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Energy Use and Greenhouse Gas Emissions during the Life Cycle Stages of a Road Tunnel - the Swedish Case Norra Länken

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Inclusion of Life Cycle Assessment during the planning of transport infrastructure is rarely used in practice, but is becoming a widely discussed issue nowadays. This study sought to improve understanding of the life cycle energy use and greenhouse gas emissions of transport infrastructure, using the example of a road tunnel. Two levels of analysis were used: 1) detailed data inventory for the construction of rock tunnels; and 2) screening assessment for the life cycle phases of the whole tunnel infrastructure (including its main parts: concrete and rock tunnels). The first level of analysis showed that production of materials (i.e. concrete and asphalt) made the largest contribution to Cumulative Energy Demand and Global Warming Potential. The second level of analysis indicated that concrete tunnels had much higher Cumulative Energy Demand and Global Warming Potential per lane-metre than rock tunnels. Moreover, the operational phase of the tunnel was found to have the highest share of energy use and greenhouse gas emissions throughout the tunnel's life cycle.

Key words: Cumulative Energy Demand, Global Warming Potential, Life Cycle Assessment, tunnel.

Introduction

Background

The transport sector is responsible for about 23% of global energy-related greenhouse gas (GHG) emissions (OECD/ITF, 2010). This figure refers to direct emissions from vehicles in use, but there are also indirect transport emissions which relate to construction, maintenance and operation of transport infrastructure, manufacturing and maintenance of vehicles, as well as fuel production. Although knowledge is incomplete, it has been shown that these indirect emissions may constitute a significant share of total transport-related GHG emissions (Chester and Horvath, 2009, Jonsson, 2007, Federici, Ulgiati and Basosi, 2009).

A number of assessments have been made of the life cycle impacts of transport infrastructure (e.g. Chester et al. (2009), Stripple (2001), Jonsson (2007), Federici (2003), Schlaupitz (2008),

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Karlsson et al. (2010), etc.). And even though it is often difficult to compare directly the results of those studies, most of them come to the conclusion that indirect energy use for transport infrastructure may be significant, but there is a need for better knowledge (Miliutenko, 2009).

Federici (2009) noted that most of the published LCA studies on transport systems "very seldom account for infrastructures in detail, mainly focusing on the construction of vehicles and their fuel use". Chester and Horvath (2009) also stated that most of the current decision making in the field of transport planning is based mostly on the analysis of "tailpipe" emissions, ignoring indirect energy use. Jonsson (2005) showed that there is a lack of knowledge concerning indirect energy use in the Swedish transport system. When performing their studies on energy use and greenhouse gas emissions of transport infrastructure, Schlaupitz (2008) and Karlsson et al. (2010) concluded that there is a need for more detailed and careful analysis of large transportation projects in order to increase the knowledge of environmental impacts of transport infrastructure.

The Swedish Transport Administration aims to contribute to the achievement of one of the 16 Swedish Environmental Quality Objectives - Reduced Climate Impact. A major pillar in the work towards achieving this quality objective is to reduce energy use during construction and operation of transport infrastructure (Vägverket, 2007). However, despite those targets, only site-specific Environmental Impact Assessment is usually performed during transport planning. Environmental impacts from a life cycle perspective (such as energy use, impact on global warming, toxicity, acidification, etc.) are not taken into account very often. Thus it can be assumed that due to the data gaps in the knowledge concerning indirect energy use and other environmental impacts throughout the life cycle of transport infrastructure, there is a severe risk of transport planning decisions being sub-optimised from an environmental point of view.

Since tunnels are considered to be some of the most energy-intensive parts of transport infrastructure, it is especially important to analyse them from a life cycle perspective. However, Schlaupitz (2008) has shown that most of the inventory data on tunnel life cycle processes are uncertain and should be improved through more detailed studies. Consequently, there is a need for method development and data collection in order to promote the use of LCAs for tunnels in everyday practice.

Goal and Scope

The overall aim of this study was to provide an improved understanding of the life cycle energy use and GHG emissions of a road tunnel. An additional aim was to provide inventory data and process flow descriptions for further tunnel LCAs. The ongoing tunnel construction project Norra Länken (Northern Link) in Stockholm was used as a case study. Norra Länken is a new traffic route in the city of Stockholm (Figure 1). Norra Länken is scheduled to open for traffic in 2015. The approximate cost of the project is estimated to be about 11.2 billion Swedish kronor in 2007 prices (Trafikverket, 2010).

Norra Länken tunnel consists of two channels. The total length of tunnel channel is about 11 km (Trafikverket, 2010). Rock tunnels make up the majority of Norra Länken. This is also the most common type of tunnel in other regions of Sweden. There are currently about 24 rock tunnels for road traffic in Sweden (covering about 22 km), and five more (covering about 30 km) are planned by 2020 (Dalmalm, 2010).

The rock tunnels in Norra Länken are being constructed according to the preliminary Bill of Quantities, which contains preliminary engineer estimates for all activities and materials to be used. These are compiled by contractors, mainly in order to chart the financial costs. Consequently, these Bills of Quantities provide easily accessible site-specific data for rock tunnel construction.

Unlike rock tunnels, concrete tunnels lack a Bill of Quantities, as they are built under 'design-built contract'. Consequently, there are no detailed site-specific data for the construction of concrete tunnels. Another point to remember is that construction of concrete tunnels is very site-dependent (in that the methods and materials used for construction depend greatly on the area in which the tunnel is being constructed). Therefore it is more difficult to generalise data from one concrete tunnel to other tunnels in Sweden or elsewhere.

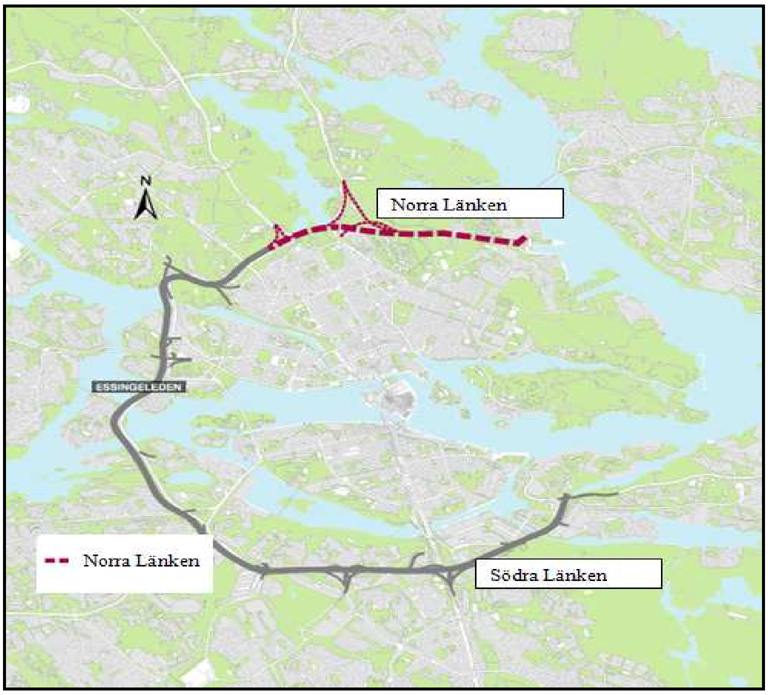


Figure 1. Map of Stockholm showing Norra Länken, part of the Stockholm ring road (Trafikverket, 2010).

