



**NTNU – Trondheim**  
Norwegian University of  
Science and Technology

# Life Cycle Assessment of Technical Solutions for High-Speed Rail: Tunnel and Track designs

**Anne Margrethe Lia**

Master in Industrial Ecology

Submission date: June 2012

Supervisor: Edgar Hertwich, EPT

Co-supervisor: Johan Pettersen, MiSA

Norwegian University of Science and Technology  
Department of Energy and Process Engineering



EPT-M-2012-57

**MASTER THESIS**

for

student Anne Magrethe Lia

Spring 2012

**Life cycle assessment of technical solutions for high-speed rail: tunnel and track designs***Livssyklusanalyse av tekniske løsninger for høyhastighetstog: tunell og spor design***Background and objective**

Life-cycle assessment studies for conventional and high-speed rail (HSR) in Norway show that the rail infrastructure stands for the major part of emissions, due to availability of low-emission electricity production. The consequence is that the way in which the infrastructure is developed controls a large part of the environmental footprint of rail solutions.

In a recently completed assessment of proposed HSR concepts for Norway, two particular issues have been found to be highly significant for the total environmental impacts from infrastructure construction: track bed and tunnel designs.

The project aims to evaluate the importance of track and tunnel designs for the total environmental impact of a Norwegian HSR concept. The work brings together an existing LCA model for Norwegian HSR compiled by MiSA, with new inventories established for track solutions in a recent student project. A soon to be completed LCA project for the Follobanen railway tunnel will make available updated inventories for tunnel blasting and drilling, which may be adapted for HSR concepts based on the technical documents issued in the ongoing Norwegian HSR assessment.

**The following tasks are to be considered:**

1. Implement available inventories to the existing HSR LCA model
  - a. Slab and ballast track inventories, from the recent student project
  - b. Tunnel drilling and blasting inventories, from the Follobanen project
2. Investigate sensitivity in tunnel parameters
  - a. Tunnel dimensions
  - b. Materials, designs, and other factors
  - c. Technical lifetime and maintenance programs
3. Compare relevant HSR line concepts
  - a. Develop a parameterized model for track and tunnel designs
  - b. Investigate the importance of technical solutions for HSR tunnel and track designs

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

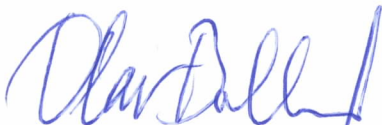
The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

Department of Energy and Process Engineering, 16. January 2012



---

Olav Bolland  
Department Head



---

Edgar Hertwich  
Academic Supervisor

Research Advisor and External Contact:  
Dr. Johan Pettersen, MiSA as

## PREFACE

This report was submitted to the institute of Energy and Process Engineering at the Norwegian University of Technology and Science (NTNU), as part of the MSc in Industrial Ecology. Further, this thesis has been a collaboration project between NTNU and MiSA, and was supervised by Edgar Hertwich (NTNU), and Johan Pettersen (MiSA).

This master's thesis would not have been possible to complete, if not for great guidance and motivating feedback from my supervisors. I would therefore like to thank Edgar and Johan for their time and encouragement through this process.

I have had the privilege of writing my thesis at the MiSA office, which have been a very positive and educational experience. I would especially like to thank Håvard Bergsdal and Christine Hung for answering all my questions with thoroughness and a smile. I particularly want to thank Christine who volunteered to proofread parts of the thesis.

Further, I would like to thank Bjørnar Gammelsæter from the Norwegian National Rail Administration and Pål Drevland Jakobsen, PhD. Candidate at the department of Civil and Transport Engineering at NTNU, for offering of their time to answer my questions. For this I am very grateful.

I am very also very fortunate to have Simon, my sister and my father in my life, who help pushing me further, whenever I need it. I especially want to thank Simon for spending his Sunday helping me with the finishing touches of this thesis, and providing me with enough motivation to finally conclude this chapter.

Anne Margrethe Lia

Trondheim, June 2012



## ABSTRACT

On the 19<sup>th</sup> of February 2010, the Ministry of Transport and Communication presented the Norwegian National Rail Administration with the task of assessing different aspects of the future of high-speed rail in Norway. The report, the Norwegian High-Speed Rail Assessment (NHSRA), consist three separate evaluations where the climate assessment by Bergsdal et al. (2012), motivated this thesis. Results from the report identify the railway infrastructure as the dominant emission source for the corridor, with the length of tunnels representing the determining factor.

Simultaneously, an ongoing debate is comparing the safety and performance of track and tunnel technologies traditionally used in Norway to that of foreign tunnelling technology such as the drill and blast method which apply a full cast (European method), and a double shielded tunnel boring machine (TBM). The newest development in track technology is the slab track, which is now evaluated for tunnels and bridges in Norway (Jernbaneverket 2011).

This thesis contributes to the ongoing debate concerning the construction of infrastructure for high-speed rail in Norway, by emphasizing the environmental impact of several relevant technologies and geological conditions. The assessment includes an evaluation of the impact of different tunnelling and track technologies, calculated for operation speeds of both 250km/h and 330km/h. Further, the environmental impact of different levels of support work and grout is assessed. In addition, this thesis includes a sensitivity analysis of the impact of service life for railway components. The assessment is calculated for two functional units: one meter tunnel and tunnel track, and for the case corridor, the potential high-speed rail corridor between Oslo-Stavanger, estimated for 250km/h obtained from the NHSRA by Bergsdal et al. (2012).

Our results from this assessment account for the use of cement, steel and copper as the environmentally most important materials. Among the railway components, the tunnel lining and grout constitute the highest emission level of the case corridor.

The different technical alternatives are compared against the technologies traditionally applied in Norway, and an average level of support work, which represents the baseline results of this thesis. Our results indicate that the double shielded tunnel-boring machine is the technology that contributes to the highest increase of emission level compared to baseline. Further, the variables that hold the greatest potential of reducing total emission level is the installation of slab track in tunnels and bridges, and level of grout in the tunnel construction.

## ABSTRAKT

Den 19. februar, 2010 gav Samferdselsdepartementet, Jernbaneverket oppgaven å evaluere potensialet for fremtidige høyhastighetstog i Norge. Høyhastighetsutredningen ble slutført og publisert i februar i år (2012).

Klimarapporten fra høyhastighetsutredningen, skrevet av Bergsdal et al. (2012), består av livsløpsanalyser for tolv ulike alternativer for høyhastighetskorridorer i Norge. Analysene viser at infrastrukturen står for hovedandelen av det totale utslippet for korridorene. Av dette er det tunnelkonstruksjon som utgjør den avgjørende faktoren.

Samtidig foregår det en offentlig debatt vedrørende valg av teknologi for fremtidig jernbaneutbygging, hvor det settes spørsmålsteget til den tradisjonelle, norske metoden for tunneldriving. En metode mye brukt i Europa er en tunnel med full utstøpning. Denne vurderes nå for alle tunneler av høyt bruk i Norge. I tillegg vurderes også økt bruk av tunnelboremaskiner (Jernbaneverket 2008). Den nyeste sporteknologien, fastspor, som til motsetning fra den tradisjonelle laget med ballast består av en solid betongplate, vurderes nå for bruk i tunneler og bruer (Jernbaneverket 2011).

Vi bidrar gjennom denne oppgaven til debatten vedrørende valg av teknologi for infrastruktur til et fremtidig høyhastighetsprosjekt i Norge, ved å legge vekt på miljøaspektet ved de ulike løsningene. Analysen består av en evaluering av miljøpåvirkningen av ulike tunnel – og spor konstruksjoner dimensjonert både for 250km/h og 330km/h. Videre evalueres miljøpåvirkningen av ulike nivåer for bergsikring og injeksjonssement. I tillegg har vi gjennomført en sensitivitetsanalyse for levetid av jernbanekomponenter. Resultatene har vi beregnet for to ulike funksjonsheter, først for en meter tunnel og tunnelspor, deretter for den utvalgte korridoren mellom Oslo og Stavanger og estimert for 250km/h, hentet fra Bergsdal et al. (2012)

Våre resultater fra analysen viser at stål, sement og kobber er de miljømessige viktigste materialene. Videre på et komponentnivå, er det tunnelhvelvet og mengde injeksjonssement for tunnelen som utgjør hovedandelen for totalutslippet for korridoren mellom Oslo og Stavanger.

Videre sammenligner vi resultatene fra våre beregninger med de teknologiene som tradisjonelt brukes i Norge, den norske drivemetoden og i tillegg et gjennomsnittlig nivå for bergsikring. Våre resultater viser at tunnelboremaskinen er den teknologien som resulterer i relativt høyest utslippsøkning sammenlignet med den norske drivemetoden. Variablene som derimot representerer det største reduksjonspotensialet representeres av mengde injeksjonssement for tunnelkonstruksjoner og fastspor for tunneler og bruer.



# Content

List of Tables .....	3
List of Figures.....	4
List of Abbreviations.....	5
Vocabulary .....	6
1. Introduction .....	7
2. Life Cycle Assessment.....	11
Phase 1 - Goal and Scope Definition.....	11
Phase 2 – Inventory.....	12
Phase 3 – Impact Assessment.....	12
Phase 4 – Interpretation .....	12
3. Description of Technologies .....	13
3.1 Track Bed Designs for High-Speed Rail in Norway.....	13
3.2 Tunneling Technology.....	14
3.2.1 The Drill and Blast Method .....	14
3.2.2 Tunnel Boring Machines.....	16
3.3 Drilling and Blasting versus the Tunnel Boring Machine.....	17
3.4 Rock Support and Waterproofing .....	18
3.5 Securing Methods .....	19
3.5.1 Rock Bolts .....	19
3.5.2 Shotcrete.....	19
3.5.3 Full Cast .....	20
3.5.4 Grouting.....	20
3.5.5 Ring Beams and Floor Cast.....	20
3.5.6 The Q – Method.....	20
3.5.7 Lining .....	21
3.6 Securing methods and the Ongoing Debate on Tunneling Technologies .....	21
4. Goal and Scope.....	23
4.1 Research Question .....	23
4.2 Functional Unit .....	23
4.3 Calculation Method for Component Service Life.....	24
4.4 System Boundary .....	26
4.4.1 System Boundary to Technology and Processes .....	26
4.4.2 System Boundary to Environment .....	28

5.	Life Cycle Inventory .....	32
5.1	Track Bed .....	32
5.1.1	Maintenance .....	33
5.2	Tunneling Method.....	33
5.2.1	Tunnel Profile and Estimated Corridor Speed.....	36
5.2.2	Grouting.....	37
5.2.3	Rock Securing .....	38
5.3	Additional Tunnels .....	39
5.4	Maintenance.....	39
6.	Results and Impact analysis.....	40
6.1	Establishing the Baseline Results .....	40
6.2	Impact of Technological and Geological Change for Functional Unit 1: One Meter of Tunnel and Tunnel Track.....	43
6.2.1	Track Technology .....	43
6.2.2	Tunnelling Technologies.....	44
6.2.3	Geological Conditions and Requirements – The Q-Method.....	50
6.2.4	Geological Conditions and Requirements – Grouting.....	51
6.2.5	Additional Tunnels.....	52
6.3	Environmental Impact for the Functional Unit 2: The Case Corridor Between Oslo and Stavanger.....	53
6.3.1	The Use of Slab Track in Tunnels and on Bridges .....	53
6.3.2	Tunnelling Technologies.....	54
6.3.3	Geological Conditions and Requirements – Q-method.....	57
6.3.4	Geological Conditions and Requirements – Grouting.....	58
6.3.5	Additional Tunnels.....	59
7.	Interpretation.....	60
7.1	Comparative Analysis.....	60
7.2	System Path Analysis of the Three Assessed Tunnel Technologies.....	62
7.3	Sensitivity Analysis.....	66
7.3.1	Sensitivity of Component Service Life .....	66
7.3.2	Sensitivity of Method for Service Life Calculations.....	68
8.	Discussion.....	70
8.1	Modelling Service Life.....	70
8.2	Choice of Tunnelling and Securing Methods.....	71
9.	Conclusions .....	73
9.1	Further Research.....	77

10. References.....	79
Appendices.....	83
Appendix I – Densities .....	83
Appendix II – Calculation of the volume of gravel for a double track.....	84
Appendix III – Relevant Impact Categories for a Tunnel Project.....	85
Appendix IV – The Q-Method.....	86
Appendix V – Volume of Cement Injection and Rock Quality.....	89
Appendix VI – Volume of Materials for Support Work.....	90
Appendix VII – Comparing the SimaPro Process for Blasting.....	91
Appendix VIII – System path analysis of the Double Shielded TBM and the European Tunneling Method.....	92
Appendix IX – Comparative Analysis, Functional Unit 2 .....	96
Appendix X – List of Parameters for the SimaPro Model.....	97

## LIST OF TABLES

Table 1 Inventory for track bed.....	33
Table 2 Service life, track bed .....	33
Table 3 Inventory for tunneling methods.....	35
Table 4 Tunnel dimensions.....	36
Table 5 Inventory for the five levels of grout .....	37
Table 6 Inventory for the Q-method. ....	38
Table 7 Additional tunnels.....	39
Table 8 Material requirements for additional tunnels per meter of the respective tunnel.....	39
Table 9 Comparative results, FU1. ....	60
Table 10 Service life of track components.....	66
Table 11 Service life scenarios, results.....	67
Table 12, Density of materials.....	83
Table 13, Calculation of ballast volume for a double track .....	84
Table 14 Relative importance of environmental aspects. ....	85
Table 15 The Q - system.....	86
Table 16 Volume of cement for grouting.....	89
Table 17 Properties of the Borsttagbolt .....	90
Table 18 Properties of ring beams .....	90
Table 19 Comparative results, FU 2.. ....	96
Table 20 List of parameters developed for the parameterized SimaPro model applied for this thesis. 98	

## LIST OF FIGURES

Figure 1 Case corridor. ....	9
Figure 2 The framework of an life cycle assessment (LCA).. ....	11
Figure 3 A ballasted railway track .....	13
Figure 4 The RHEDA 2000 slab track design .....	14
Figure 5 Step by step illustration of the drill and blast tunneling method .....	15
Figure 6 The double shielded tunnel boring machine .....	16
Figure 7 Potential tunnel damage.....	18
Figure 8 Rock bolting. ....	19
Figure 9 The Q-method simplified.....	22
Figure 10 Method for service life calculation used for the Follo Line. ....	24
Figure 11 Method for service life calculations used for this thesis.....	25
Figure 12 System model for this thesis. ....	27
Figure 13 Impact aspects. ....	29
Figure 14 Endpoint results.. ....	30
Figure 15 Selected midpoint categories and indicators. ....	31
Figure 16 Illustration of the tunneling methods.....	34
Figure 17 Baseline results, functional unit 1.....	40
Figure 18 Baseline results, functional unit 2.....	42
Figure 19 Comparing ballasted and slab track design.. ....	44
Figure 20 Compare the relative impact of the three assessed tunneling methods.....	45
Figure 21 Comparing one meter of tunneling technology 330km/h. ....	47
Figure 22 Comparing tunnel maintenance. ....	48
Figure 23 TBM lining. ....	49
Figure 24 TBM segment size. ....	50
Figure 25 Level of support work FU1. ....	50
Figure 26 Level of grouting FU1. ....	51
Figure 27 Additional tunnels FU1. ....	52
Figure 28 Track design FU2. ....	54
Figure 29 Tunneling methods, FU2. ....	55
Figure 30 Tunneling technology 330km/h. FU2.....	56
Figure 31 Level of support work FU2.. ....	57
Figure 32 Level of grouting, FU 2. ....	58
Figure 33 Additional tunnels, FU2. ....	59
Figure 34 Comparative results, FU1. ....	60
Figure 35 System path analysis, baseline scenario, climate change .....	63
Figure 36 System path analysis, baseline scenario, human toxicity .....	65
Figure 37 Service life scenarios. ....	67
Figure 38 Sensitivity of service life calculation.....	68
Figure 39 Q-method, classification of rock quality .....	88
Figure 40 Process for blasting.....	91
Figure 41 System path analysis, European tunnel technology, climate change.....	92
Figure 42 System path analysis, double shielded tunnel boring machine, climate change.....	93
Figure 43 System path analysis, European tunnel technology, human toxicity.....	94
Figure 44 System path analysis, double shielded tunnel boring machine, human toxicity.....	95
Figure 45 Comparative results, FU2 .....	96

