$ | 110 | Plywood |
| Gasoline, 2- stroke blend | kg | 540 | Alkylate gasoline |
| Petrol | tonne | 4 | Gasoline 95 okt |
| Diesel MK1 | $m^3$ | 6 990 | ACP Evolution diesel; compressor; concrete pump, crane; diesel heavy truck; jet cutting (diesel); light truck/pick-up; bulldozer; excavating machine |
| Electricity, Nordic mix | GWh | 2 | Electricity, Swedish average mix Environmental labelled electricity; jet-cutting (electricity); local wind electricity |
| Marine gas oil | tonne | 24 000 | |

**Table A11. Operation of sea transport infrastructure: material and energy input for different activities. Fuel use for vehicle operation slightly overlaps with fuel use for construction, maintenance, and reinvestment at ports, since the on-site vehicles are used for different activities.**

| Activity | Material and energy input | Unit | Quantity |
|---|---|---|---|
| Operation of buildings | Electricity | MWh | 105 950 |
| | District heating | MWh | 4 600 |
| | Oil | litre | 112 310 |
| | Gas | $m^3$ | 902 300 |
| Operation of vehicles | Biogas | kWh | 5 030 |
| | Gas | litre | 39 210 |
| | Ethanol | litre | 1 540 |
| | Petrol | $m^3$ | 190 |
| | Diesel | $m^3$ | 19 230 |
| Leakage from handling petrol | Emissions of volatile organic compounds | kg $CO_2$ equivalents | 29 830 |
| Lightening of fairways | Electricity | MWh | 2 330 |
| | Copper | tonne | 750 |
| Ice breaking | Marine gas oil | tonne | 11 600 |
| Piloting | Marine gas oil | tonne | 2 460 |

**Table A12. Process data used to quantify GHG emissions and energy use of material and energy production. Table continues on the next page.**

| Material and energy input | Process data |
|---|---|
| Aluminium | Swedish Transport Administration (2017) |
| Asphalt, 6.2% bitumen | Swedish Transport Administration (2017) |
| Biogas, for vehicle operation[1] | Ecoinvent, version 3.2: Transport, passenger car, medium size, natural gas, EURO 5 (RER)\| Alloc Rec, S |
| Bitumen | Swedish Transport Administration (2017) |
| Cement | Swedish Transport Administration (2017) |
| Concrete | Swedish Transport Administration (2017) |
| Copper | Swedish Transport Administration (2017) |
| Core board | Ecoinvent, version 3.2: Core board (RER)\| production \| Alloc Rec, S |
| Diesel | Swedish Transport Administration (2017) |
| District heating, Swedish average | Liljenström et al. (2015) |
| Electricity, Nordic mix | Swedish Transport Administration (2017) |
| Ethanol, for vehicle operation | Ecoinvent, version 3.2: Ethanol, without water, in 95% solution state, from fermentation (RER)\|ethanol production from rye \| Alloc Rec, S |
| Explosives, tovex | |
| Formate | Ecoinvent, version 3.2: Sodium formate (GLO)\| production \| Alloc Rec, S |
| Gas, for heating[2] | Ecoinvent, version 3.2: Heat, district or industrial, natural gas (Europe without Switzerland)\| market for heat, district or industrial, natural gas \| Alloc Rec, S |
| Gasoline, 2-stroke blend | Ecoinvent, version 3.2: Petrol, two-stroke blend (Europe without Switzerland)\| petrol blending for two-stroke engines \| Alloc Rec, S |
| Glass fibre for opto cable | Swedish Transport Administration (2017) |
| Glass reinforced plastic | Hammond and Jones (2011): Glass reinforced plastics – GRP – Fibreglass |
| Glass wool | Swedish Transport Administration (2017) |
| Glass, toughened | Swedish Transport Administration (2017) |
| Gravel | Swedish Transport Administration (2017) |
| Ground insulation | Swedish Transport Administration (2017) |
| Iron | Hammond and Jones (2011): Iron, general |
| Lead | Swedish Transport Administration (2017) |
| Lime | Swedish Transport Administration (2017) |
| Liquefied petroleum gas | Ecoinvent, version 3.2: Liquefied petroleum gas (RoW)\| market for \| Alloc Rec, S |
| Marine gas oil | Winnes et al. (2016) |
| Natural gas[3] | Ecoinvent, version 3.2: Transport, passenger car, medium size, natural gas, EURO 5 (RER)\| transport, passenger car, medium size, natural gas, EURO 5 \| Alloc Rec, S |
| Neoprene elastomer | Swedish Transport Administration (2017) |