As a result of this difference in data availability, the study was divided into two different levels of analysis. This subdivision was made in order to make the study more transparent and more applicable for further data collection and methodological development of other tunnel LCAs.

In Part 1, a detailed LCA of the construction phase of rock tunnel parts of Norra Länken was performed in order to identify the materials and processes that contribute most to greenhouse gas (GHG) emissions and energy use during tunnel construction. This part of the study also explored the possibility of using the inventory data from the preliminary Bill of Quantities for LCA.

In Part 2, a screening LCA of the construction, operation and maintenance phases for both the rock and concrete tunnels in Norra Länken was performed, in order to analyse potential energy use and GHG emissions of the whole tunnel throughout its life cycle stages. Screening LCA is usually performed using easily accessible data (Moberg, Johansson, Finnveden and Jonsson, 2009). Thus this analysis included only materials and processes identified as being of major importance for the scope of the study.

As Table 1 shows, this study covered most of Norra Länken. Considering that the total length of tunnel is 11 km, only 1 km of tunnel was not included in the study. This consisted of small sections of mixed (concrete and rock) tunnel, bridges, motorways and intersections used for connecting the tunnel with other parts of the road network. It was estimated that about 78 000 m^3 of concrete were used for construction of these other structures.

Table 1. Lengths of the tunnel parts 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 study also accounted for the materials and energy used for the construction of access tunnels (additional short tunnels built in order to access the main tunnels during their construction and operation).

Methodology

Life Cycle Assessment (LCA) is the main tool applied in this study. LCA is used to assess the potential environmental impacts and resource consumption throughout a product's life from raw material acquisition through production, use and disposal (ISO, 2006).

The study was performed as an attributional LCA (Baumann and Tillman, 2004). Attributional LCA allows identification of major contributing processes of a system in the current situation. As a consequence of this methodological choice, average process data were used in the main calculations, as opposed to marginal data in consequential LCA (Finnveden, Hauschild, Ekvall, Guineé, Heijungs, Hellweg, Koehler, Pennington and Suh, 2009). However, section on ¨Data uncertainty and variability¨ examines the impact on emissions of assuming marginal electricity. Data for marginal electricity represent the technology (often referred to as "marginal technology"), which is most likely to respond to a change in demand for electricity as a consequence of a decision (Lund, Mathiesen, Christensen and Schmidt, 2010, Finnveden, 2008).

Excel-sheets and the LCA software tool SimaPro (PRéConsultants, 2008) were used for modelling, inventory analysis and impact assessment. A detailed description of the materials and processes included in LCA modelling is shown in Appendix A, Table A-1.

Impact assessment categories

Two impact categories were chosen for the Life Cycle Assessment: Cumulative energy demand (CED) and Global Warming Potential (GWP).

The CED represents the direct and indirect energy (including feedstock energy) in units of MJ throughout the life cycle of a good or a service. The total CED is subdivided into the main sources of energy: fossil CED (i.e. from hard coal, lignite, peat, natural gas and crude oil) and the CED of nuclear, biomass, water, wind and solar energy in the life cycle (Huijbregts, Hellweg, Frischknecht, Hendriks, Hungerbuhler and Hendriks, 2010, Hischier, Weidema, Althaus, Bauer, Doka, Dones, Frischknecht, Hellweg, Humbert, Jungbluth, Köllner, Loerincik, Margni and Nemecek, 2009). Calculation of CED was based on the method published by EcoInvent v 2.0 version 1.01 and expanded by PRéConsultants for raw materials available in the SimaPro 6 database (Frischknecht, Jungbluth and al, 2003).

Greenhouse gas emissions were measured as GWP-100, expressed in terms of carbon dioxide equivalents (CO_2-eq) over 100 years, as in the ReCipe method (Goedkoop, Heijungs, Huijbregts, Schryver, Struijs and Zelm, 2009).

System boundaries and inventory data

The functional unit, which is a reference unit that quantifies the performance of the system, is determined by the object of assessment (Weidema, Wenzel, Petersen and Hansen, 2004). In Part 1, it corresponded to the rock tunnels in Norra Länken, covering only the construction phase. In Part 2, it corresponded to the rock and concrete tunnels in Norra Länken, covering construction, operation and maintenance (see Table 1).

The total lifetime of the tunnel was considered to be 100 years, which determined the period of time for which operation processes were calculated. However, different lengths of lifetime were considered for different parts of the tunnel, requiring maintenance at certain intervals during the total lifetime.

Most of the materials used in construction were assumed to be produced in countries in the European Union. Crushed aggregates, gravel, cement, concrete and asphalt were assumed to be extracted or produced in Sweden. The term asphalt is used in the study for asphalt concrete-mixture of aggregates and bitumen. Swedish electricity mix, mainly consisting of hydro and nuclear power, was assumed for the construction and operation phases. The influence on the results of other electricity scenarios is shown and discussed in section on ¨Data uncertainty and variability¨.

The system boundaries for Parts 1 and 2 of the study are illustrated in Figure 2.

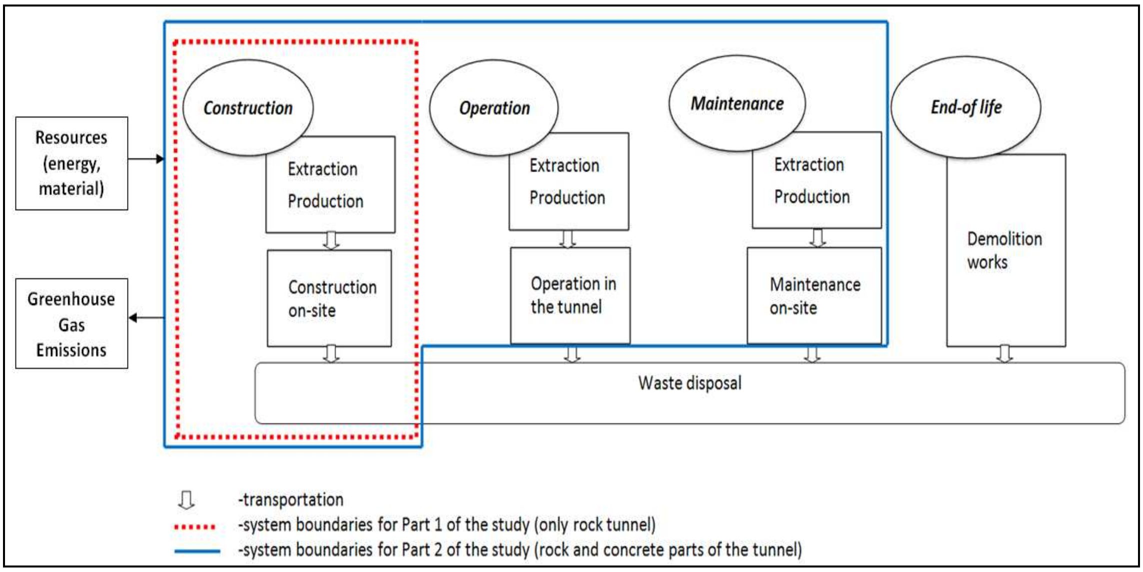


Figure 2. System boundaries for the two parts of the study

In order to describe in detail all data sources, it is first necessary to distinguish between foreground and background systems (concepts which are often used in LCA methodology). The foreground system consists of processes directly connected to the study object, while the background system represents information about the environmental interventions of pre and post steps to the foreground system (Tillman, 2000, Schaltegger, 1996).