## LIST OF ABBREVIATIONS

D & B	Drill and blast
FU1	Functional unit 1
FU2	Functional unit 2
HSR	High-speed rail
JBV	The Norwegian National Rail Administration
NHSRA	Norwegian High-Speed Rail Assessment
NPRA	Norwegian Public Roads Administration
S8:Q	The HSR alignment estimated for 250km/h between Oslo-Stavanger by Bergsdal et al. (2010)
SL	Service life
TBM	Tunnel boring machine

## VOCABULARY

<b>English</b>	<b>Norwegian</b>
Adit	Tverrslag
Ballasted track	Ballastspor
Cast	Utstøpning
Concrete membrane	Betong membran, Brukes for Europeisk tunnel
Concrete segments	Metong segmenter, brukes for TBM tunnel
Cross section	Tverrforbindelse/tverrsnitt
Environmental account	Miljøbudsjett
European	Europeisk tunneldrivemetode, også kalt sveitsisk. Beskriver en fullt utstøpt tunnel med bergsikring.
Fissures	Sprekker
Floor cast	Utstøpning for gulvet i tunnelen
Gravel	Grus/ballast
Grout/ cement grout	Injeksjonssement
Jointed rock	Oppsprekket berg
Lining grout	Betong masse som brukes til å tette mellom og bak betongsegmenter for en TBM tunnel
Norwegian	Norsk tunneldrivemetode. Beskriver frittstående betongelementer og bergsikring
permeability	Gjennomtrengelighet
Pre-bolting	Forbolting
Pre-injection	See grouting
Rebar	Armeringsjern
Reinforced ring beams	Armerte betongbuer
Scaling	Rensk
Securing level	See: support work
Slab track	Fastspor
Sleeper	Sville
Stuff	Stuff, the inner wall of the tunnel
Support work	Bergsikring
Tunneling method	Drivemetode

# 1. INTRODUCTION

As the regulations for emission reduction become more demanding, more efficient modes for transportation are becoming increasingly important. Traveling by railway is considered to be one of the most efficient means of transportation and is thus a focus for development and growth in many countries. The Norwegian geography, with its long mountainous ranges, makes train a less appealing choice for consumers in comparison to cheap flights, which take much less time. The realization of such a transition, from airplanes and cars to trains, will therefore require a modernization of the current railway with an emphasis on speed and comfort.

## *Motivation for the Report*

The introduction of high-speed rail system is assumed to represent a good incentive to induce for a mode change toward trains, thus the issue has been under debate in Norway for several years. The first approach to a high speed rail line was the corridor between Oslo Central Station (Oslo S) and Oslo airport, Gardermoen. The train however, only reach a speed of 200km/h over the corridor, which is considered at the lower range of speed, in an international perspective (Tempo 2012).

On February 19<sup>th</sup>, the Ministry of Transport and Communication presented the Norwegian National Rail Administration (JBV) with the task of assessing the future of high-speed rail in Norway. The assessment was to consider both positive and negative impacts on the cost, construction strategy and the environment. The report was completed in February 2012 and consisted of several aspects of high speed rail, including the climate assessment by Bergsdal et al. (2012) that motivated this thesis. The report constitutes a life cycle assessment for twelve proposed high-speed corridors. The different alignments are estimated for both operational speeds of 250 and for 330km/h, depending on the geographic location. Results from the report identify the railway infrastructure as the dominant emission source for the corridor, with the length of tunnels representing the determining factor.

Further, a project was performed by Korsmo and Bergsdal (2010), which consisted of an environmental account of the proposed Follo Line, which is a new railway project under development. The results indicate that steel and cement constitute the most important materials from an environmental perspective. The report further presents a material inventory for the Norwegian tunneling method as calculated for the specific requirements of the tunnel, which is part of the Follo Line corridor.

Simultaneously, an ongoing debate is comparing the safety and performance of track and tunnel technologies traditionally used in Norway to that of foreign tunneling technology. The traditional rail track used in Norway is the ballasted track that consist of concrete sleepers placed on a bed of gravel (Løhren 2011). The newest development is the slab track, which instead of gravel, consists of a solid concrete foundation (Ogilvie & Quante 2001).

Norway's mountainous geography has, over the years, required a vast amount of tunnels in order to build effective routes for transportation. The Norwegian tunneling method is thus considered among the elite of the tunneling society and are especially known for their knowledge for support work and grouting technology (Nilsen 2011).

The quality of the Norwegian method, strongly relies on the knowledge and thoroughness of the constructor, and represents a technology the Norwegian tunneling society is proud of. However, due to several reasons, including an accident in the Hanekleiv tunnel in 2006, the safety of these methods has been questioned. A proposal state that the methods applied in other European countries which

include a full cast also should be used in Norwegian tunnels. This method requires considerably less dependence on the knowledge and experience of the construction contractors. Tunneling specialists therefore fear that the implementation of this new technology will weaken the faith in the Norwegian tunneling expertise and the craftwork itself (Seehusen 2012). In addition, since Norway has, in the past, specialized within drilling and blasting (D&B) methods, a different tunneling method that uses a tunnel boring machine has received less attention in Norway. However, the tunnel boring machine is now under consideration for use in the proposed Follo Line (Jernbaneverket 2008).

As a result of this debate, an inventory for the tunnel on the Follo Line has been compiled both for the European method (Vianova 2011a) and a double shielded tunnel boring machine (Vianova 2011b) in order to compare the impact of the different methods. Subsequently, a recent student project established material inventory for different ballasted and slab track solutions for high speed rail (Lia 2011)

In the wake of the Norwegian High-Speed Rail Assessment, the focus has been shifted somewhat towards intercity trains, as these are less expensive, have a lower environmental impact and a shorter payback time both economically and environmentally. These corridors are estimated for 250km/h (Jernbaneverket 2012c), which is also the speed applied to corridors that are used for multiple purposes (Gammelsæter 2012), that is, both passenger and freight trains.

### ***The Case Corridor***

The report by Bergsdal et al. (2012) assesses 12 different HSR corridors, all of which have Oslo S as the origin terminal. Two of the alignments end up in Trondheim, six head to Stavanger, where two take the path south through Kristiansand, four west through Bergen, and four east to Sweden (Stockholm and Gothenburg) (Bergsdal et al. 2012).

The corridor with the highest potential in an environmental perspective is one of the corridors to Trondheim with a payback period of 36 years. However, since the south corridor, going from Oslo to Stavanger via Tønsberg and Kristiansand, is projected to have the highest number of passengers, this corridor is assessed to have the most relevant construction potential. This corridor, OSLO – STV would result in an estimated travel time of 3:20 – 3:30h depending on speed and stops at specific places (Stillesby & Botnen 2012).

There are two assessed corridors for the distance between Oslo and Stavanger. One is estimated for 250km/h (labeled S8:Q) and the second for 330mk/h (labeled S2:P).

According to a specialist from the JBV, corridors considered for multiple uses, are most likely be designed for 250km/h (Gammelsæter 2012). As a consequence of the increased focus on intercity trains, which are more likely to run on these multi-use corridors, we decided that the corridor labeled S8:Q, from Oslo-Stavanger and estimated for 250km/h, will constitute the case corridor for which we will test the changes in technology and geology is tested, for this thesis.

The case corridor has a total length of approximately 461 km, of which 207 km is open section, 246 km consists of tunnels and the remaining 7.7 km are bridges of varying sizes. This presents a corridor where about 53% of total track length is made up of tunnels. Further, the corridor consists of 14 passing loops, 14 platforms and 184 rail switches.



Figure 1 presents the relative impact of the different railway components for the case corridor as presented in the report by Bergsdal et al. (2012). The figure includes the construction, the maintenance and the operation phase. The result is an emission level, just below 9 million ton CO<sub>2</sub>, estimated for the life cycle phase of 60 years. The tunnel is clearly the dominant factor in the figure, followed by the operation of the train and the track structures.

Emissions of approximately 9 million ton CO<sub>2</sub> eq. represents approximately 1.8 million ton CO<sub>2</sub> eq. per capita divided over the life cycle of 60 years, if one assumes a national population of 5 million people in 2012 (SSB 2012).

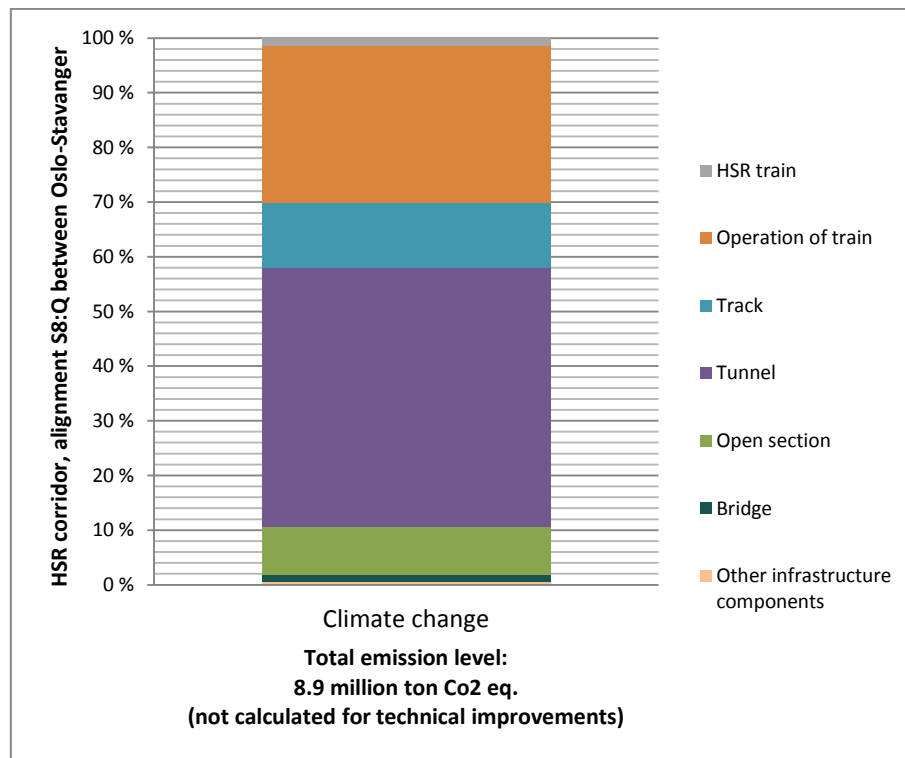


Figure 1 Case corridor. Total emission level for the HSR corridor between Oslo-Stavanger. The corridor represents alignment S8:Q, which is one of twelve alignments assessed for the Norwegian High Speed Rail Assessment (Bergsdal et al. 2012). “The HSR” train and “Operation of train” represent the operation phase of the corridor. The remaining components indicate the construction and maintenance of the different infrastructure component. “Other infrastructure” constitutes platforms, rail switches and passing loops.

### *Strategy and Content*

This thesis contributes to the ongoing debate concerning the construction of infrastructure for high-speed rail in Norway, by emphasizing the environmental impact of several relevant technologies and geological conditions. Through this thesis we thus answer the following research questions:

- To what extent is the emission level presented for the case corridor from Oslo to Stavanger in Bergsdal et al. (2012) affected by the following changes in technology and geology:
  - Design requirements for increased speed (250km/h and 330km/h)
  - Track technology (ballasted and slab track)
  - Tunneling technology (Norwegian, European, Double Shielded TBM)
  - Geology (level of support work and grout)

- Which of the system processes are the main sources of emissions?
- What is the relevance of the service life calculations applied to the inventory?

The different technical alternatives are compared against the technologies traditionally applied in Norway, and an average level of support work, which represents the baseline of this thesis. In this thesis our results are calculated for two functional units that both include all activities that occur within the estimated life cycle of 60 years:

Functional unit 1: One meter tunnel and tunnel track

Functional unit 2: The case corridor between Oslo-Stavanger, including all measurements for tunnel, bridge and length of open sections as presented in Bergsdal et al. (2012).

### ***Results***

In this thesis we present a comparison between different technological and geological solutions for high speed rail. This we have completed by performing several adjustments and expansions (presented in detail in Section 4.4.1) of the process model developed by Bergsdal et al. (2012) For the Norwegian High-Speed Rail Assessment (NHSRA). Our results from this assessment account for the use of cement, steel and copper as the environmentally most important materials. Among the railway components, the tunnel lining and grout constitute the highest emission level of the case corridor. Further, our results indicate that the double shielded tunnel-boring machine is the technology that contributes to the highest increase of emission level compared to baseline. Further, the variables that hold the greatest potential of reducing total emission level is the installation of slab track in tunnels and bridges, and level of grouting for tunnels.

### ***Structure of the Report***

After the introductory section we continue by presenting a brief overview of the life cycle assessment method in Section 2. In Section 3 we give an introduction to the different technologies assessed in this thesis. Subsequently we present a brief overview of the ongoing debate on the application of the different tunneling technologies.

In Section 4, we present the goal and scope of the report, including the functional unit, the system model and boundary to technology and environment. Section 5, consist of the material inventory for the different technologies of this thesis. Subsequently, in Section 6, we present the results and impact assessment both for one meter tunnel and tunnel track and for the case corridor between Oslo – Stavanger. The results are followed by the interpretation in Section 7, which constitute of a comparative analysis, a system path analysis and a sensitivity analysis of the impact of service life. Section 8 consist of our discussion of our obtained results followed by the conclusion in Section 9 and our recommendations for further work.

## 2. LIFE CYCLE ASSESSMENT

“Life cycle assessment (LCA) is a methodological tool used to quantitatively analyze the life cycle of products/activities within the context of environmental impact” (Goedkoop et al. 2009, p.1). Over the years, the method has undergone major changes and was thus standardized by the ISO 14040 – series at an international level (Goedkoop et al. 2009). The following section is based on the methodology presented in the ISO 14040: 2006 by Standard Norge (2006).

According to ISO 14040 and 14044 standards, a life cycle assessment is carried out in four distinct phases as illustrated in Figure 2.