| | |
|---|---|
| Oil, for heating[4] | Ecoinvent, version 3.2: Heat, central or small-scale, other than natural gas (Europe without Switzerland)\| heat production, light fuel oil, at boiler 10kW, non-<br>modulating \| Alloc Rec, S |
| Petrol, for vehicle operation[5] | Ecoinvent, version 3.2: Transport, passenger car, medium size, petrol, EURO 5 (RER)\| transport, passenger car, medium size, petrol, EURO 5 \| Alloc Rec, S |
| Plywood | Ecoinvent, version 3.2: Plywood, for outdoor use (RER)\| production \| Alloc Rec, S |

| **Material and energy input** | **Process data** |
|---|---|
| Polyamide | Swedish Transport Administration (2017) |
| Polycarbonate | Ecoinvent, version 3.2:<br>Polycarbonate (RER)\| production \| Alloc Rec, S |
| Polyester | Swedish Transport Administration (2017) |
| Polyester fabric | Swedish Transport Administration (2017) |
| Polyethylene | Swedish Transport Administration (2017) |
| Polyethylene, high density | Swedish Transport Administration (2017) |
| Polyethylene, low density | Swedish Transport Administration (2017) |
| Polypropylene | Swedish Transport Administration (2017) |
| Polypropylene | Swedish Transport Administration (2017) |
| Polystyrene | Swedish Transport Administration (2017) |
| Polyvinylchloride | Ecoinvent, version 3.2: Polyvinylchloride, bulk polymerised (RER)\| polyvinylchloride production, bulk polymerisation \| Alloc Rec, S |
| Rape seed methyl ester | Ecoinvent, version 3.2: Vegetable oil methyl ester (Europe without Switzerland)\|esterification of rape oil \| Alloc Rec, S |
| Reinforcing steel | Swedish Transport Administration (2017) |
| Road salt | Swedish Transport Administration (2017) |
| Sand | Swedish Transport Administration (2017) |
| Sekundol 85[6] | Ecoinvent, version 3.2: Ethanol, without water, in 95% solution state, from fermentation (RER)\| ethanol production from rye \| Alloc Rec, S |
| Steel, galvanized | Swedish Transport Administration (2017) |

| | |
|---|---|
| Steel, general | Swedish Transport Administration (2017) |
| Steel, low-alloyed | Ecoinvent, version 3.2: Steel, low-alloyed, hot rolled (RER)\| production \| Alloc Rec, S |
| Steel, stainless | Swedish Transport Administration (2017) |
| Steel, stainless, galvanised, general, reinforcement | Swedish Transport Administration (2017) |
| Sulfuric acid | Swedish Transport Administration (2017) |
| Transformer oil | Swedish Transport Administration (2017) |
| Wood | Swedish Transport Administration (2017) |
| Zinc | Ecoinvent, version 3.2: Zinc \| gold-silver-zinc-lead-copper mine operation and refining \|Alloc Rec, S |

1. Fuel density 0.8 kg/m$^3$ and fuel consumption 0.04 kg/km
2. Heating value 11 kWh/m$^3$
3. Fuel density 0.8 kg/m$^3$ and fuel consumption 0.04 kg/km
4. Fuel density 850 kg/m$^3$ and heating value 40 MJ/kg
5. Fuel consumption 5 litres/100 km
6. Density 0.5 kg/litre