Extraction/production phases were assumed to include the following processes: extraction of raw materials, production of construction materials and provision (transportation) of raw materials within this phase. These processes constituted the background system, for which inventory data were taken from EcoInvent (Frischknecht and Rebitzer, 2005). See processes chosen for modelling in EcoInvent in Appendix B (Table B-2 and Table B-3). For the rock part of the tunnel, this stage included production and provision of the following materials: concrete, aggregates, asphalt, cement, steel, aluminium etc. (see Table 2). Quantities of materials used for rock tunnel construction were taken from the Bill of Quantities (considering a waste factor of about 5-10% for main types of materials, except for cement, where the waste factor was considered to be 30%, as shown in Appendix B, Table B-1). Some of the material quantities were also based on expert assumptions (through personal communications with Swedish Transport Administration). Projected figures on the amount of blasted rock were updated with actual data from the current activities. Some of the processes during rock tunnel construction were excluded due to their expected low significance with regard to energy use and GHG emissions. Extraction and production of the following materials were excluded: polyurethane, silicone compounds, acrylic paint, fibreglass, lightweight aggregate blocks, epoxy, and joint strips.

Actual manufacturing of steel bolts, concrete plates and similar products was also excluded. However, extraction and transportation of raw materials used for their production was included.

Materials representing a fraction less than 0.01% of the total weight for construction materials used in Norra Länken (shaded fields in Table 2) were excluded from further LCA analysis. It was assumed that such small volumes are insignificant for the results of energy use and GHG emissions. Having made a rough estimate, the share for such materials would be less than 0,5% of the total CED and GWP of on-site construction for rock tunnel. However this assumption should be reconsidered if other types of impact categories are chosen, such as toxicity, acidification, etc.

Table 2. Material quantities for the main rock tunnels in Norra Länken (7.5 km)

Material	Quantity (ton)	Weight %
Shotcrete, concrete: exacting, without reinforcement	159 639	22%
Crushed aggregates, gravel	490 553	68%
Asphalt	52 296	7%
Wood (sawn timber formwork)	2 611	0.36%
Steel (reinforcing, galvanised, stainless)	4 186	1%
Cement, portland	5 102	1%
Aluminium	46	0.01%
Ductile cast iron	142	0.02%
Polypropylene (geotextile, PP-pipes, PP-fibre)	122	0.02%
Styrofoam	69	0.01%
Polyethylene	316	0.04%
Explosives	2 123	0.30%
Plastics, electronics	5	Excluded
Chemical substance-polyurethane	32	Excluded
Silicone-based substance	1	Excluded
Acrylic varnish	3	Excluded
Glass fibre (bolts)	0.08	Excluded
Total quantity of materials (ton)	717 244	100%

For the concrete tunnels in Norra Länken, the extraction/production stage was assumed to include production of concrete, steel and asphalt. Rough data on material quantities used for construction of concrete tunnels were collected with the help of expert assumptions and own calculations. The quantities of concrete, steel and asphalt used in concrete tunnels are shown in Table 3 (after Andersson (2010)).

Table 3. Material quantities for the concrete tunnels in Norra Länken (2.5 km)

Material	Quantity (ton)	Weight %
Concrete	301 920	89%
Steel	25 550	7%
Asphalt	13 522	4%
Total	340 992	100%

Transport of the main materials (concrete, steel, cement, aggregates, asphalt, etc.) to and from the construction site constituted the foreground system. Fuel production was part of the background system. Emissions standard Euro5 was chosen when evaluating GWP and CED for the vehicles. See Appendix B (Table B-3) for transport distances assumed for rock and concrete tunnels in Norra Länken. The following types of transport were excluded: 1) transportation of ductile cast iron, polypropylene products, polystyrene products, polyethylene products, plastics, electronics; and 2) transportation of machinery to the construction site.

On-site construction was assumed to include work aboveground and in the tunnel. For the rock tunnels, the amount of electricity/fuel used during construction constituted the foreground system. It was calculated that about 3 270 000 litres of diesel and 43 GWh of electricity were used during the whole phase of rock tunnel construction (based on Harryson (2010)). The following activities were excluded from the on-site construction phase: 1) preparatory work, such as investigations, demolition, tree felling, etc.; 2) control, monitoring; 3) water consumption; 4) production of machinery used for construction; and 4) deforestation and extra traffic generated during construction.

Waste disposal during the construction phase of the tunnel considered handling of inert waste (blasted rock and excavated soil) for both rock and concrete tunnels. About 3 million tons of blasted rock and excavated soil were assumed for the rock tunnels in Norra Länken and about 1.3 million tons for the concrete tunnels. The blasted rock was assumed to be transported a distance of 20 km and then crushed. It was assumed that 100% of the blasted rock would be reused (gravel from natural pits was assumed to be an avoided product), with about 15%-20% reused for construction of Norra Länken and 75%-80% sold on the open market (Gröndahl, 2010). Disposal of ordinary waste (packaging waste from the products used in tunnel construction) and hazardous waste (waste generated during the use and maintenance of vehicles, oil waste for example) was excluded from the analysis. The quantities of these types of waste are relatively small and difficult to estimate (Mroueh, Eskola, Laine-Ylijoki, Wellman, Juvankoski and Ruotoistenmäki, 2000).

Operation of the total tunnel includes electricity consumption for lighting, ventilation, pumps, monitoring systems, etc. It was assumed that there is no difference in operation between rock and concrete tunnels. Approximate electricity use during tunnel operation was projected based on the effect of the motors that will be used in the tunnel (Karlsson, 2010). Thus it was projected that approximately 27 GWh/year of electricity will be used during the operation of the whole Norra Länken tunnel. The electricity during operation is mainly used for: ventilation, lighting, telecommunications, heating, water pumping and other (Karlsson, 2010). The traffic volume in the main tunnel during the operation phase is expected to be about 90 000 vehicles/day (Bellinder, 2010).

Production and maintenance of electrical equipment was excluded from the operation phase.

Maintenance phase for the whole tunnel included the following assumptions (Bellinder, 2010):

- That 40 mm of asphalt for both concrete and rock tunnels will be replaced 13 times (on average) during the life-time of 100 years.
- That tunnel lining for rock tunnels will be changed twice during the life-time of 100 years.
- That about 50 mm of concrete for concrete tunnels will be replaced once during the life-time of 100 years.

According to the assumptions made at Trafikverket, the special lining used for rock tunnel construction will decrease the need for tunnel maintenance (Bellinder, 2010). That is why so few processes were considered for the phase of tunnel maintenance.

The following processes were excluded during the analysis of the maintenance phase: on-site activities used for replacement of the materials, machinery used for maintenance activities, transportation of materials.