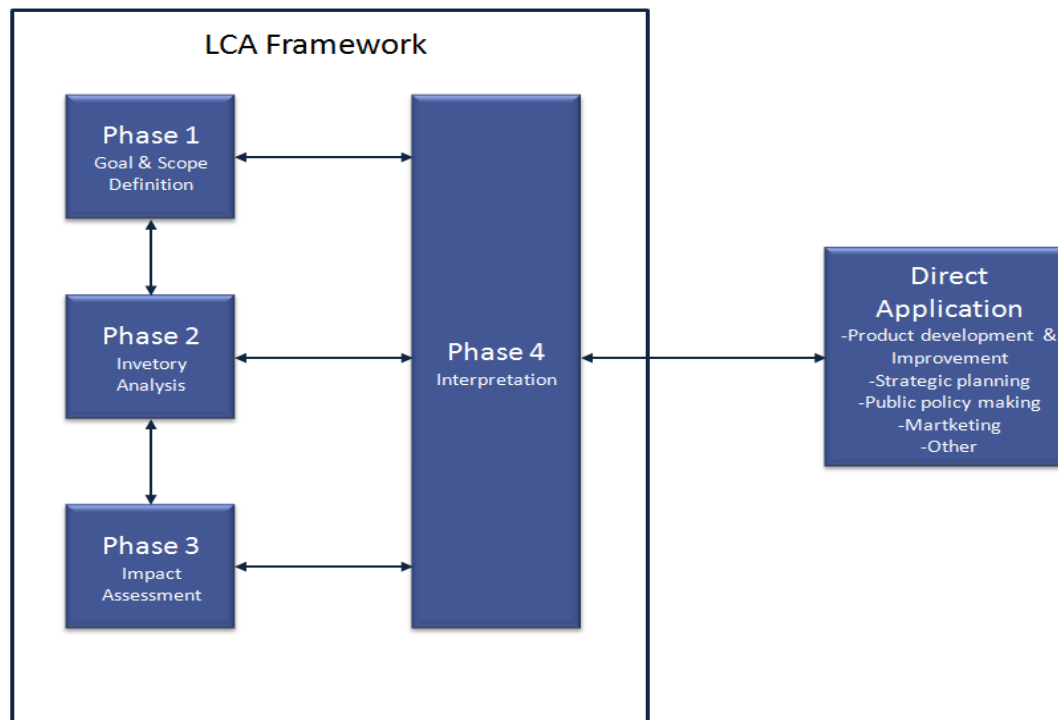


Figure 2 The framework of a life cycle assessment (LCA). The figure illustrates the four phases of a life cycle assessment and the interconnectivity between these phases.<sup>1</sup>

An LCA has a wide range of applications and may contribute to aspects such as decision-making, product development, identification of improvement measures, benchmarking and environmental product declarations.

### PHASE 1 - GOAL AND SCOPE DEFINITION

The definition of the goal and scope has to describe the purpose and for which use and audience, the study is intended. Further, a thorough description of system boundaries, the functional unit and of the investigated product or process, and its life cycle should follow. This first phase must also present all major assumptions, limitations and the most important methodological choices.

<sup>1</sup> Illustration obtained from: (Standard Norge 2006)

## PHASE 2 – INVENTORY

Phase 2 is called the life cycle inventory phase and constitute of the building of the system model. This model must be in line with goal and scope and based on the functional unit. According to Baumann and Tillmann (2004) the activities in the LCI can be summarized as following:

- 1) Constructing of a flow model
- 2) Data collection of all the flows of the model
- 3) Calculation of resource use and pollutant emission in relation to functional unit

It is normal to distinguish the data collection into two types:

- 1) Foreground data, represents data needed to model the specific system of the assessment.
- 2) Background data, represents generic data which is usually obtained from a database such as Ecoinvent etc.

The boundary between these two types may seem unclear, and will depend on the specific assessment.

## PHASE 3 – IMPACT ASSESSMENT

The impact assessment is known as the life cycle impact assessment (LCIA). The purpose of the LCIA is to calculate and evaluate the impact on the environment from the LCI. The phase therefore includes the selection of impact categories and indicators which is evaluated as the most relevant for the specific assessment. Further, according to the ISO 14040, the LCIA must as a minimum include classification and characterization. Classification sorts the inventory parameters to the impact category they contribute to, meaning that all the indicators causing for example global warming, which could include CO<sub>2</sub> and CH<sub>4</sub>, are grouped together. Characterization calculates the relative contribution of the emission and resource use for each environmental impact.

Additionally, a normalization, grouping, and/ or weighting may be carried out, this step is however optional (Standard Norge 2006). Normalization constitutes the process of relating the impact to a relevant reference point. The purpose is to obtain a better understanding of the magnitude of the specific impact. Population of a specific area is often used for such purposes. Grouping is used to combine several impact categories. Weighting is a procedure that presents the different impact categories with a number of relative importances; subsequently they are weighted against one another. One of the most established methods for doing so, is the damage oriented method Eco-indicator 99, which weights various impacts in terms of eco points (Baumann & Tillmann 2004). Of these three methods, only weighting and grouping is briefly used as a tool to help select relevant impact categories at midpoint level for this thesis.

## PHASE 4 – INTERPRETATION

The interpretation constitute of an analysis of obtained results, with the aim at drawing a meaningful conclusion. Further, the discussion should reflect the goal and scope of the assessment. A sensitivity analysis may further be included to investigate the magnitude of assumptions and decisions.

### 3. DESCRIPTION OF TECHNOLOGIES

In the following section, a detailed description of the technological solutions assessed in this study is included. The presentation begins with the two track designs, one ballasted, and one slab track. The track designs are a selection of the seven track technologies assessed by Lia (2011), and are described in greater detail in that report. Furthermore, three tunnelling methods are included of which two are the traditional drill and blast method and the third a double shielded tunnel boring machine (TBM). Subsequently, the traditional types of support work used in Norway, are explained followed by a brief simplified presentation of the relation between securing level and rock quality. The three tunnelling technologies are the methods chosen for evaluation for the tunnel on the Follo Line, and may thus not include all available technologies.

#### 3.1 TRACK BED DESIGNS FOR HIGH-SPEED RAIL IN NORWAY

The track bed is the main component of the railway infrastructure as this supports the train and determines comfort, speed and security of a railway corridor. There exist two main track bed designs: the conventional ballasted track way and the slab track. The ballasted track is the most commonly used track design in Norway and consist of sleepers made from wood, concrete or steel placed on a bed of gravel. The design is illustrated applying concrete sleepers in Figure 3.

The NSB 95 concrete sleeper, is the most commonly used sleeper in Norway today (Løhren 2011), and will therefore represent the sleeper design assessed for this study.



Figure 3 A ballasted railway track<sup>2</sup>

The slab track was developed to meet the requirements of increased speed and traffic loads. Instead of a gravel layer, as illustrated above, the slab track consist of a solid concrete or asphalt slab (Bilow & Randich 2000). There has been developed several types of slab track designs, which differ in the how the rails are fastened to the slab. Three main variations are either directly on the slab, on top of a sleeper placed on a slab or embedded directly into the slab (Ogilvie & Quante 2001). The RHEDA 2000 is a slab track design where rails are fastened unto reinforced sleepers, which in turn are embedded in the concrete slab, as illustrated in Figure 4. The RHEDA 2000 received comparatively good results both for the technical assessment (Pöyry et al. 2011) and the environmental assessment

---

<sup>2</sup> Image obtained from: (L2B 2012)

(Lia 2011). The RHEDA 2000 will therefore represent the specific track category in this assessment. In Norway, the slab track design will first and foremost be considered for tunnels and bridges (Jernbaneverket 2012b) and are therefore not evaluated for open sections in this report.

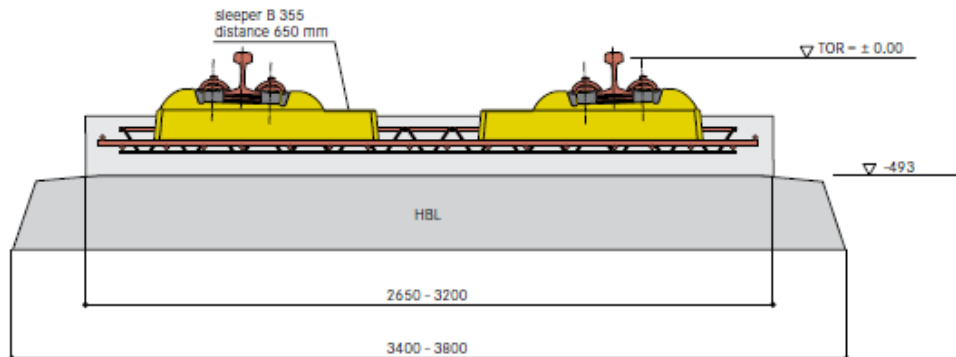


Figure 4 The RHEDA 2000 slab track design<sup>3</sup>

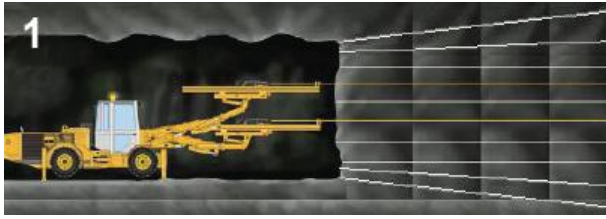
## 3.2 TUNNELING TECHNOLOGY

A tunnel is basically a tube hollowed through soil or stone and constitutes a significant construction component in the development of transport infrastructure. How a tunnel is built depends on the material through which it must pass. Tunneling through soft ground for instance, requires very different techniques than tunneling through hard rock or soft rock. Tunneling technology has been developed over the years to cope with increasingly various geological conditions and may be divided in two type of methods; the conventional drill and blast (D&B) and the use of tunnel boring machines (TBMs) (ITA WG Mechanized Tunneling 2000).

### 3.2.1 THE DRILL AND BLAST METHOD

The conventional tunneling method in Norway is the drill and blast method. The blasting normally includes a cycle which consist of five main steps; grouting, boring, blasting, load up and support work. This process, including the five steps will be thoroughly explained in the coming illustration in Figure 5, which is obtained from the JBV website (Jernbaneverket 2010b).

<sup>3</sup> Image obtained from:(RAIL.ONE GmbH 2011)



For the grouting process, workers normally drill 21–27 meter long holes around the entire tunnel cross section. Cement, is subsequently pumped into these holes under high pressure. The purpose of the grouting before the blasting process is to fill cracks with cement, such that ground water will not leak into the tunnel and damage the tracks. This step however, is highly time consuming, and if it may be avoided, the penetration rate may be doubled.

Subsequently, the explosives are filled into approximately five meter long holes that are drilled into the rock.



The actual explosion is divided into several blasts to reduce the vibration in the mountain and surroundings. Each round is adjusted to the specific properties of the rock and the surrounding environment.

After the blasting, excess rock is removed from the tunnel site. The material is transferred onto trucks, and transported out of the tunnel to specific landfills.



The final step is scaling and support work. A hydraulic hammer, removes the loose rock as illustrated in image 5 to the left, which represents the scaling activity.

**Figure 5 Step by step illustration of the drill and blast tunneling method**

The tunnel must oppose forces placed upon the structure both from dead loads (the weight of the structure itself) and live loads (weight of the vehicles and people that move through the tunnel) and is therefore reinforced with strong materials, such as masonry, steel, iron and concrete. The process of support work will be thoroughly described later in the chapter. After the securing, the cycle is then repeated (Jernbanverket 2010b).

### 3.2.2 TUNNEL BORING MACHINES

The tunnel boring machine represents a comparatively newer tunnelling method compared to the traditional drill and blast. The technology has increased in use over the years because of technological developments that allows for tunnel boring in harder, as well as less competent rock. Several different tunnel boring machines exist, each designed for specific purposes and geologic properties. The TBM in focus for this study, is the double shielded TBM, as this is the machine recommended for the Follo Line (Jernbaneverket 2008). The following description of the TBM is based on information gathered from Robbins (2012a).

The name “double shielded” is rooted in the special design of the machine. Three shields, (a telescopic, a gripper and a tail shield) allow the machine to advance into the rock while keeping everything in the machine under cover and protected. On the front of the machine is a rotating cutter head, which consist of several disc cutters. When the cutter head rotates, the rock is crushed or fractured. Buckets placed on the cutter head scoops up rock cuttings from the bottom of the tunnel floor and transfers it unto a conveyor belt that subsequently transfer the cuttings out of the tunnel. To advance into the rock, the machine uses a gripper system that with the help of thrust cylinders pushes the gripper shoes into the mountain wall.

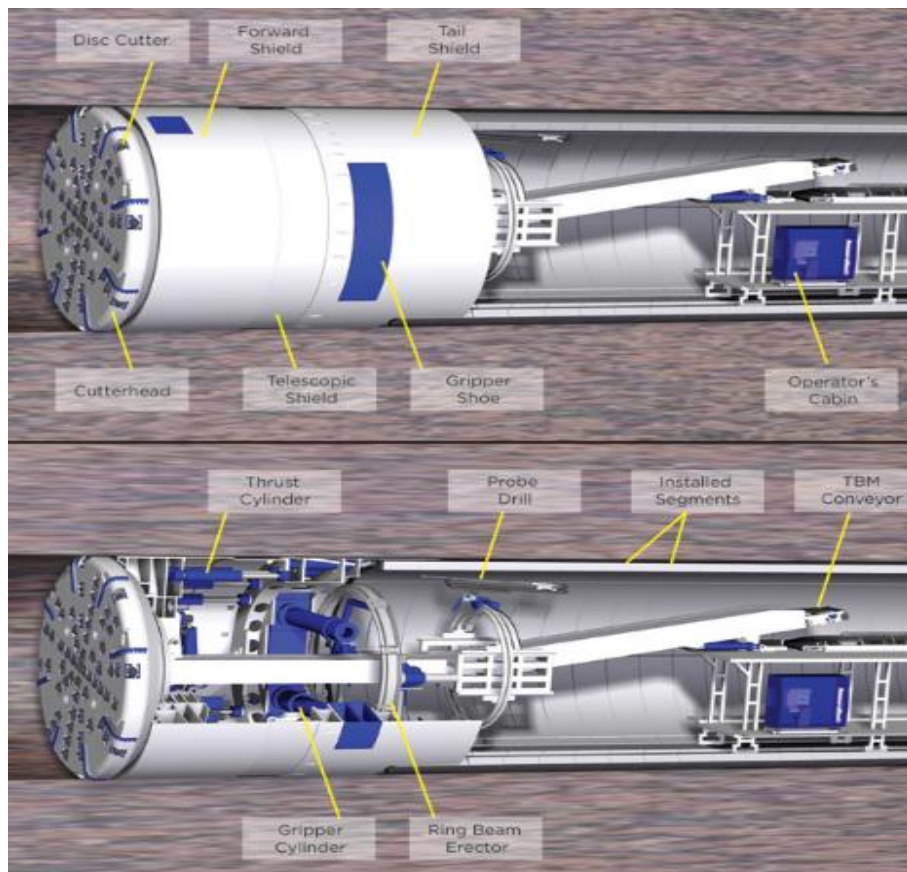


Figure 6 The double shielded tunnel boring machine

The rear-legs are then lowered and the grippers and thrust cylinders are retracted. Subsequently, the retraction of the thrust cylinders repositions the gripper assembly for the next boring cycle. Simultaneously, a segment erector, fixed to the gripper shield, erects pre-cast concrete segments, which ultimately becomes the tunnel wall. The machine is suited for drilling in hard rock where geological fault zones occur, and has in addition a mechanism for using the segments as support for



the gripper legs, which is used if the machine advance in unstable rock. When the liner is in place, grout (a construction mixture), is pumped into the space between the liner and the excavated area, to seal the tunnel in place. In this way “the TBM is a completed factory both excavating and building while moving through the rock”(Robbins 2012a).

The main beam TBM is a different type of tunnel boring machine that is mainly used for hard rock as it is not protected from falling rock with the same shields. The open design allows for rock support work right behind the cutter head. A variety of options for support work is available, which will be thoroughly explained in the next chapter. “The main beam is ideal for unlined tunnel solutions”(Robbins 2012b).

### 3.3 DRILLING AND BLASTING VERSUS THE TUNNEL BORING MACHINE

According to Hansen (2008), there is not one optimal solution as to which of the tunnelling methods that generally may be considered superior. Both have positive and negative aspects depending on different drilling situations. The best method therefore depends on the specific circumstances and expectations. There are, however, some general statements that describe the differences between the methods, as was offered by the consultant companies Messrs. AMH Consult AS in the presentation by Nord (2006) and Hansen (2008).

The excavation process using the tunnel boring machine results in fewer changes in rock fissures during excavation, which ultimately results in a more stable rock compared to a drill and blast process. The assumption is therefore that this method requires less support work. However, according to Nord (2006), this will depend on the initial rock conditions. The relative reduction in required support work for the tunnel boring machine is primarily for hard or stable rock. For loose rock, the support work needed, may be enhanced and even take more time compared to the drill and blast method. Time is an important factor in tunnel constructions as time has a clear relation with the total cost of the project. The preferred method will therefore often represent the method that reduces total construction time. The TBM is the method, which initially is associated with the highest penetration rate, but the method would experience considerable delay if areas with difficult rock were encountered. This is because the process of doing support work in front of the machine is very time consuming. Both the Norwegian and the European tunnelling methods are affected by the geological conditions of the rock, but this has a significantly higher impact on the TBM as the drill and blast method is more flexible and easier to adjust to unforeseen circumstance. In addition, the TBM may experience downtime for changing of cutters, maintenance, breakdowns etc. (Nord 2006).

The working environment in the tunnel is, however, preferable with the TBM method, as no blasting fumes linger in the tunnel air. Additionally, less required construction of additional tunnels such as adits and working halls would reduce the total impact of the TBM tunnel. Further, the use of energy, because of the Norwegian hydro power production and the use of an electric conveyor belt to transport muck out of the tunnel is expected to reduce the environmental impact of the TBM machine compared to the conventional drill and blast method (Hansen 2008).

### 3.4 ROCK SUPPORT AND WATERPROOFING

The securing of rock is optimally designed to utilize the properties of the rock masses in such a way that the mountain supports itself, to the greatest extent possible. A mistake in the securing assessment may cause damage to tunnel infrastructure or in the worst case a lethal collapse of the tunnel structure. The main concerns with the stability of a tunnel are presented in the four images in Figure 7. Image 1 presents fall out of masses which may occur as a result of reduced tension in the rock, causing heavy rock to lose hold. Image 2 presents flaking, or chipping of the rock masses. This may happen as a result of too high tension in the rock. Outburst of masses is presented in image 3 and is a result of swelling pressure in some clay masses when in contact with water or it may occur from the rock pressure on weak rocks. Water may also influence all three problems presented above. The final image, number 4, presents outwash of masses and is a consequence of water damage in the tunnel.

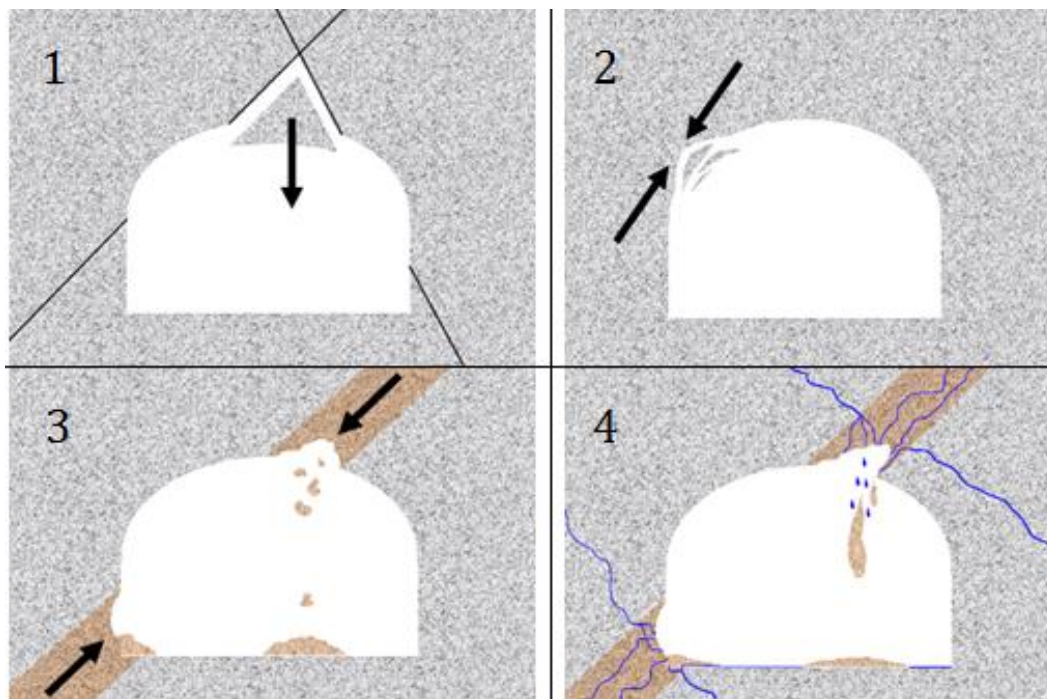


Figure 7 Potential tunnel damage. The figure illustrates the four most important types of damage that may occur in a tunnel<sup>4</sup>. Image 1 demonstrates a fall out of masses, image 2, flaking of rock, image 3 illustrates outburst of masses and image 4, the outwash of masses.

The water and stress level in the rock differ both between sites and between locations in one construction. This results in numerable types and sizes of stability challenges. To achieve the optimal level of securing, a good understanding of the conditions of the tunnel is continuously required.

The geological conditions of the rock, such as cracks, fissures and water conditions will dominate when choosing a stability strategy. Further, the time perspective is important as geological features may change over time. In addition, non-geological conditions affect which securing method is applied. Securing for workers is an important aspect of the securing work as this is to ensure a safe working environment in the tunnel. Further, anticipated use of the tunnel is a determining factor of the level of securing, as a railway tunnel will require a much higher safety in comparison to a tunnel for water or sewage. Other factors may include the availability of securing materials, the experience of the workers and tradition for method applied in the area or country. In addition, time is determining, and one would prefer the securing method, which requires the least amount of time. Lastly, the

<sup>4</sup> Image obtained from: (Moen 2008)

psychological factor is important, for both the permanent and the temporary securing, people must feel safe in the tunnel (Broch & B. Nilsen 2001)

### 3.5 SECURING METHODS

The most common securing methods applied in Norway are rock bolts, shotcrete, grouting and for some cases a full cast. In addition a “scaling” is performed as presented on page 14. Over the last years, the use of scaling has decreased and has been replaced by shotcrete. An explanation may be that the scaling process is relatively time consuming and represent one of the most dangerous tasks of the tunneling process. However, in most cases, not performing this task will represent an even bigger threat. The following section is based on the introduction to support work, presented by Brock and Nilsen(2001).

#### 3.5.1 ROCK BOLTS

The use of rock bolts is one of the most common methods for rock securing. It is performed either systematically or sporadically as illustrated in Figure 8. Bolts of specific length and strength are inserted into the rock to reinforce the rock wall. This activity is applied after scaling, but may also be used before blasting for difficult rock. The effectiveness of the rock bolting is determined by the performance and precision of the workers.

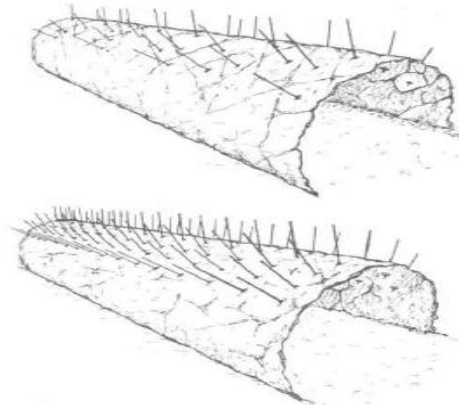


Figure 8 Rock bolting. The upper image present sporadic bolting and the bottom figure a tunnel with systematic rock bolting<sup>5</sup>

#### 3.5.2 SHOTCRETE

The application of shotcrete has increased over the last years because of great technological improvement such as the use of mechanized robots and the introduction of fiber-reinforced shotcrete. Shotcrete is sprayed onto the rock wall to a specific thickness dependent on the estimated rock quality in order to prohibit loosening of rock. Shotcrete is mostly used in densely jointed rock and has a good performance rate. The main problem for shotcrete is however weakness zones with swelling clay, which has lead to several incidents of rock fall.

---

<sup>5</sup> Image obtained from: (Moen 2008)

### 3.5.3 FULL CAST

Traditionally, the full cast has only been used for areas consisting of particularly fragile rock. The disadvantage of the full cast is that the method is very time consuming and expensive. The application of shotcrete and bolts has therefore been a preferable method in Norway. There is, however, a current discussion of the increased use of full cast in future railway tunnels. When constructing a full cast a mobile casting shield is brought into the tunnel and at the same time acts as a work securing for the crew. Concrete is then filled in between the profile and the rock wall. This profile is normally not reinforced and has a minimum thickness of 30 cm. The full cast will result in a construction similar to what is illustrated in Figure 16.

### 3.5.4 GROUTING

Grouting of the tunnel includes the injection of a grouting material into the rock before (pre-injection) or after blasting in accordance with image 1 in Figure 5. The purpose of the injection of grout in tunnels and caverns will in most cases be to seal for water leakage and is performed in cases where there are high requirements for maximum water leakage or for stabilizing weak rock. There are two types of injection materials: cement based, and a chemical based material. The cement is the most commonly used product, but since this will not normally not will penetrate small cracks, the application of chemical agents such as “microcements” are applied for sections with high permeability requirements (Broch & B. Nilsen 2001). Microcements are cement substances which, due to the small grain size and low viscosity and have excellent penetrability. In addition, the substance harden rapidly (Holter & Hognestad 2010). The amount of injection material varies depending on the regulation and the rock type. However, grouting is primarily used for tunnels of high permeability requirements, to stabilize weak rock and for areas, the amount were a leakage will results in large problems both in the construction, and the operation phase (Jernbaneverket 2012d).

### 3.5.5 RING BEAMS AND FLOOR CAST

Ring beams are reinforced concrete arches installed in specific intervals depending on support requirements. The floor cast consist of a concrete foundation installed over the entire floor of the tunnel. These methods are usually applied for sections with very fragile rock (Pedersen et al. 2010)

### 3.5.6 THE Q – METHOD

The Q – method is a classification system for rock quality developed by the Norwegian Geotechnical Institute (NGI), the following introduction to the method is therefore based on publications by the NGI (1997).

The Q-method applies six parameters to determine a value between 1 and 10, whereas a high value indicates good stability, and low values, poor stability. The ranges of Q values subsequently are matched with one of six categories which describe the rock quality and present a recommendation for which of the securing methods (presented above) should be applied, and to which extent, as presented in Table 15 in the appendix. The six parameters of the Q-value represent the three main factors; degree of jointing, joint friction and active stress (NGI 1997, p.20). These factors are thoroughly described in Table 15 in the appendix. (NGI 1997, p.20).

A liability study of the Q-system was performed by Palmstrøm et al. (2002) where the conclusion stated that the “Q–system, used with awareness on its partly serious limitations, may be applied for classification of stability of tunnels and rock caverns, preferably in jointed rock.”

This was however mainly for planning purposes and the authors continued by emphasizing the importance of cautiousness when using the Q-system for rock support during construction and

permanent securing. They also concluded that it is not a system for evaluating the required grouting level and that the Q-method developed for the tunnel boring machine (Qtbm) was recommended not to be used.

### 3.5.7 LINING

In addition to the securing methods, a lining may be installed. This will constitute the finished wall of the tunnel and is often used to reduce permeability and prevent rock from falling onto the rail track or road. The lining structure is based on the designer's best judgment and experience. Whether or not a lining is included, will depend on the geological conditions and political requirements. The lining methods evaluated in this thesis are the cast in place concrete lining for the drill and blast method and the precast segment lining for the TBM. The cast in place lining may be used in any tunnel by any tunneling method. It requires some kind of initial ground support maintaining the opening while the lining is formed and placed. In this study the lining is placed after initial ground support is installed. Cast-in-place concrete linings are cast against a waterproofing membrane which may cause damage on the membrane. The precast segmental linings are used exclusively for soft and hard tunnels excavated by a TBM. This system provides both ground support and also forms the final lining of the tunnel (FHWA 2011).

## 3.6 SECURING METHODS AND THE ONGOING DEBATE ON TUNNELING TECHNOLOGIES

The securing methods presented in the previous section are used in combination or alone and are applied in accordance with the Q-method (see Table 15 in the appendix). Figure 9 presents a very simplified illustration of Table 15. Further, the figure indicates which of the securing methods that are used for each of the Q-categories. The illustration gives however, no indication of the volume of securing material for the different categories, but as a general rule, the volume of the support work will increase if rock quality decreases. This simply means that the volume of shotcrete increases when moving from category A to G.

The scaling process, illustrated at the top of the column is represented in all categories. Sporadic bolting is only used for the A and B categories while systematic bolting is applied for group C and onwards. Shotcrete is used for all categories except the very stable rock in category A. Pre-bolting is used for fragile rock, starting at category D. For E and F support measures such as ring beams and floor cast is applied. For the category G, the Table 15 in the appendix only indicates that support work, will be executed through continuous evaluation. However, Figure 39 (also in the appendix), which represents a comparatively more advanced illustration of the classification system, presents the full cast as a securing method for the category G. This indicates that according to the Q-method, which represents the traditional Norwegian tunnelling method, the concrete cast is only used as the uttermost extreme measure for support work.

Currently there is an ongoing debate in Norway concerning the limitations of the traditional securing methods. The debate was partly fuelled by the accident in 2006 when the Hanekleiv tunnel collapsed on Christmas day. The cause of the fall out was blamed on the poor knowledge and judgement in the support work (Carstens 2007). According to a statement by Bjørn Johnsrud (Skanska) in *Teknisk Ukeblad*, a full cast would have prevented the damage in Hanekleivtunnelen (Tunmo 2011). Also other specialists on infrastructure are positive to increased use of full cast, as it is expected to have less maintenance, a comparatively longer service life and thus constitute lower life cycle costs (Tunmo 2011). Others however, do not agree that these measures are required. An argument used for the application of the full cast in other European countries, is the reduced possibility to use the rock as

carrying construction, because of comparatively more fragile rock than Norway. Further, Eiving Grøv (Sintef) state that such measures may risk undermining the Norwegian tunnel technology, which is starting to experience attention abroad. Another aspect is, that with an installation of a full cast, a membrane must also be installed (see illustration on page 34) which may experience leakage. This kind of damage is much harder to repair on a full cast compared to the traditional tunnel construction (Seehusen 2012). The disagreement, is therefore rooted in whether the securing method that according to Norwegian tunnel technology only is applied for very fragile or unstable rock (represented by category G in the Q-method), is needed for tunnels in Norway to provide the required safety. It is important to note that the full cast is to be considered mainly for tunnels of high use and speed.

The tunnel boring machine have received less attention in Norway over the last years, but is now considered an alternative for the tunnel in the Follo Line, what is maybe becoming Norway’s longest railway tunnel (Strande 2009).

Through this thesis, we evaluate the environmental relevance of this debate by comparing the environmental impact of the three tunnelling methods among others.

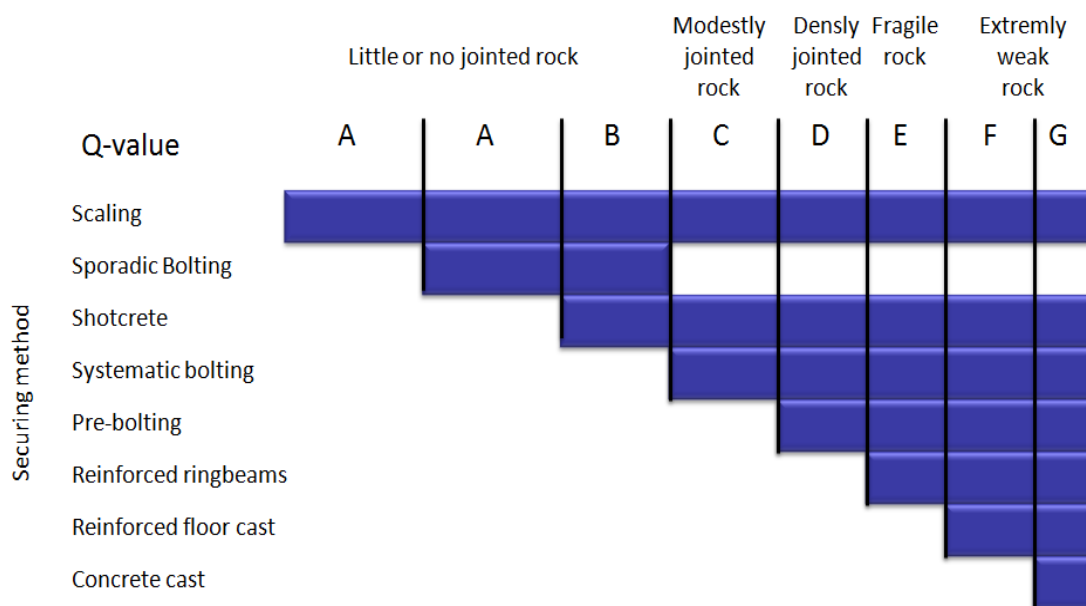


Figure 9 The Q-method simplified. The figure presents a very simplified illustration of the relation between rock quality (Q-value) and which of the securing methods presented in the left column that is applied for the specific category.<sup>6</sup>

<sup>6</sup> Figure 9 present a simplified illustration of the Q-method (NGI 2008).