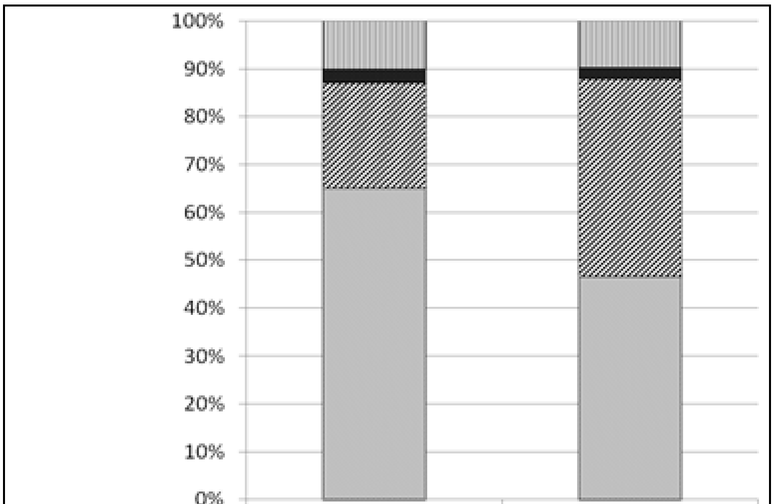
End-of-life stage of the tunnel was excluded due to the long life-time of tunnel structures and the fact that tunnels/roads are usually not demolished (Mroueh, Eskola, Laine-Ylijoki, Wellman, Juvankoski and Ruotoistenmäki, 2000).

It should be noted that CO_2 uptake of concrete during its lifetime was not considered in the analysis. These processes can occur over several hundreds or thousands of years, usually as waste processes (Stripple, 2001).

Results

Global Warming Potential and Cumulative Energy Demand for rock tunnel construction

The total CO_2-eq emissions for the construction phase of the rock tunnels in Norra Länken (Part 1 of the study) amounted to about 66 kiloton CO_2-eq. The corresponding cumulative energy demand (CED) was about 1384 TJ-eq.



	kg CO2-eq	CED (MJ eq)
Inert waste disposal	10%	10%
Transportation	3%	2%
Construction on-site	22%	41%
Material production	65%	47%

Figure 3. Share of CO_2-eq emissions and cumulative energy demand (CED) during rock tunnel construction

Production of materials used for rock tunnel construction had the highest share of GWP and CED, while on-site construction had a higher share of CED than GWP (Figure 3). This can be explained by the fact that tunnel construction is electricity-intensive and that Swedish electricity mix (which has a large share of nuclear and hydro power) was used in this study.

A more detailed analysis of the contribution of materials to the CED and GWP of rock tunnel construction indicated that concrete had the highest share in terms of GWP (about 34%), and asphalt in terms of CED (about 14%). Such differences can mainly be explained by the fact that the CED methodology also considers feedstock energy. Since the feedstock energy of liquid bitumen used for asphalt production is very high, the results show large energy demand for asphalt.

High CO_2-eq emissions during concrete production are partly caused by a large share of CO_2 emissions not related to energy use. These are direct emissions during cement production (i.e. processes of calcination). The CO_2 emissions for concrete production could have been slightly lower if CO_2 uptake of concrete had been considered, but the influence of this factor can be assumed to be minor (Stripple, 2001).

Global Warming Potential and Cumulative Energy Demand during the main life cycle phases of rock and concrete tunnels in Norra Länken

Comparing the construction phases of rock and concrete tunnels, it can be seen that the concrete tunnels had much higher GWP and CED per lane-km (see Table 4). The screening LCA of the concrete tunnels in Norra Länken revealed that concrete and steel had the highest share of GWP during concrete tunnel construction (about 48%and 43%, respectively), and steel was responsible for the highest share of CED (about 60%).

Table 4. Cumulative Energy Demand and Global Warming Potential during the life cycle of the entire Norra Länken (including rock and concrete parts)

Phase	**ton CO_2-eq**	**ton CO_2-eq/lane-km**	**Energy (TJ-eq)**	**TJ-eq/ lane-km**
Construction				
Rock tunnels	66 412	4 807	1 384	100
Concrete tunnels	88 247	22 062	1 041	260
Total (construction of rock and concrete tunnels)	154 658	8 681	2 425	136
Operation (whole NL for 100 years)	241 908	13 578	26 203	1 471
Maintenance (whole NL for 100 years)	34 326	1 927	744	42
Total (construction, operation, maintenance)	430 893	24 186	29 372	1 649

As Figure 4 and Table 4 indicate, operation of the tunnel (for 100 years) had the highest share of both GWP and CED during the life cycle phases of Norra Länken. Unlike other parts of road infrastructure (ordinary roads, bridges), tunnels use a lot of electricity for lighting, ventilation, etc. during the operation phase.

It can be noted that the operation phase had a much lower share of CO_2-eq than CED. This can be explained by the fact that Swedish average electricity mix was assumed for that phase. Since Swedish electricity mix has a large share of nuclear and hydro power, the resulting levels of GHG emissions were low.

It can also be observed that such stages as tunnel construction and maintenance have higher GWP than CED. This is mainly explained by the fact that there is a large share of fossil-dependant processes during tunnel construction and maintenance.

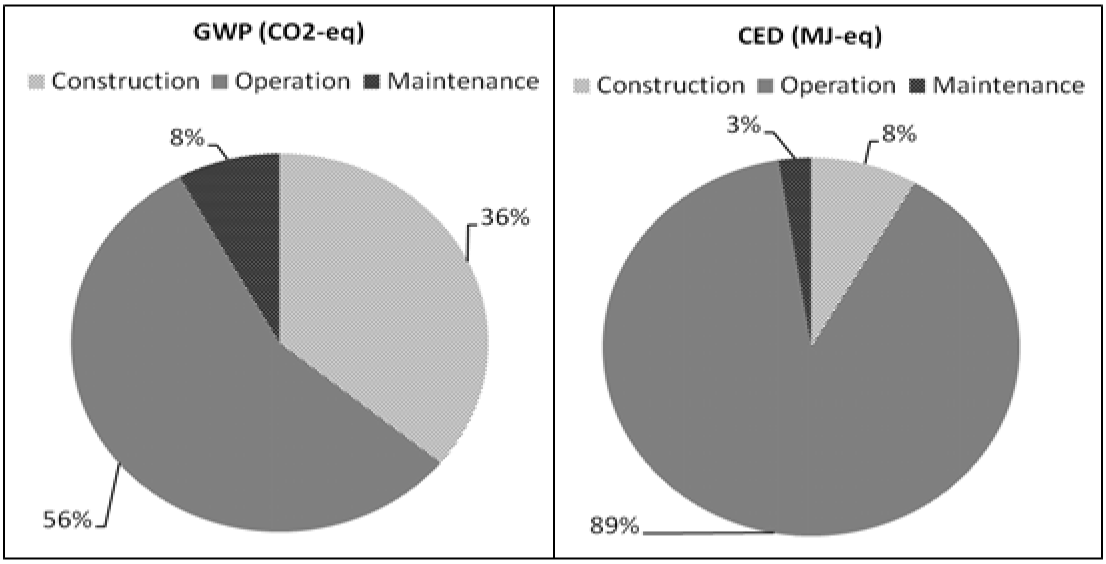


Figure 4. Share of Cumulative Energy Demand (CED) and CO_2-eq emissions during the main life-cycle stages of Norra Länken.

The processes that contribute the most to GWP and CED for the construction phase were production of asphalt, concrete and steel. Ventilation fans contributed most to the GHG emissions of the operation phase, and production of concrete and asphalt to those of the maintenance phase.