## 4. GOAL AND SCOPE

In this section, we present the purpose and the content of this thesis. First, we describe the research question and the functional unit. Following, we give an explanation of the differences in calculation method for service life of components previously used, in contrast to the method we use in this thesis. Subsequently, the system boundary to technology and environment is explained. In the section presenting the system boundary to technology, we present the adjustments, additions and expansions that we have completed for the inventory by Bergsdal et al. (2012). In the description of system boundary to the environment we present the eight impact categories that we have chosen for this thesis, and explain how and why these are selected.

### 4.1 RESEARCH QUESTION

The purpose of this thesis is to evaluate the impact of technological and geological changes for the case corridor, the alignment S8:Q,<sup>7</sup> developed by Bergsdal et al. (2012). Further, to expand the current Climate Assessment to include additional impact categories.

This thesis contributes to the ongoing debate concerning the construction of infrastructure for high speed rail in Norway, by emphasizing the environmental impact of several relevant technologies and geological conditions. These we evaluate for eight impact categories. Through this thesis we answer the following research questions:

- To what extent is the emission level presented for the case corridor from Oslo to Stavanger affected by the following changes in technology and geology:
  - Design requirements for increased speed (250km/h and 330km/h)
  - Track technology (ballasted and slab track)
  - Tunneling technology (Norwegian, European, Double Shielded TBM)
  - Geology (level of support work and grout)
- Which of the system processes are the main sources of emission?
- What is the relevance of the service life calculations applied for the inventory?

The different technical alternatives are compared against the technologies traditionally applied in Norway, and an average level of support work, which represents the baseline of this thesis. This thesis is developed as a parameterized modeled in Simapro and uses the ReCiPe method.

### 4.2 FUNCTIONAL UNIT

In this thesis our results are presented for two functional units that both include all activities which occur within the estimated life cycle of 60 years. Waste is modeled as transport of waste materials to deponi.

Functional unit 1 (FU1): One meter tunnel and tunnel track

Functional unit 2 (FU2): The case corridor between Oslo-Stavanger

---

<sup>7</sup> The alignment, the S8:Q, was developed by Bergsdal et al. (2012) for the Norwegian High Speed Rail Assessment and constitute one of twelve assessed alignments for different corridors in Norway.

### 4.3 CALCULATION METHOD FOR COMPONENT SERVICE LIFE

Figure 10 illustrates the method of service life calculation applied for the Follo Line (Korsmo & Bergsdal 2010) and the Climate Assessment by Bergsdal et al. (2012). Each of the track components are presented in to the left of the figure, where the green arrow indicate the construction phase, and the length of the arrow represents the service life of the specific component. The purple arrows indicate the maintenance phase. The number of arrows thus and the number of maintenance activities (number of new installations) included in the calculations.

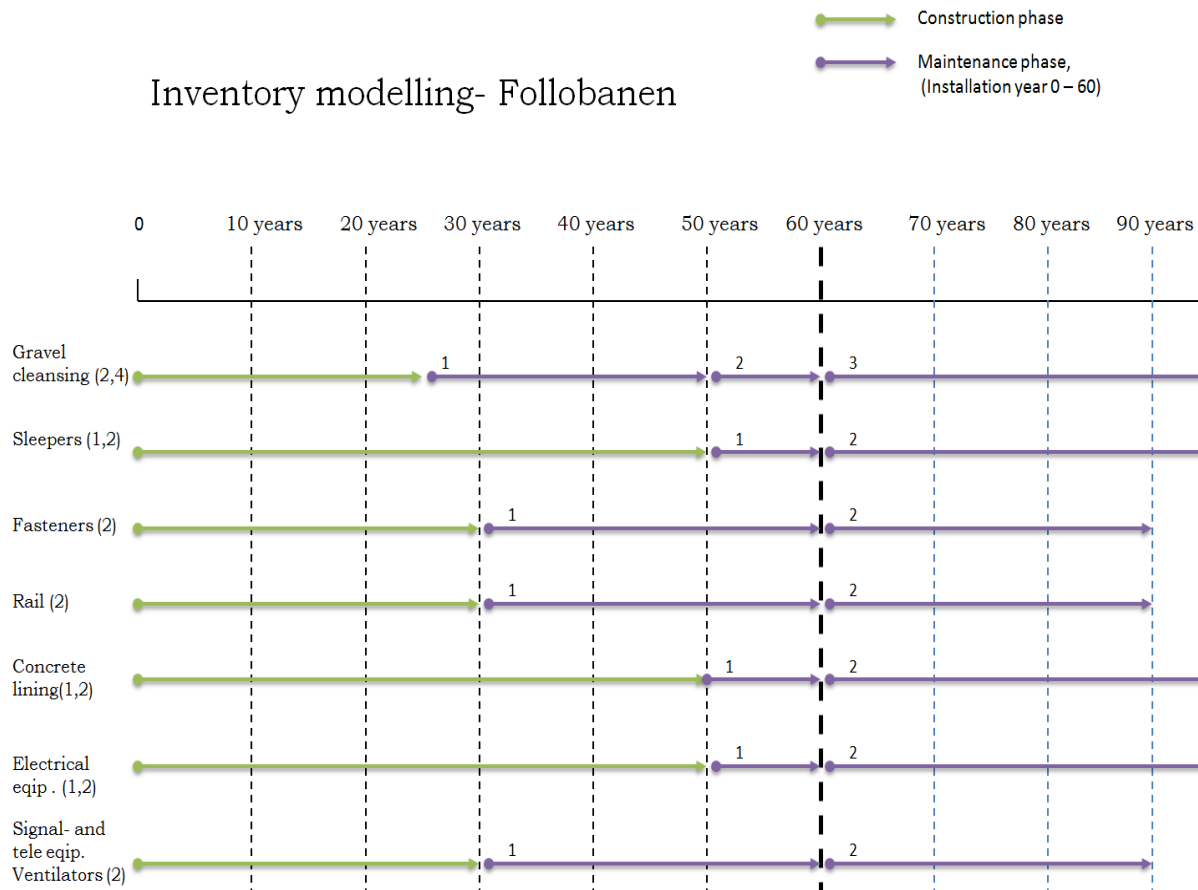


Figure 10 Method for service life calculation used for the Follo Line (Korsmo & Bergsdal 2010). The green arrows represent the construction phase, where the length indicates the service life. The purple arrows present the maintenance phase and the number of purple arrows represents the number of maintenance activities included in the environmental report. Since the inventory first is normalized to 60 years, some maintenance activities are not fully accounted for. The total number of activities for the maintenance phase is thus indicated in the brackets behind the component label.

The illustration present a calculation method that first normalize the amount at maintenance activities to that of what is needed for the life cycle phase of 60 years, thereafter, new components are installed, leaving the corridor new in year 61. This calculation method presents an environmental account that includes a usable corridor of minimum 90 years. Since the decided life cycle phase is 60 years, we have decided to apply a different calculation method for service life for this thesis. The environmental implications of this choice are discussed later, in section 7.3.2 of this thesis.

Our method of calculation service life in this thesis is illustrated in Figure 11. The colour of the arrows represents the same activities as for Figure 10, where the green arrows indicate the construction phase and the purple colour the maintenance phase. Further, the number placed above the



purple arrow gives the number of new installations required for the specific component. In this method, all installations that are required within the 60 years are fully accounted for.

## Inventory modelling - Thesis

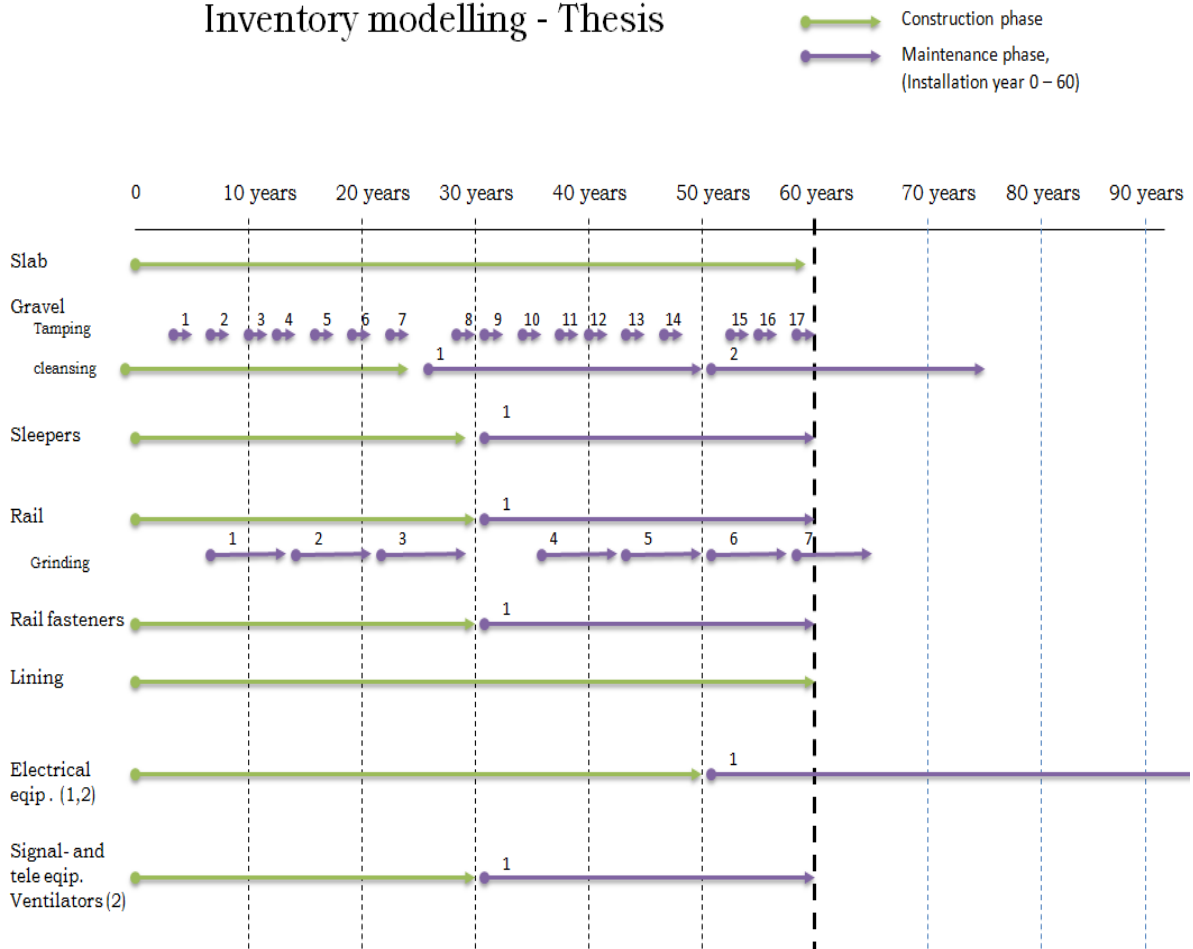


Figure 11 Method for service life calculations used for this thesis. The green arrows represent the construction phase, where the length indicates the service life. The purple arrows present the maintenance phase and the number of purple arrows represents the number of maintenance activities included in the environmental account of this study.

Our method presents a track that is considered incomplete after 60 years according to the technical component service life. The service life of the tunnel lining is changed from 50 to 60 years. The implication of these adjustments is discussed more thorough in the final discussion of the report.

## 4.4 SYSTEM BOUNDARY

The system boundary of this thesis has a technological and an environmental aspect. The technological system boundaries give details of the processes and activities and technological solutions included in the study while the system boundary to the environment describe which environmental categories is included in the study and what types of impact is calculated for within the environmental categories.

### 4.4.1 SYSTEM BOUNDARY TO TECHNOLOGY AND PROCESSES

In Figure 12 we present the system model that we have used to calculate the functional units of this thesis. The major part of the processes of this model is developed by MiSA for the report by Bergsdal (2012). For this thesis, some of these processes we have adjusted, some we have totally altered, and in addition are the model expanded to include additions we have developed for this thesis. These differences are indicated by the colors in the model.

- The gray boxes represent inventory that are kept equal to what was the initial inventory. This includes the operation phase (first row), and parts of the inventory which did not require any adjustments or additional functions (platform, switches and passing loop, in row two).
- Purple boxes are adjusted processes. These are either changed as a consequence of the altered service life calculations (the maintenance phase, as described in the previous section) or the inventory for construction has been disaggregated to extract the track inventory, or both of the above.
- The green boxes are inventory obtained from Vianova (2011c) and represents the alternative tunneling technologies.
- The blue boxes are developed based on inventory gathered and calculated by the author.

The maintenance phase is adjusted for all processes in accordance with Figure 11, the method of service life calculations for this report. For the construction minor adjustments are done for the open section and the bridge, by extracting track inventory, which is separated and placed as an alternative track design in line with the NSB 95 and RHEDA 2000. In that way there is possible to shift between the traditional and the HSR track design. Further, several adjustments are done to the tunnel inventories. Firstly, for both the drill and blast methods, the material for securing and grouting is extracted. Separate processes are created for five different levels for both these variables. Further, the inventories are stripped down to include only what is required for the specific tunneling method, as presented in Figure 16. This means that extra material added for the Follo Line inventory due to specific site requirements are removed. Further, a concrete membrane of 10 cm is included for the European method. For the TBM method, the concrete segments are extracted and added as a separate process, making it possible to include the segment lining for only parts of the tunnel and to adjust the thickness of the segments.

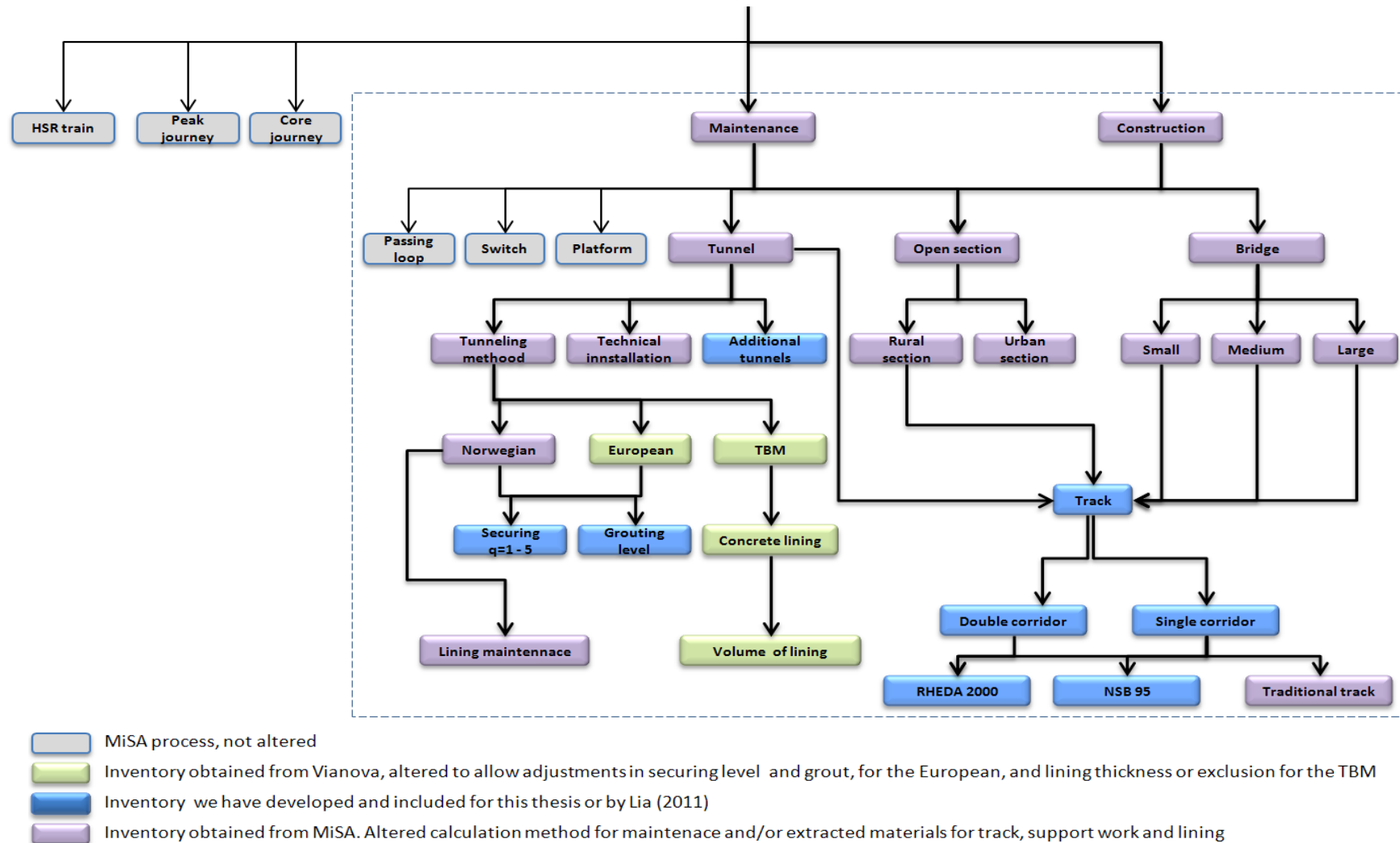


Figure 12 System model for this thesis. The system model is developed in Simapro and used for our calculations in this thesis. The major part of the processes of this model is developed for the report by Bergsdal (2012) or Bergsdal and Korsmo (2010). For this thesis, some of these processes we have adjusted, some we have totally altered, and further are some parts of the model expanded to include additions we have developed for this thesis. These differences are indicated by the colors in the model, which are explained on the bottom left of the image.

We have used the model to evaluate several scenarios, technological, geological and methodological changes. We have further performed a number of adjustments to create a parameterized model. The list of the parameters we have developed for the model is presented in Table 20 in the appendix. The parameters make possible the following changes in the model:

- 1) Cross section of tunnels
- 2) Service life of tunnel applying Norwegian tunneling method
- 3) Service life of track components
- 4) Selection of life cycle phase
- 5) Choice of tunneling method (Norwegian, European, TBM)
- 6) Choice of securing level (Q= A,B,C,D,E,F)
- 7) Choice of grouting level (1,2,3,4,5)
- 8) Choice of including TBM segments
- 9) Thickness of TBM segments
- 10) Choice of including additional tunnels
- 11) Choice of track design (NSB 95 and RHEDA 2000)
- 12) Single corridor and double corridor for tunnels
- 13) Volume of gravel shifted for tamping and cleansing

#### *4.4.2 SYSTEM BOUNDARY TO ENVIRONMENT*

The construction of a tunnel has an impact on several areas of the surrounding environment. The purpose of this section is to identify the most relevant impact categories, which will represent the impact assessment of this study.

According to Geldermalsen (2004), a tunnel construction project, affects four types of environmental aspects: natural environment, man-made environment, humans and society. The natural environment refers to the natural fauna and biodiversity, while the man made environment denotes the landscape, design or cultural quality. The third and fourth category represents the impact on humans and the society. This relation was illustrate by Geldermalsen (2004) in a figure similar to the Figure 13.

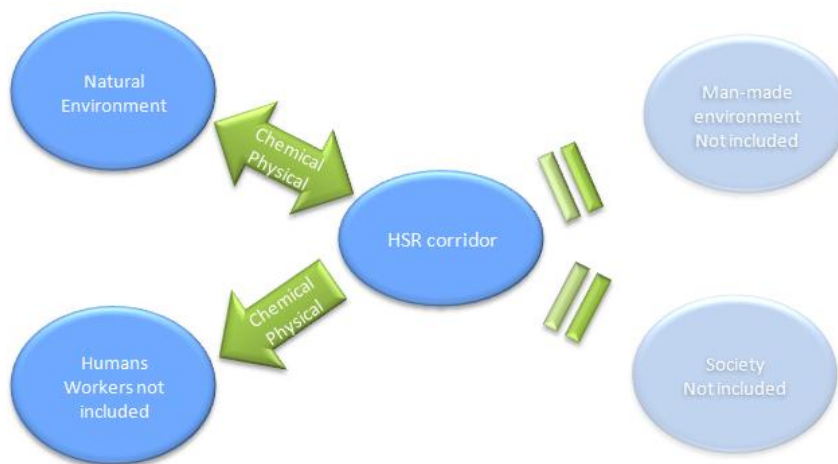
In the study, Geldermalsen (2004) excluded the impact on workers and the society. Further, the author continues by explaining the cause of the impact for each of the environmental aspects. He states that the impact on the natural environment, the man-made environment and on humans is caused by either chemical or physical impacts. The chemical impacts are caused by emissions of various kinds. Physical impacts may be caused by

- Living conditions for humans (noise)
- Habitat of fauna around the tunnels (natural environment)
- Cultural quality “man-made environment” (landscape, design)
- Use of resources “natural environment” (depletion of energy and materials).

The model developed by Geldermalsen (2004) was initially presented for only a tunnel. The implications of construction a full railway corridor is assumed similar as for a tunnel, only in a larger scale. The model and results may thus be used for this report.

While Geldermalsen (2004) included the impact on man-made environment, this aspect will not be included for this assessment. Geldermalsen (2004) continued by identifying an inventory of all environmental aspects that has a considerable impact during the process of planning and constructing a tunnel and thereafter continued by evaluating which were the most important aspects. The list is presented in Table 14 in the appendix, where the twelve most important aspects, according to the author, are indicated by the arrows at the top of the table. These include air pollution, energy use, living conditions, environmental and cultural quality. Since this report does not consider noise and vibration or impact on man-made environment the main conclusion to draw from the report by Geldermalsen (2004), is the importance of air pollution, environmental degradation and energy use.

In the introductory to life cycle assessment by Goedkoop et al. (2010), the author indicate relevant environmental aspects for an assessment of transportation methods. These include small particles, land use and noise. In addition categories such as climate change, acidification, eutrophication, toxicity and ozone depletion is emphasized. The author's continues by advising the reader to assess the results using endpoint calculations to uncover main impact areas.



**Figure 13 Impact aspects. Environmental impact from a tunnel construction based on the illustration by Geldermalsen (2004)**

Figure 14 illustrates the results presented by Bergsdal et al. (2012), for the high speed rail assessment for the corridor between Oslo and Stavanger estimated for a speed of 250 km/h. The results are calculated in weighted eco-points and presented by the three methods; hierarchic, egalitarian and individualist.

The differences between the three methods for calculation are summarized as a short time perspective for the individualist perspective attributed by a technological optimism and believe in human adaptation, which results in a comparatively low impact perspective. One reason is the reserved amount of substances included in calculations and the timeframe for how long they are included. The individualist perspective is for this assignment fairly similar to the hierarchic perspective, which includes the most common policy goals regarding time frame and other issues. The egalitarian perspective presents a much higher impact as the method has a comparatively long time perspective. This is the most precautionary perspective (Goedkoop et al. 2009).

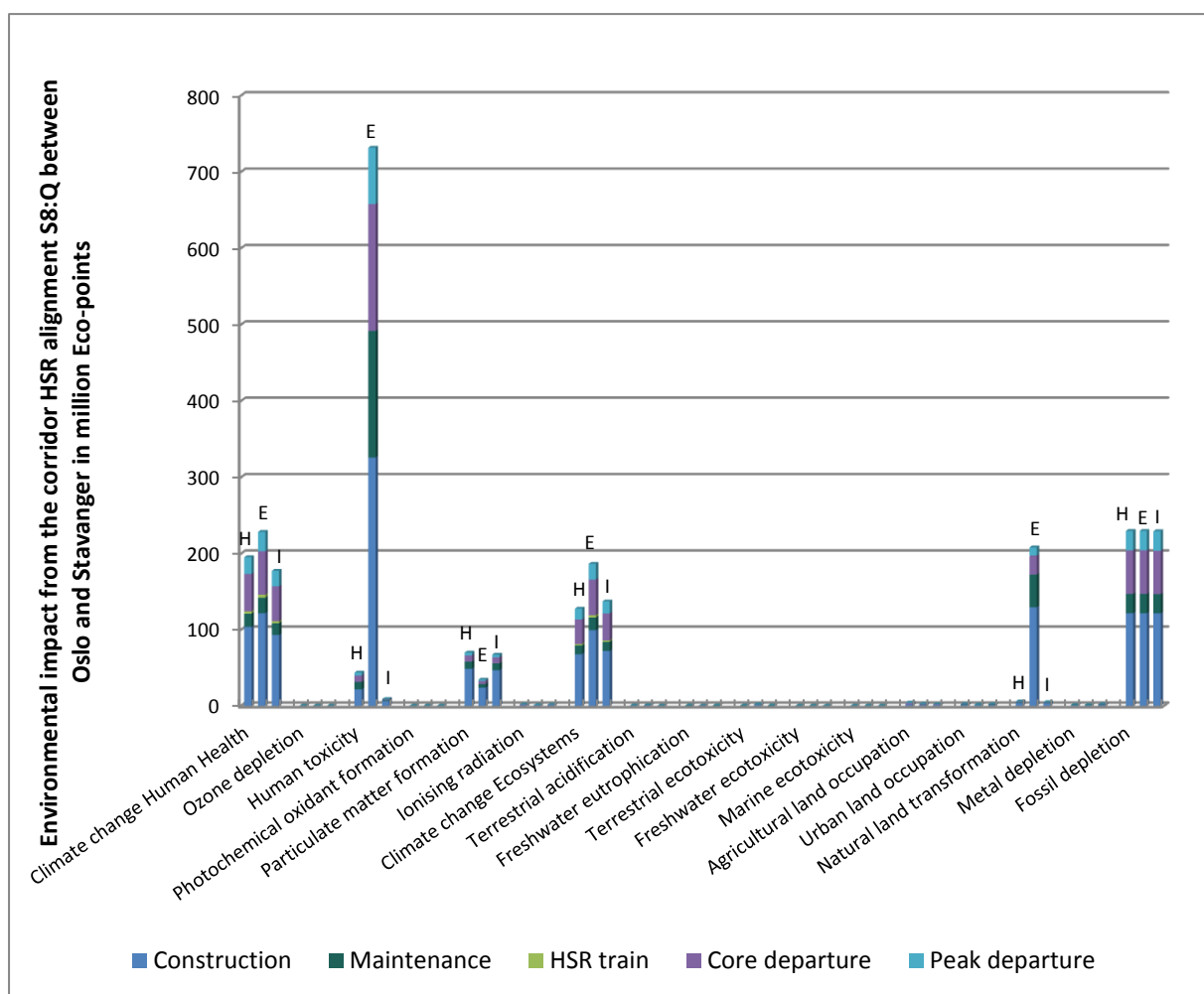


Figure 14 Endpoint results. The figure illustrates the environmental impact from the high speed rail corridor between Oslo and Stavanger, the S8:Q alignment in Bergsdal et al. (2012). Calculated in weighted endpoint results. Further, the results are presented by the three methods for calculation: hierarchal (H), the egalitarian (E) and the individualist (I).

Figure 14 present a fairly similar impact distribution between the three calculation methods. Fossil depletion and climate change for ecosystems and human health are approximately equally weighted for the three methods. The egalitarian method constitutes a fairly higher impact for both human

toxicity and natural land transformation as a result of a set of more precautionary assumptions in calculations. Lastly the category particulate matter formation is represented by all the categories.

This indicates a correspondence with the environmental aspects presented both by Geldermalsen(2004) and Goedkoop(2010). Further, all impact categories and all methods present a result where the infrastructure constitute more than 50% of total impact which support the initial statement and purpose of this assignment.

Based on the conclusions drawn from the previous discussion, eight impact categories are chosen to represent the range of environmental impact leading from a railway construction project. Figure 15 presents the selected categories and illustrates the relation between the midpoint categories and the endpoint results. The figure therefore illustrates that the categories included represent all three damage categories at endpoint level, and is thus evaluated to represent total impact at a satisfactory level.

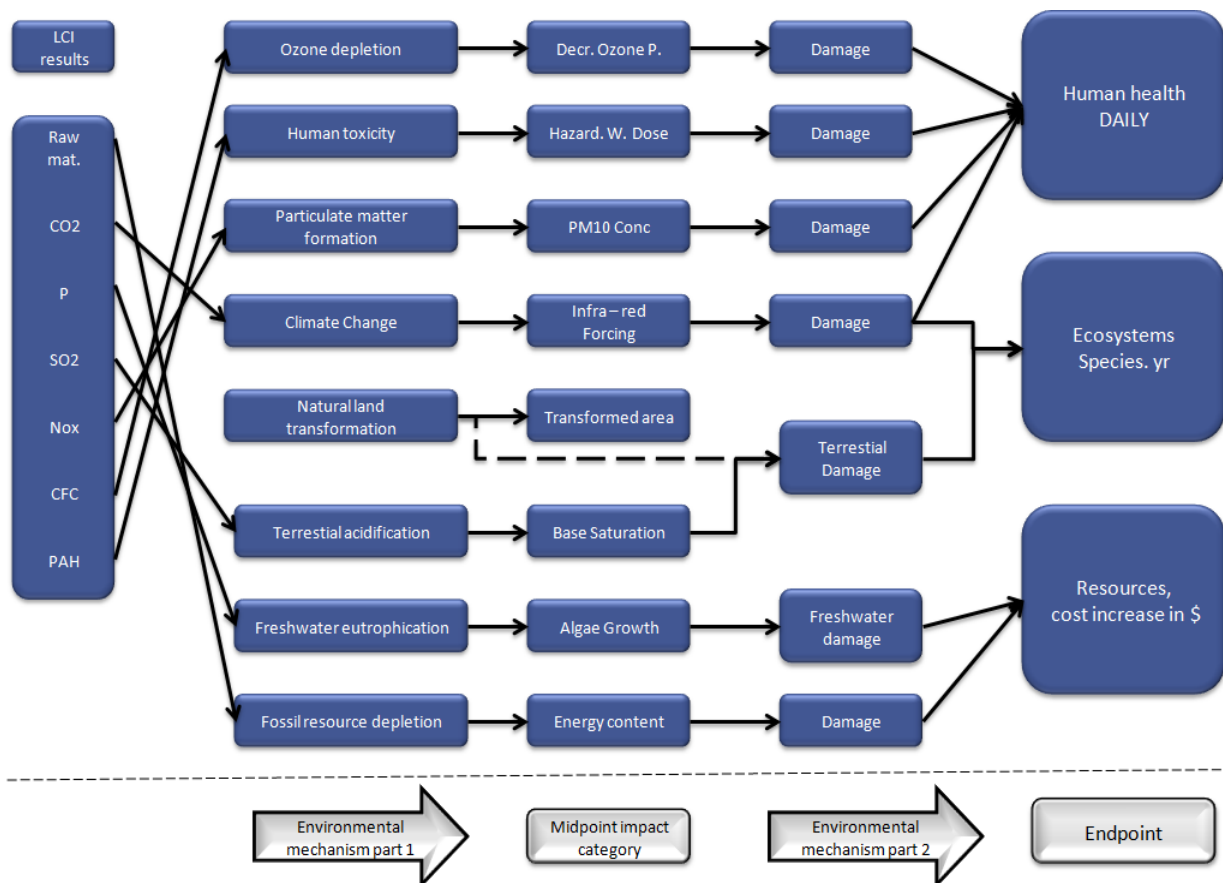


Figure 15 Selected midpoint categories and indicators. Illustration of the selected midpoint categories and their link to endpoint results.