Data uncertainty and variability

Different types and sources of data uncertainty and variability have been identified by several researchers (for example Huijbregts and colleagues (2001), Björklund (2002), Lloyd and Ries (2007), etc.). First of all, it should be noted that data uncertainty and variability can occur throughout all phases of LCA: goal and scope definition, inventory, choice of impact categories, classification, characterisation (Björklund, 2002). It is also important to make a distinction between data uncertainty and variability, where uncertainty refers to values that are not known with precision and can be reduced by additional research, while variability cannot be reduced as it corresponds to inherent differences between individuals, places, time, processes, etc. (Heijungs and Huijbregts, 2004, Hertwich, McKone and Pease, 2000).

Sources of data uncertainty and variability in the current study can be also subdivided according to the LCA modelling components (Lloyd and Ries, 2007, Huijbregts, Gilijamse, Ragas and Reijnders, 2003). They are as follows:

1. **Parameter** (input data), for example: uncertainty and variability regarding volumes of materials used, measurement errors, lack of representative inventory data, ignorance of relevant parameters, uncertainty in parameters during impact assessment, etc.
2. **Scenario** (normative choices), for example: uncertainty in assumptions regarding future electricity use, future technological developments, choice of functional unit, system boundaries, impact assessment methodology, etc.

3. **Model** (mathematical relationships), for example: ignorance about modelled processes, uncertainty during modelling of real-world processes (such as tunnel structure, maintenance and operation of a tunnel, etc.)

According to Kendall et al. (2009), one of the main sources of uncertainty in LCAs of transport infrastructure is prediction of future events and conditions, which corresponds to scenario-type data uncertainty. In this study, large variability was found regarding inventory data on certain construction materials (such as cement used for concrete production and bitumen used for asphalt production), which can be classified as parameter uncertainty. For instance, emissions data for different types of concrete have variability from 125 kg CO_2-eq/m^3 to 330 kg CO_2-eq/m^3 in EcoInvent database, with 324 kg CO_2-eq/m^3 being used in this paper.

As noted by Kendall (2009) and Schlaupitz (2008), assumptions on the carbon intensity of electricity have a major impact on the results. Therefore a sensitivity analysis was performed on how different types of electricity influenced the final results (with regard to GWP-100 and CED). The types of electricity selected for this analysis are shown in Table 5. The choice of marginal or average electricity depends on the purpose of the LCA. Average electricity is used for accounting (attributional, retrospective) LCA, while marginal electricity is used for consequential (change-oriented, prospective) LCA. Accounting LCA is usually used for description of the current status of environmental performance during the life cycle, while consequential LCA is mostly used to support well-defined decisions, where the model accounts for the full effects of the actions considered (Tillman, 2000).

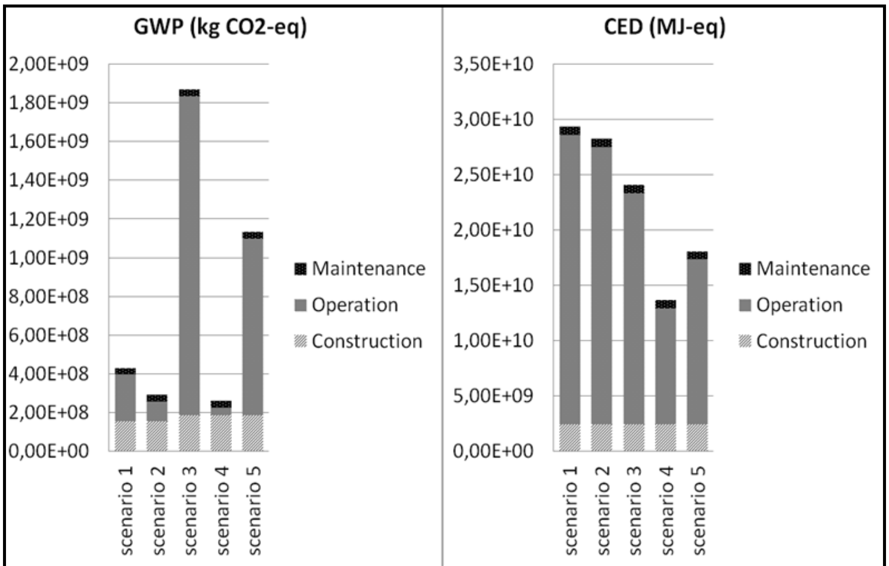
Thus in order to test the influence on the final results of assumptions made regarding carbon intensity for electricity mix, the following scenarios were chosen:

- Scenario 1:
  - Construction and operation stages – 'average present' electricity mix
- Scenario 2:
  - Construction – 'average present' electricity mix
  - Operation – 'average future' electricity mix
- Scenario 3:
  - Construction – 'marginal present' electricity mix
  - Operation – 'marginal future-high' electricity mix
- Scenario 4:
  - Construction – 'marginal present' electricity mix
  - Operation – 'marginal future-low' electricity mix
- Scenario 5:
  - Construction – 'marginal present' electricity mix
  - Operation – 'marginal base case 2030' electricity mix

Marginal present electricity is very difficult to define, as it varies over the year. Future electricity production (both marginal and average) may change significantly over the life of the tunnel. Here, for simplicity one type of electricity was assumed for the whole phase of tunnel operation. The scenarios for future electricity production were based on forecasts provided by the Swedish Energy Agency.

Table 5. Types of electricity chosen for sensitivity analysis

Description of electricity for scenarios	Type	MJ-eq/MWh	kg CO_2-eq/MWh	reference
Average present	Swedish, at grid, with imports	9520	91.3	EcoInvent database
Average future	Electricity average mix Sweden 2030	9130	37.8	Energimyndigheten (2009), see Appendix C (Table C-1)
Marginal present	Marginal electricity, 2010	10100	792	Energimyndigheten (2006), see Appendix C (Table C-1)
Marginal future-high	Marginal electricity produced by high amount of fossil fuels	7590	599	Finnveden (2008), see Appendix C (Table C-1)
Marginal future-low	Marginal electricity produced by low amount of fossil fuels (in case the CO2 cap is introduced over the electricity production system in EU)	3830	14.6	Finnveden (2008), see Appendix C (Table C-1)
Marginal base case 2030	Marginal electricity, 2030	5420	332	Energimyndigheten (2006), see Appendix C (Table C-1)



Scenario 1: Construction and Operation- ¨average present¨

Scenario 2: Construction-¨average present¨, Operation- ¨average future¨

Scenario 3: Construction- ¨marginal present¨, Operation- ¨marginal future- high¨

Scenario 4: Construction-¨marginal present¨, Operation- ¨marginal future- low¨

Scenario 5: Construction-¨marginal present¨, Operation-¨marginal base case 2030¨

Figure 5. Sensitivity analysis for the choice of electricity mix

Data regarding the CED and GWP for the types of electricity considered in Scenarios 1-5 were calculated with the help of SimaPro (see in Table 5).

The choice of future electricity for LCA of tunnel structure had a considerable influence on the final results, from an approx. 40% decrease (when Marginal future-low electricity was chosen for the operation phase) to an approx. 330% increase (when Marginal future-high electricity was chosen for the operation phase) (Figure 5).