## 5. LIFE CYCLE INVENTORY

In this section we present the material inventory for the different technologies and components used for this thesis. First, we present the inventory for track construction and maintenance. This is followed by a presentation of the material requirements for the three tunneling technologies included in this thesis. Within this section, we present the specific material requirements for each tunneling technology, followed by a description of the specific tunnel dimensions for a tunnel estimated for 200km/h, 250km/h and 330km/h. Subsequently we present material inventory for the different levels of support work and grouting assessed in this thesis. Further, we present the density and inventory for the additional tunnels such as working halls and cross sections. Lastly, we briefly discuss the maintenance phase of a tunnel.

Inventory for the track technologies are obtained from Lia (2011). The inventory for the Norwegian inventory is gathered from Korsmo and Bergsdal (2010) and the inventory for the European and the TBM tunnel from Vianova (2011a) and (2011b). Inventory for the different levels of support work and grouting, we have calculated based on the theoretical background for this thesis.

### 5.1 TRACK BED

The inventory obtained for the different track solutions are presented in Table 1 below. The “traditional track” represents the original track inventory presented in the environmental account for the Follo Line (Korsmo & Bergsdal 2010). The inventory for the NSB 95 track bed and the RHEDA 2000, is collected from the student project performed by Lia (2011) and adjusted to include double tracks and to meet the requirements for bridges and tunnels.

The adjustment to a double track includes a double amount of sleepers and fasteners while the amount of gravel is calculated according to instructions provided by a specialist employed by the JBV (Ramsland 2011). The calculation is presented in Table 13 in the appendix and adjusted for a HSR track by including an extra of 50 mm thick layer of gravel (Jernbaneverket 2012a). The density applied for the calculations of the gravel is given in Table 12 in the appendix and is obtained from the calculations performed for the Follo Line inventory. Further, the RHEDA 2000 is adjusted for tunnels and bridges, by removing the hydraulic bounded layer, which was applied for the student project. The RHEDA 2000 slab may be placed directly on the floor or onto a concrete layer for tunnels and bridges (RAIL.ONE GmbH 2011).

Table 1 presents the inventory for the track applied by Bergsdal et al. (2012) for the Norwegian High Speed Rail Assessment, labeled as the traditional track, and the track inventory gathered from the student project (Lia 2011), with the mentioned adjustments. Both single track and double track is presented for all designs, as the parameterized model developed in SimaPro for this assignment allows for both a single loop and a double loop. Only the single loop is applied for this thesis.

Table 1 presents a slightly smaller amount of concrete for the NSB 95 compared to the traditional track, indicating smaller sleepers, this indirectly leads to a smaller amount of reinforcement steel as this is calculated as 2% of concrete volume (Vianova 2011c). The amount of reinforcement steel in the traditional track is higher compared to the mentioned 2% and is therefore assumed to also include the steel for the rail fasteners. The amount of diesel and machinery wear for the traditional track is not available. The RHEDA 2000 uses considerably more concrete because of the concrete slab, which in turn also results in a higher diesel and machinery wear due to increased demand on machinery because of installation of the slab.



Track construction per meter for a double track							
	Traditional track <sup>8</sup>		NSB 95 – double track <sup>9</sup>		RHEDA 2000 9		Units
	Single track	Double track	Single track	Double track	single track	Double track	
Concrete	0.17	0.339	0.13	0.25	0.7	1.3	m3
Reinforcement steel	0.27	0.054	0.006	0.012	0.015	0.029	ton
Gravel	5.3	10.6	6.9	13.4	-	-	ton
Diesel	Na	Na	0.09	0.2	0.14	0.26	ton
Machinery wear	Na	Na	0.033	0.063	0.05	0.096	h
fasteners	Na	Na	2.2	4.4	2.3	4.5	Nb
Rail	0.12	0.24	0.12	0.24	0.12	0.24	ton

**Table 1 Inventory for track bed. The table presents the inventory applied for the system model for the different track designs. Na indicates not available values.**

### 5.1.1 MAINTENANCE

There is, however, a significant difference in the service life assumed for the different track designs. The traditional track is assumed to have a service life of 50 years for all its components and a replacement of 2% of ballast for each cleansing, which occurs every 25th year. The HSR track, consisting of the NSB 95, calculate a service life of its components as presented in Table 2, were 50% of the volume of ballast is changed every 25<sup>th</sup> year, and additionally is a tamping process which increase the total volume with about 2% added every 3 years. The result is a much higher material turnover.

Component	Service life	Estimated technical service life	Maintenance dimension
Ballast cleansing	15 – 25	25	50 % of volume
Ballast tamping	3	3	2 % of volume
Sleepers	15 – 50	30	Entire component
Slab	60 – 120	60	Entire component
Fasteners	10 – 30	30	Entire component
Rail	10 – 40	30	Entire component

**Table 2 Service life, track bed<sup>10</sup>**

## 5.2 TUNNELING METHOD

The material inventory for the Norwegian tunneling method is obtained from the project of the Follo Line (Korsmo & Bergsdal 2010). The inventory is adjusted to exclude special requirements for the Follo Line tunnel by removing material used for special weak zones. The European and the TBM tunneling methods are obtained from Vianova (2011c), where the European method is adjusted to include a cement membrane. Further, the inventory for support work and grouting are extracted from the two D and B methods to allow two different geological scenarios. The TBM inventory has not been altered. The construction of the three tunneling methods is assumed a composition as illustrated in Figure 16.

<sup>8</sup> Data obtained from: (Korsmo & Bergsdal 2010)

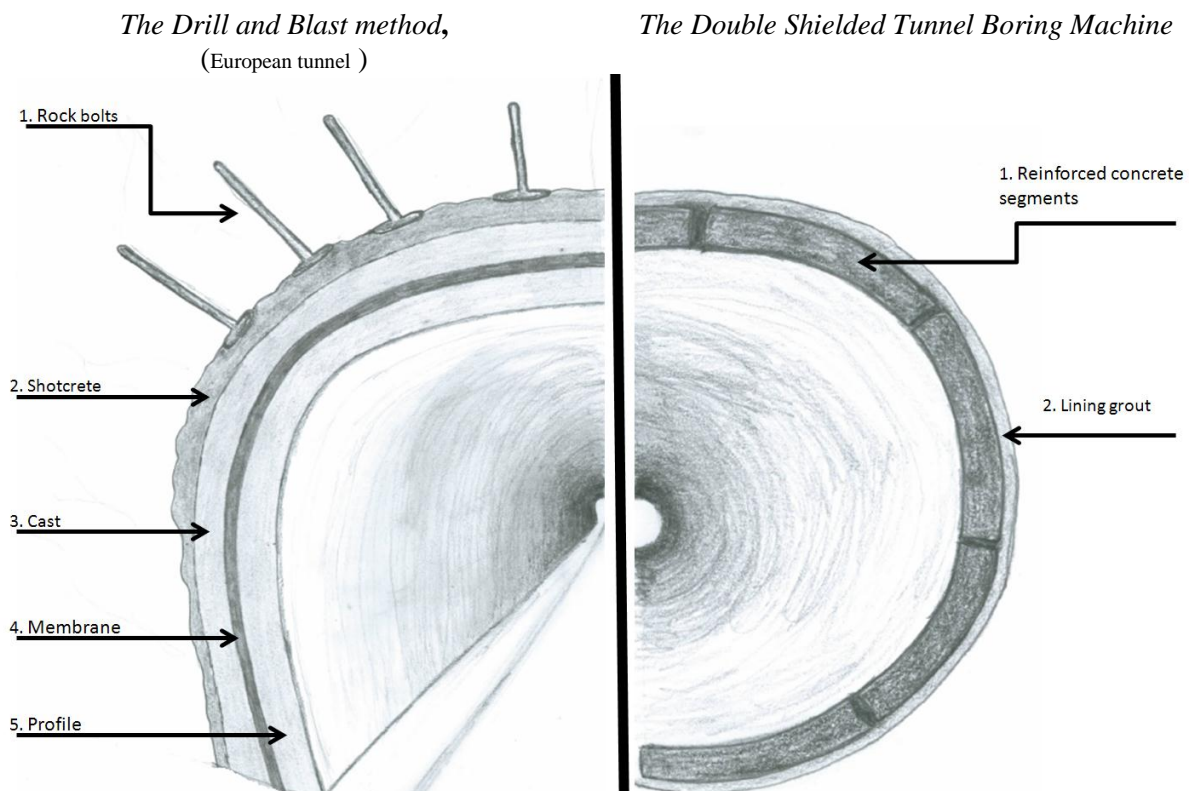
<sup>9</sup> Data obtained from:(Lia 2011)

<sup>10</sup> Estimates for NSB95 obtained from: (Jernbaneverket 2011) and for the RHEDA 2000 from: (Kiani et al. 2007)

### ***Calculation Method for Tunnel Inventory per m<sup>2</sup>***

One notion, which is worth some attention, is the calculation method of material per m<sup>2</sup> of tunnel cross section. To divide total material volume per m<sup>2</sup> of a rectangular tunnel profile will produce correct results and the thickness of a specific material will equal the volume of the same material per m<sup>2</sup>. For a tunnel that is arched, the material volume of a material per m<sup>2</sup> will be marginally smaller than the thickness as a result of the decrease in length between the outer and the inner level of the arch. For this thesis however, calculations of materials are only used for relatively thin components. Consequently, the result of this small error is assumed insignificant, and volume is assumed equal to the thickness of the component or material.

### ***The Structure of the Tunneling Methods Illustrated***



**Figure 16 Illustration of the tunneling methods. The image on the left present the casted drill and blast method. If removing the cast and membrane, the image will present a simplified illustration of the Norwegian method. The image on the right presents the double shielded tunnel boring machine, which install reinforced concrete segments.**

The image on the left in Figure 16 presents the cross section of a D and B tunnel constructed by the European method. After a series of explosions, rock bolts (1) are inserted into the rock wall (Vianova 2011c). Secondly, the shotcrete is sprayed on the tunnel wall (2). The thickness of the shotcrete is determined by the securing level and covers the insulation plates made of expanded polystyrene (XPS). Subsequently, in the European method, a membrane is installed (4), which for this assignment is assumed to be a concrete membrane, and erect a concrete lining (5). Lastly, the space behind the membrane is filled with concrete, the cast (3). Both the cast and the profile may vary between 23 – 30cm (Gammelsæter 2012). The Norwegian method however, only installs a reinforced concrete lining, leaving a space between the shotcrete and the lining.

The TBM install concrete segments (1) around the entire cross section, which thereafter fill in the space between the segments and the wall with concrete and seal this with a concrete grout, in this thesis labeled “lining grout” (2).

Table 3 presents the material requirements for the three tunneling methods. Technical installations which are obtained from the project on the Follo Line (Korsmo & Bergsdal 2010), is assumed equal for the three tunnels, and are therefore not included in the table.

Material requirement per m2 cross section				
	European D&B <sup>11</sup>	Norwegian D&B <sup>12</sup>	TBM <sup>13</sup>	Unit
Explosives	0.005	0.005	-	Ton
Concrete cast	0.55	-	-	M3
XPS	0.000012	0.0004	0.000012	Ton
Concrete grouting	-	-	0,15	M3
Machinery wear	0.3	-	0.05	Hr
Diesel	7,5	8,85	5	Kg
Electricity	125	154	309	kWh
Concrete membrane	0.1	-	-	M3
Concrete elements for lining	-	0.2	-	M3
Reinforcing steel	-	0.03	0.07	Ton
Cuttering Chrome	-	-	0.022	Ton
Concrete segments	-	-	0,4	M3
Concrete fill for segments	-	-	0,12	M3
Injection cement	Extracted(0,08)	Extracted(0,08)	0.003	Ton
Polyurethane	0.004	0.005	0.0002	Ton
Bolts	Extracted (0,004)	Extracted (0,004)	-	Ton
Shotcrete	Extracted(0,07)	Extracted(0,07)	-	M3
Gravel (reinforcement layer)	0,6	0,6	-	Ton

**Table 3 Inventory for tunneling methods. The table presents the material requirements for the double shielded tunnel boring machine, the Norwegian and the European and the tunneling methods assessed in this thesis per m2**

The amount of explosives is equal for the two drill and blast methods, while the amount of XPS, insulation material, is relatively larger for the Norwegian method, as this is not insulated with a membrane such as the European, or with the lining grout, which is used as insulation for the TBM. The membrane is an approximately 10 cm thick insulating component applied for the European tunnel method. The membrane may be constructed from different materials, but are for this report assumed a concrete membrane. The lining for the Norwegian method is constructed from 20 cm thick concrete elements installed mainly to insulate, but also to protect traffic from falling rock. Reinforcement steel is the reinforcement for the Norwegian lining and the TBM segments and constitutes 2% of the concrete volume. Chrome for the TBM cutter is the required steel for the disc cutters in front of the TBM. The segments, for the TBM tunnel, are 40 cm concrete segments which may vary between 400–600 mm. The concrete “fill inn” is the concrete used to fill out the space between the rock wall

<sup>11</sup> Values are calculated based on data obtained from: (Vianova 2011a)

<sup>12</sup> Values are calculated based on data obtained from: (Korsmo & Bergsdal 2010)

<sup>13</sup> Values are calculated based on data obtained from: (Vianova 2011b)

and the concrete segments for the TBM. This space is about 10–15 cm and does not change significantly between different tunnels (Gammelsæter 2012).

The injection materials are the cement and the polyurethane. The amount of polyurethane is considerably higher for the D&B methods and as with XPS highest for the Norwegian method. The injection of cement for the TBM is estimated to about 3 kg per m<sup>2</sup>.

The amount of bolts and shotcrete, used for support work, is about equal for the two D&B methods. The amount of diesel is much lower for the TBM as it applies a conveyor belt on the TBM to transport material out of the tunnel, while the D&B use lorries and an excavator to load and carry materials. Electricity is considerably higher for the TBM since the machine is electric.

### 5.2.1 TUNNEL PROFILE AND ESTIMATED CORRIDOR SPEED

The size of the tunnel is determined by several factors; among these is the expected speed of the corridor an important factor. Table 4 presents the profiles for each of the analyzed tunneling methods for 200, 250 and 330km/h.

	200 km/h <sup>14</sup>			250 km/h			330 km/h		
	Norwegian	European	TBM	Norwegian <sup>15</sup>	European <sup>16</sup>	TBM <sup>17</sup>	Norwegian	European <sup>18</sup>	TBM <sup>19</sup>
Drilled/blasted profile	70	-	-	83.9	85.9	89	-	80.8	95
Normal profile	47.7			60	60	61.8		64.4	64.4
<b>Cross section for materials</b>	<b>22.3</b>			<b>23.9</b>	<b>25.9</b>	<b>27.2</b>		<b>16.4</b>	<b>30.6</b>

Table 4 Tunnel dimensions. Presentation of the estimated blasted/drilled and normal profile for the different tunneling methods for 200, 250 and 330km/h.