GWP-100 was considerably higher in Scenario 3 than in Scenario 2, but CED was slightly lower. This can be explained by the fact that electricity for the operation phase in Scenario 3 has a large share of electricity produced by coal power (about 60%), and that the electricity for the operation phase in Scenario 2 has a large share of nuclear power (about 41%) and hydropower (39%) (Finnveden, 2008, Energimyndigheten, 2009). In contrast to GWP-100, there are no large differences between nuclear and coal power with respect to CED.

The operation phase of the tunnel had the highest share of energy use throughout the tunnel life cycle for all scenarios (irrespective of the type of electricity chosen for the operation phase) (Figure 5). Regarding GWP-100, operation dominated in Scenarios 1, 3 and 5, while construction dominated in Scenarios 2 and 4.

Discussion and conclusions

The purpose of this study was to improve our understanding of the life cycle energy use and greenhouse gas (GHG) emissions of a road tunnel. According to this paper, the total GHG emissions from construction of the tunnel Norra Länken amount to about 155 000 ton CO2-eq (which equals approximately 6% of yearly greenhouse gas emissions from car travel in Stockholm county). It was found that construction of a concrete tunnel causes five times more GHG emissions per lane-km than construction of a rock tunnel. The cumulative energy demand (CED) was about three times higher per lane-km for concrete tunnels. Concrete, asphalt and steel had the highest contribution in terms of the studied impacts.

When comparing the different phases throughout the life cycle of the tunnel in a 100 year perspective, the operation 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. These figures are, however, much dependent on what carbon intensity of electricity that is assumed. When we tested the impact of different electricity mixes in a sensitivity analysis, the results for GWP from operation varied with a factor 40, from less than 40 000 tons CO2-eq to about 1.6 million tons CO2-eq.

We also tested the possibility of performing LCA on the basis of the project's preliminary Bill of Quantities. These are prepared for many construction projects, not only in the sphere of road infrastructure, but also for railways and buildings. Preliminary Bills of Quantities have not been often used for environmental assessments of transport infrastructure construction. However, several studies show the usefulness of data collected from the preliminary Bill of Quantities for LCA of buildings (Li, Zhu and Zhang, 2010, Crawford and Treloar, 2005).

When the data provided in the preliminary Bill of Quantities were compared with updated real data on blasted rock from the construction phase of Norra Länken, the differences were quite small (1-15% depending on site). However, it should be noted that there is a need to improve statistical information on tunnel construction regarding the use of main materials (asphalt, concrete, steel) and in particular regarding waste treatment. The preliminary Bill of Quantities can be slightly modified in terms of data reporting (with a little extra effort by the contractors) in order to make it more feasible for practitioners to collect inventory data for LCA.

In the current study we collected detailed process-specific data for rock tunnel construction, which can be used to refine future LCAs for tunnel planning. It should be noted that the choice of a 100-year time horizon is an uncertain factor. It is also difficult to predict the number of electric cars being used in the future (which can significantly decrease the need for ventilation fans) or the extent to which the technology for construction material production and maintenance will be improved. Moreover, the extent of diminishing fossil fuel resources within the next 100 years is also unclear, which adds more uncertainty to the calculations of GHG emissions from fuel consumption in the future. Thus it should be emphasized that the results regarding tunnel operation for the full 100 year period can vary depending on the assumptions made.

The results of this LCA can be compared with those in Karlsson et al. (2010), where life cycle energy use and GHG emissions of a road tunnel were roughly estimated. Since different system boundaries and functional units were chosen, it is difficult to compare the studies directly. For example, Karlsson et al. (2010) calculated energy consumption in MJ, while the current study used MJ-eq. The chosen time horizon of the Karlsson et al. (2010) study was 60 years, while in the current study it was 100 years. Therefore here we normalised the data to the common functional unit- one metre of one lane of a tunnel structure per year.

According to Karlsson et al. (2010), the construction phase makes up 5% of total energy use of the tunnel life cycle, while the corresponding figure in the current study is 8%. The total energy use in Karlsson et al. (2010) is about 3700 MJ/year/lane-metre, while here it is 16500 MJ-eq/year/lane-metre. The differences in results can mainly be explained by the fact that Karlsson et al. (2010) considered secondary energy use, while the current study considered primary energy use (which included feedstock energy and accounted for electricity network losses). This corresponds to almost a factor three regarding energy use for operation. It also appears that the current study, due to the use of Bill of Quantities, achieves a more detailed coverage of all materials actually used in the construction phase.

A general policy implication from this paper is that GHG emissions and energy use related to infrastructure may be significant, and that it needs to be taken into consideration from the very start of the policy process. New road tunnels are often considered as a response to a perceived demand for increased road capacity in urban areas, where land prices are high. In some cases, an alternative approach to building tunnels might be to instead use available land and existing transport infrastructure in a more efficient way, e.g. by using congestion charging and adjusting parking charges to better reflect the true cost for 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 like tunnels. Due to the importance of the carbon intensity of electricity production for the total life-cycle emissions of a tunnel, such alternative strategies may obviously be especially important for countries/regions with a high carbon intensity in their electricity production.

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Appendices

Materials and processes included in LCA modelling

Table A-1 Specification of materials included in LCA modelling for construction phase of a rock tunnel

Processes	Elements and materials included
Piling, soil reinforcement (C)	
Soil Excavation (CBB) Rock Excavation (CBC)- Fall B Rock drilling (CBD) Soil reinforcement (CDB) Rock Anchoring (CDC) Grouting etc. (CDD); Filling, ground layers (CE)	excavated soil blasted rock steel steel (galvanized) steel (galvanized), steel (untreated), cement cement, chemical substance (polyurethane) crushed aggregates, gravel
Land superstructures, additional structures (D)	
Layers of geotextile, Styrofoam (DB) Land superstructures (DC) Prefabricated elements (DEF)	Polypropylene, Styrofoam Crushed aggregates, asphalt, concrete Steel (stainless), aluminium, plastics, electronics
Moulded structures on-site (E)	
Molds, bearing forms (EBB) Reinforcement etc (EBC) Concrete moulding (EBE) Shotcrete (sprayed concrete) (EBF) Molds for casting concrete (ESB) Reinforcing, casting etc (ESC) Concrete casting in house (ESE)	Wood Concrete (reinforced) Concrete Sprayed concrete, steel reinforcing Wood Steel (reinforcing) concrete
Construction of ready mounted elements (G)	
Mounted constructions (GB)	concrete
Constructions of long-formed elements (H)	
Metallic constructions (HSB)	Steel (galvanized)
Paint, protective coating (L)	
Painting (LC) Protective impregnation (LFB)	Acrylic paint Silicone-based impregnation substance
Appliances and pipes (P)	
Pipelines (PB) Wells (PD)	Ductile cast iron, stainless steel, concrete, polyethylene pipes, polypropylene pipes, concrete
Materials and processes which were not included in the bill of quantities:	
Lining, culvert	pp-fibre, polyethylene (LLDPE), sprayed concrete, steel (reinforcing), concrete
Asphalt layer	asphalt
Fuel/electricity consumption during construction phase	Diesel, electricity

Table A-1 shows phases from the preliminary bill of quantities which were included in LCA modelling for rock tunnel construction. Each phase and relevant to it processes are numbered by capital letters in the same way as in the bill of quantities.

Material and elements used during each process (which were included in LCA modelling) are shown in the second column.

Assumptions

Data in the preliminary bill of quantities are often provided in an aggregated form that cannot be directly used for LCA modelling. Thus additional calculations and assumptions were made in order to get quantities of materials suitable for LCA analysis. Table B-1 shows assumptions made for each type of material and phase indicated in the project's preliminary bill of quantities (BOQ).

Table B-2 and Table B-3 show assumptions made for materials and transportation modes when modelling in SimaPro.

Table B-1 Assumptions made when calculating material quantities from the preliminary bill of quantities (BOQ)

Material	Code of Phase/products	Assumptions	Waste factor	References
steel (galvanized)	CDB (safety net)	weight of a net is 1.7 kg/m²	5%	Minova (2010)
	CDC (bolts of galvanized steel)	weight of one bolt is assumed to be 3.85 kg/m	5%	VIK Orsta AS (2010)
	HSB (steel pillars)	No assumptions made, as the data in BOQ was provided in kg of steel	5%	BOQ
steel (reinforcing)	CDC (rock bolts)	weight of one bolt is assumed to be 3.85 kg/m	5%	VIK Orsta AS (2010)
	EBC (reinforcement steel)	No assumptions were made, as the data in BOQ was provided in kg of steel	5%	BOQ
	EBF (reinforcement)	No assumptions were made, as the data in BOQ was provided in kg of steel	5%	BOQ
	ESC (reinforcing steel)	No assumptions were made, as the data in BOQ was provided in kg of steel	5%	BOQ
	Tunnel lining	30 kg/m³ of shotcrete (spray concrete)	5%	Larsson (2010), Backe (2010)
steel (stainless)	SE (sign bridge)	weight of a sign bridge (in kg)- 100% stainless steel: 1-lane road- 122.4 kg 2-lane road- 214.2 kg 3-lane road- 321.3 kg	5%	Buvik et al (2008), Larsson (2010)
	PB(stainless steel pipe)	weight of a stainless steel pipe: 100*2 mm- 3 kg/m 300*4 mm- 7.8 kg/m 200 *3 mm- 5.2 kg/m 100*3 mm- 3 kg/m	N/A	von Matern (2004)
steel (untreated)	CDC (bolts of ¨ obehandlat stål ¨)	weight of one bolt is assumed to be 3.85 kg/m	5%	VIK Orsta AS (2010)
Steel (stainless)	Steel fibre for shotcrete (spray-concrete)	Quantity of steel fiber per m3 of shotcrete- 50 kg/m3 Density of shotcrete together with steel fiber- 2400 kg/m3 density of stainless steel fiber- 7910 kg/m3	N/A	Dalmalm (2010), Backe (2010)

ductile cast iron	PB (ductile iron pipe)	weight of a ductile iron pipe: DN 200- 43.3 kg/m DN 100- 21.5 kg/m	N/A	Gustavsberg Rörsystem AB (2010)
Aluminium	DEF (signs)	Weight of a sign (aluminium- 90%, 10%- electronics, plastics): 1-lane road- 489.6 kg 2-lane road- 856.8 kg 3-lane road- 1285.2 kg	N/A	Buvik et al (2008), Larsson (2010)
cement, Portland	CDC(bolts fixing)	Calculated the volumes of cement having the following values: water/cement ratio- 0.3	30%	Dalmalm (2010), Backe (2010)
	CDD (grouting)	No assumptions were made, as the data in BOQ was provided in kg of steel	30%	BOQ
Shotcrete (spray concrete)	CD (soil reinforcement work)- only for access tunnel	The volume (in m3) is calculated by multiplying the thickness and area of the steel fibre-reinforced shotcrete layer	10%	BOQ
	EBF (shotcrete)	The volume (in m3) is calculated by multiplying the thickness and area of the steel fibre reinforced shotcrete layer	10%	BOQ
	Tunnel lining	The thickness of pp-fibre reinforced shotcrete (spray concrete) for tunnel lining= 0.12 m	10%	Dalmalm (2010), Backe (2010), Larsson (2010)
Concrete	DCG (concrete plates)	Density of concrete= 2400 kg/m3 weight of a concrete plate-114.4 kg/m2	5%	DSI (2010)
	EBE (concrete moulding)	Amounts of concrete (water/cement ratio <0.40 and water/cement ratio <0.55) are given in m^3	5%	BOQ
		Concrete (reinforced) used for fans concrete base- 2 m^3/piece	5%	Backe (2010)
		Concrete (reinforced) used for measuring ponds- 3.2 m^3/piece	N/A	Dalmalm (2010)
	ESE (concreting in house)	Concrete water/cement <0.55- data are given in m^3 Reinforcement is taken into account in BOQ	5%	BOQ
	GB (mounted constructions- socket elements)	Data on amount of reinforced concrete are provided in ton	N/A	BOQ
	PB (Concrete pipes)	Concrete (unspecified), weight of a concrete pipe, A=300 mm- 80 kg/m not reinforced	N/A	KCG (2010)
	PD (Wells)	Weight of wells: Concrete well: 1250 kg/piece Ivar 1B (concrete well)- 3000 kg/piece Ivar 2 (concrete well)- 6360 kg/piece Concrete well (D 600 mm)- 600 kg/piece Concrete well (D 400 mm)- 250 kg/piece Plastic well (D 400 mm)- 250 kg/piece	N/A	Dalmalm (2010), Alfarör (2010)

	Culvert element	The culvert element is 15 cm wide and 5 m high Reinforced concrete	N/A	Backe (2010)
crushed aggregates	CE (filling, ground layers) DCB (unbound layers)	All blasted rock- crushed aggregates(with average density - 2.7 ton/m3 Average density of soil (fixed volume)- 2 ton/m3	N/A	Backe (2010) Stripple (2001)
gravel	CE (filling, ground layers)	Density of gravel- 2.7 ton/m^3	N/A	Persson (1998)
asphalt	DCC	density of asphalt concrete-2.24 ton/m3	5%	
polystyrene	DB (Styrofoam)	Thermic isolation-polystyrene, 30 kg/m3	N/A	Byggtjänst (2010)
polypropylene	DB (geotextile)	Weight of different classes of geotextile: N1- 112 g/m2 N2- 155 g/m2 N3- 227 g/m2 N4- 295 g/m2 N5- 395 g/m2	N/A	Byggtjänst (2010)
	PB (pipelines)	PP-pipes (polypropylene): Dim 160- 6.38 kg/m Dim 250- 15.5 kg/m Dim 315- 24.6 kg/m ADR 200 (dim 200 mm)- 9.95 kg/m A 110- 3.01 kg/m	N/A	Georg Fischer (2010)
	PD (wells)	A plastic well (with dim 400 mm) has a weight of about 250 kg/piece	N/A	Alfarör (2010)
	Tunnel lining	1.2 kg of pp-fibre per m^3 of spray concrete density of pp-fiber 910 kg/m3 density of shotcrete with pp-fiber 2300 kg/m3	N/A	Backe (2010)
polyethylene	PB (pipes)	PE-pipes, all different pipes indicated in BOQ are assumed to be the same (with diameter 110, and weight- 2.19 kg/m)	N/A	GPA (2010)
polyethylene (LLDPE)	Tunnel lining	Thickness- 0.0015 m	N/A	Backe (2010), Dalmalm (2010)
chemical substance- polyurethane	CDD (grouting)	No assumptions were made, as the data in BOQ was provided in kg of a chemical substance	N/A	BOQ
silicone	LFB (protective silicone-based impregnation)	quantity of silicone used for impregnation liquid- 4 m2/l	N/A	Beckers (2010)
acrylic varnish	LCS (painting)	use of paint (on the example of the paint - silicon modified acryl-latex paint)- 5 m2/l- average is taken (from the range 4-6 m2/l), weight per litre of acrylic paint- 1.3 kg/l	N/A	Alibaba (2010)
Wood (sawn timber formwork)	EBB (formwork)	0.084 m3/m2 of wood	N/A	Backe (2010), Dalmalm (2010)
	EBE (wood for temporary measuring ponds)	0.084 m3/m2 of wood	N/A	Backe (2010), Dalmalm (2010)
	ESB (moulds for casting concrete)	0.084 m3/m2 of wood	N/A	Backe (2010), Dalmalm (2010)

glass fibre	CDC (bolts)	0.88 kg/m is the weight of a bolt with dim 25 mm	N/A	DSI (2010)
explosives	CB (rock blasting)	Assumed to be slurries, with the rate of use- 2 kg/m3 of blasted rock	N/A	Dalmalm (2010)
Drilling for blasting	CBD (rock blasting)	One meter per m3 of blasted rock and meters specified in BOQ	N/A	Harryson (2010)

Table B-2 Assumptions for each group of materials in SimaPro modelling

Material	Varieties	Assumptions
Steel	Steel-galvanized	Based on inventory data provided by Stripple (2001)
	Steel reinforcing	Based on inventory data provided by EcoInvent for ¨Reinforcing steel at plant¨
	Steel stainless	Based on inventory data provided by EcoInvent for ¨X10Cr13-Stainless steel applied for cutlery and bolts and nuts¨
	Steel (untreated)	Based on inventory data provided by EcoInvent for ¨Construction steel- Fe360I¨
Ductile cast iron		Based on inventory data provided by EcoInvent for ¨Cast iron-GG15 I¨
Aluminium		Based on inventory data provided by EcoInvent for ¨Aluminium, production mix, wrought alloy¨
Portland cement		Based on inventory data provided by EcoInvent for ¨Portland cement, strength class Z 42.5, at plant¨
Concrete, spray concrete		Based on inventory data provided by EcoInvent for ¨Concrete, exacting, at plant, in m3¨
Gravel		Based on inventory data provided by EcoInvent for ¨Gravel from pit¨ (with Nordic electricity mix)
Crushed aggregates		Based on inventory data provided by Stripple (2001)
Asphalt		Based on inventory data provided by Stripple (2001)
Polyethylene	PE-pipes	Based on inventory data provided by EcoInvent for ¨HDPE-pipes¨
	LLDPE-lining	Based on inventory data provided by EcoInvent for ¨LLDPE-resin E¨
Diesel		Based on inventory data provided by EcoInvent for ¨Diesel, burned in building machine S ¨
Electricity		Based on inventory data provided by EcoInvent for ¨Electricity, Swedish, at grid, with imports ¨
polystyrene		Based on inventory data provided by EcoInvent for ¨Polystyrene, general purpose, at plant¨
wood		Based on inventory data provided by EcoInvent for ¨Sawn timber, Scandinavian softwood, raw, plant-debarked, u=70%, at plant/NORDEL¨
polypropylene (geotextile and PP-pipes)		Based on inventory data provided by EcoInvent for ¨PP ETH U¨
explosives		Based on inventory data provided by EcoInvent for ¨Explosives ETH U¨

Table B-3 Assumptions regarding the type of material transportation in SimaPro modelling

Material	EcoInvent Inventory	Distances
Assumed for all types of steel	Road: Transport, Lkw >32t, EURO5 Water: bulk carrier- Marine transport of ore, coal, wood, vehicles and other cargo.	All steel is transported from Poland (approximately 530km by water transport and 500km by truck)
cement	Road: Transport, Lorry>32t, EURO5 Water: bulk carrier- Marine transport of ore, coal, wood, vehicles and other cargo.	10 km by truck and 150 km by water
Shotcrete, concrete	Road: Transport, lorry >32t, EURO5	150 km (as an average for transportation)

Crushed aggregates, gravel	Transport, Lkw >32t, EURO5	Crushed aggregates- 20 km, gravel-30 km
Blasted rock	Transport, Lkw >32t, EURO5	20 km
asphalt	Transport, Lkw >32t, EURO5	10 km
explosives	Truck 28t B250, fleet average	240 km
wood	Transport, lorry >32t, EURO5	500 km by truck

Electricity choice for sensitivity analysis

Table C-1 Modelling of electricity mix

Inputs for production of marginal future-low electricity, 1 kWh (Finnveden, 2008)		
Electricity, at wind power plant/RER S	0.2179	kWh
Electricity, nuclear, at power plant/UCTE S	0.2309	kWh
Heat, at cogen, biogas agricultural mix, allocation exergy/CH S	0.3572	kWh
Electricity, hard coal, at power plant/NORDEL S	0.0077	kWh
Electricity, at cogen 1MWe lean burn, allocation heat/RER S	0.1995	kWh
Electricity, hydropower, at power plant/SE S	0.001	kWh
Electricity, oil, at power plant/SE S	-0.0141	kWh
Inputs for production of marginal future-high electricity, 1 kWh (Finnveden, 2008)		
Electricity, at wind power plant/RER S	0.1132	kWh
Electricity, nuclear, at power plant/UCTE S	0	kWh
Heat, at cogen, biogas agricultural mix, allocation exergy/CH S	0.0053	kWh
Electricity, hard coal, at power plant/NORDEL S	0.5999	kWh
Electricity, oil, at power plant/SE S	0.0303	kWh
Electricity, at cogen 1MWe lean burn, allocation heat/RER S	0.2533	kWh
Inputs for production of marginal electricity base case 2030, 1 kWh (Energimyndigheten, 2006)		
Electricity, at cogen 1MWe lean burn, allocation energy/RER S	0.95	kWh
Electricity, hydropower, at power plant/SE S	0.09	kWh
Inputs for production of marginal electricity 2010 , 1 kWh (Energimyndigheten, 2006)		
Electricity, hard coal, at power plant/NORDEL S	0.82	kWh
Electricity, hydropower, at power plant/SE S	0.18	kWh
Inputs for production of future electricity average mix Sweden 2030, 1 kWh (Energimyndigheten, 2009)		
Electricity, hard coal, at power plant/NORDEL S	0.003431	kWh
Electricity, peat, at power plant/NORDEL S	0.000572	kWh
Electricity, oil, at power plant/SE S	0.001715	kWh
Electricity, natural gas, at power plant/NORDEL S	0.005146	kWh
Electricity, industrial gas, at power plant/NORDEL S	0.01315	kWh
Electricity, hydropower, at power plant/SE S	0.388794	kWh
Electricity, nuclear, at power plant/UCTE S	0.413951	kWh
Electricity, at wind power plant/RER S	0.038308	kWh
Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH S	0.097199	kWh
Electricity, at cogen with biogas engine, allocation exergy/CH S	0	kWh
Electricity, at cogen 1MWe lean burn, allocation exergy/RER S	0.037736	kWh