Table 4, presents information obtained for the relation between tunnel dimension and speed for the three tunneling methods. The blasted/drilled profile represents the cross section excavated by explosives or a bore machine. The normal profile represents the cross section or the hole of the tunnel which is visible when the tunnel is finished. The difference between these two values represents the area which holds materials for support work and lining. For this assignment, this area is referred to as the material cross section.

The dimensions for the project on the Follo Line were for the environmental account calculated for a tunnel estimated for 200km/h (Korsmo & Bergsdal 2010). Later, dimensions for 250 km/h have been developed for all the three tunnelling methods, all calculated for the Follo Line tunnel.

For the Norwegian High-Speed Rail Assessment by Bergsdal et al. (2012), the Norwegian method estimated for 200km/h was used for all tunnels. For the economic calculations however, the dimensions for the European and the TBM for 330km/h presented used.

The increase in blasted and normal profile for the Norwegian tunnelling method is approximately similar for both profiles, indicating that the level of securing and thickness of tunnel lining is maintained equal to the original inventory for the Follo Line. This was confirmed by a specialist from within the JBV(Gammelsæter 2012). There is however no estimate for dimensions representing a

<sup>14</sup> Dimensions obtained from: (Korsmo & Bergsdal 2010)

<sup>15</sup> Dimensions obtained from:(Jernbaneverket 2010a)

<sup>16</sup> Dimensions obtained from: (Vianova 2011a)

<sup>17</sup> Dimensions obtained from:(Vianova 2011b)

<sup>18</sup> Dimensions obtained from: (Norconsult 2011a)

<sup>19</sup> Dimensions obtained from: (Norconsult 2011b)

speed of 330km/h. The reason for this is the increased focus on alternative tunnelling methods for tunnels of high speed and use, as was mentioned introductory. The application of the Norwegian tunnelling method is however, not technically impossible, but because of the increased pressure and suction power, the Norwegian technology would be better suited for shorter tunnels (Gammelsæter 2012). Based on this statement, we have estimate dimensions for a Norwegian tunnel designed for 330km/h for this thesis based on obtained information. Both the European and the TBM method use a 64, 4 m<sup>2</sup> normal profile for the 330km/h scenario, this is therefore also assumed for the Norwegian method. Further, the same thickness of the tunnel wall is assumed. This results in a blasted profile of approximately 90m<sup>2</sup>. The result is a material cross section of approximately 25.6m<sup>2</sup>.

The increase in tunnel dimensions for a TBM tunnel of 330km/h constitutes a fairly equal increase in both the drilled and the normal profile, which indicates that the same thickness of the concrete segments is applied.

The dimensions presented for the European tunnel however, result in a relatively thinner material cross section, (tunnel wall), a speed of 330km/h compared to 250km/h. Figure 16, which illustrates the European tunnelling method, represent a cast and concrete profile, which may alter in thickness from 25 to 30 cm. The reduced thickness of the tunnel in questing may therefore be a result of such a variable. However, the total decrease of material cross section is significantly higher compared to the potential reduction of concrete thickness. The dimensions are developed by different actors, and may thus be based on dissimilar assumptions. The results for the corridor of 330km/h should therefore be interpreted with caution.

### 5.2.2 GROUTING

The amount of grout will vary depending on geological conditions and requirements. In a report by the Norwegian Public Roads Administration (NPRA), the level of cement injection per m<sup>2</sup> of a tunnels is presented for a range of different rock species (Statens Vegvesen 2004).

In order to obtain a practical number of grouting levels, we divided the different cases of the mentioned report into five groups, dependent on the injection level applied. This distribution is presented in Table 16 in the appendix.

Subsequently, we calculated the average injection level of each group that will represent the five levels of cement injection assessed in this study. The five levels are presented in Table 5.

The largest difference occurs between the categories four and five, with a total difference of 44 kg of cement per m<sup>2</sup>. The amount of grout initially applied in the Follo Line tunnel has a material intensity equal to that of category 5, indicating either weak rock, high permeability requirements or both.

Amount of grout ton/m <sup>2</sup>				
Nr 1	Nr 2	Nr 3	Nr 4	Nr 5
0.012	0.027	0.032	0.052	0.096

Table 5 Inventory for the five levels of grout

### 5.2.3 ROCK SECURING

For this thesis we assume that the material requirements for the different levels of support work are represented by the different categories given in the Q-method. Our estimations for the material volumes are based on the recommendations given in Table 15 in the appendix and presented in Table 6.

Material requirements for support work based on the Q-method per m2 tunnel						
	A/B	C	D	E	F	Unit
Shotcrete	0.08	0.08	0.1	0.15	0.175	M3
Systematic bolts		0.0040	0.0044	0.005	0.006	Ton
Sporadic bolts	0.002					Ton
Pre-bolting				0.005	0.010	Ton
Total steel for bolts	0.002	0.0040	0.0044	0.010	0.015	Ton
Concrete for ring beams				0.01	0.046	M3
Reinforcing steel for ring beams				0.00663	0.01	Ton

**Table 6 Inventory for the Q-method. The table present the materials estimated for each of the categories of the Q-method for rock support.**

The volume of shotcrete decided for each of the categories is explicitly presented in Table 15 and we have therefore based the volume of concrete on these values. According to Gammelsæter(2012), is the category C, the level of support work, which for the most part is used for the inventory for the Follo Line. The calculated 0, 07 ton/m2 is approximately equal, were the marginal difference may be a result of the marginal calculation error mentioned in the beginning of this section.

Category F is the only category, which give a range and not a specific depth for the volume of concrete, which is applied as shotcrete. We have therefore assumed that the average is used for this thesis.

Next, follows the calculation of steel for rock bolts. The inventory for the tunnel of the Follo Line, indicate the application of 5.5 bolts of approximately 16 kg per piece per meter tunnel (Korsmo & Bergsdal 2010). Further, according to the NPRA, the amount of bolts normally used ranges between 5-7 bolts per meter (Statens Vegvesen 2012). Therefore, we have assumed the following number of bolts per meter tunnel:

- A/B: 2.5 bolts per meter tunnel
- C: 5 bolts per meter tunnel
- D: 5.5 bolts per meter tunnel
- E: 6 bolts per meter tunnel
- F: 7 bolts per meter tunnel

To continue, the categories E and F also include pre-bolts and reinforced ring beams. For these bolts we have assumed the use of the “borstangbolt” (Statens Vegvesen 1999), since this specific bolt meet the requirements presented in the Q-method. The specific properties of the bolt are presented in Table 17 the appendix.

The calculation of the material requirements for the reinforced ring beams we performed based on information obtained in Pedersen et al (2010). The specific properties of the ring beams and the calculation method we applied are present in Table 18 in the appendix. The report presents the dimensions of both a single and a double reinforced ring beam, which is used for category E and F respectively. The floor cast for the category G is not included in this study.

### 5.3 ADDITIONAL TUNNELS

In addition to the main traffic tunnel, smaller tunnels are required for safety, water and working activities. These are all blasted and apply varying levels of securing. The inventory presented by Vianova<sup>20</sup> for the three different tunneling methods, presents the density of the additional tunnels per tunnel meter for each of the methods as presents in Table 7.

Tunnel	Meter additional tunnel per tunnel meter	Tunneling method
Cross section	0.14	All
Adit	0.14	All
Escape tunnel	0.02	Norwegian
Water tunnel	0.02	European and TBM
Access tunnel	0.05	TBM
Workinghall	0.05	TBM

**Table 7 Additional tunnels. The table presents the density of the additional tunnels included in the assessment and for which tunnel method they are assumed.<sup>20</sup>**

Each of these additional tunnels has a specific set of material requirements for support work. The inventory obtained from the same sources is presented in Table 8, per meter of additional tunnel.

	Entrance hall	Working hall	Adit	Cross-connection	Escape tunnel	Water tunnel	Unit
Bolts	0.10	0.10	0.04	0.04	0.05	0.04	Ton
Cement	2.01	2.26	1.08	0.85	0.69	0.85	Ton
Shotcrete	2.55	2.50	1.10	1.00	1.30	1.00	M3
Polyurethane	0.11	0.13	0.06	0.05	0.04	0.05	Ton
Explosives	0.12	0.14	0.07	0.04	0.04	0.04	Ton
Concrete cast	-	19.8	-	-	-	-	M3
Plastic	-	0.004	-	-	-	-	ton

**Table 8 Material requirements for additional tunnels per meter of the respective tunnel**

Since there is reason to believe that these numbers may vary depending on location and geological conditions, as well as cross sections of the additional tunnels, these are not included in the main calculations of the results. Instead a scenario calculation is performed to evaluate the impact of the additional tunnels assuming the inventory presented.

### 5.4 MAINTENANCE

The maintenance of a tunnel mainly concerns the technical installations, (with a service life of 30 years), the rail track and maintenance as a result of rock fall out or other damage problems. The service life of the tunnel lining for the Norwegian method is however calculated for 50-70 years while the European and the TBM method for 100 years according to tunneling specialists (Gammelsæter 2012). The service life of the Norwegian tunneling method was estimated for 50 years in the Follobanen project. The implication of this difference will be investigated in the next section of the report. Whether it is realistic to assume that the concrete elements will be taken down after 50 -70 years and new installed is not a main focus of this study, but its implications are investigated in the next section of the report followed by a brief discussion of the matter.

<sup>20</sup> Data for the Norwegian method is based on (Korsmo & Bergsdal 2010), the European is based on data from (Vianova 2011a), finally, data for the TBM is based on information from (Vianova 2011b)

## 6. RESULTS AND IMPACT ANALYSIS

In this section we present our results and analysis of the life cycle assessment calculated based on the inventory presented in Section 5. We begin the section by presenting our results of the baseline for the functional unit 1, one meter tunnel and tunnel track, followed by our results of the baseline for functional unit 2, the case corridor between Oslo and Stavanger.

Subsequently follows a section where we present our results of the technical and geological alternatives compared to our baseline for functional unit 1. Thereafter, we present our results for the same technical and geological alternatives for our baseline for functional unit 2.

### 6.1 ESTABLISHING THE BASELINE RESULTS

Our baseline results for this thesis constitute the technology traditionally used in Norway, the Norwegian tunneling method and the average level of support work, category C from the Q-method presented in Table 6, further the level 5 of grouting in Table 5, is included as this was the estimated volume for the Follo Line. Further, the ballasted track, the NSB95, presented in Table 1, is used for the entire corridor.

#### Functional Unit 1

Our baseline results for the functional unit 1, which represent one meter tunnel and tunnel track, are presented in Figure 17. Total emission level is indicated below each column.

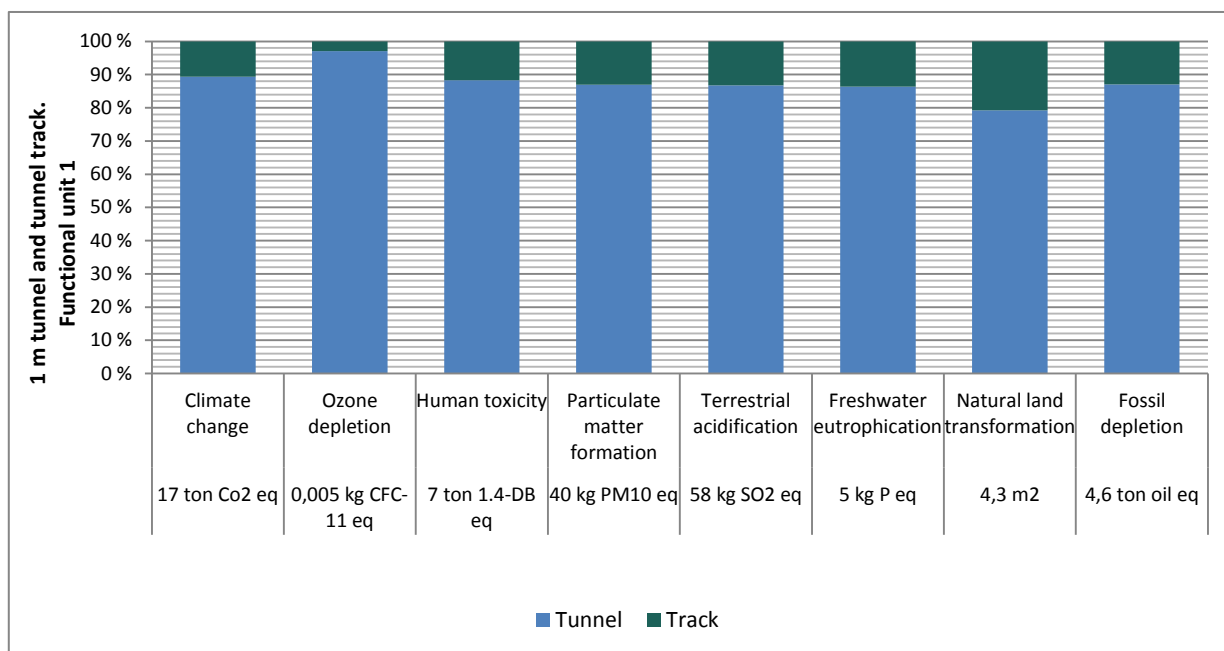


Figure 17 Baseline results, functional unit 1. The figure presents our results for the environmental impact of 1 meter tunnel and tunnel track for the baseline scenario 1. All processes for the 60 years of the estimated life cycle phase is included in the figure and in the total numbers indicated below the columns.

The tunnel represents the larger source of emission compared to the track for the FU 1 varying in the range 80–97% of total emission level depending on the specific environmental category. The average impact of the track is about 14% and constitute about 1.8 ton CO<sub>2</sub> eq. per meter tunnel, (including both directions). This presents an emission level of approximately 15 ton CO<sub>2</sub> eq. per meter tunnel.



For the category human toxicity, the tunnel represents about 6.8 ton 1.4-DB eq. and the track 0.8 ton 1.4-DB eq.

The relative largest impact of the tunnel occurs for the category ozone depletion while the comparatively smallest, for natural land depletion. The source and reason for these dissimilarities will be thoroughly investigated in the coming section of the report.

## **Functional Unit 2**

The total emission level we have calculated for the baseline results for the functional unit 2, we present in Figure 18. The total emission level is indicated below the columns.

The most dominating component presented in Figure 18 is the tunnel is indicated by the purple color. The construction and maintenance of the tunnel constitute about 30–70 % of total emission level depending on the specific environmental category. Figure 18, thus support the argument, that the tunnel constitute the major source of emission for a railway corridor, presented in Bergsdal et al.(2012)

The orange color, representing the operation phase constitutes the second largest emission source, which is mostly a result of the use of electricity. The operation phase and the train is not a topic of this report, but are included for the calculation of the FU2 so this will reflect all aspects of the life cycle of the rail corridor.

The rail track, indicated by the green color is the second main topic of this thesis and together with the tunnel construction result in the major bulk of total emission level. For climate change this share of about 55 % results in approximately 4.5 million ton CO<sub>2</sub> eq. For human toxicity the share is fairly similar representing about 2 million ton 1.4-DB eq.

The open section refers to the distances of the railway corridor which is installed directly on the ground in open areas. The section contributes with an average of 15% over the eight impact categories, with the relative highest impact for human toxicity. Bridges which are constructed from cement, steel, or both has a considerably impact on a per meter level, but because of the relative small share of bridge length estimated for the corridor, the bridge component have a relatively smaller impact on the total emission level.

The small share indicated by the light blue color, labeled “other infrastructure components” constitutes platforms, passing loops and rail switches.

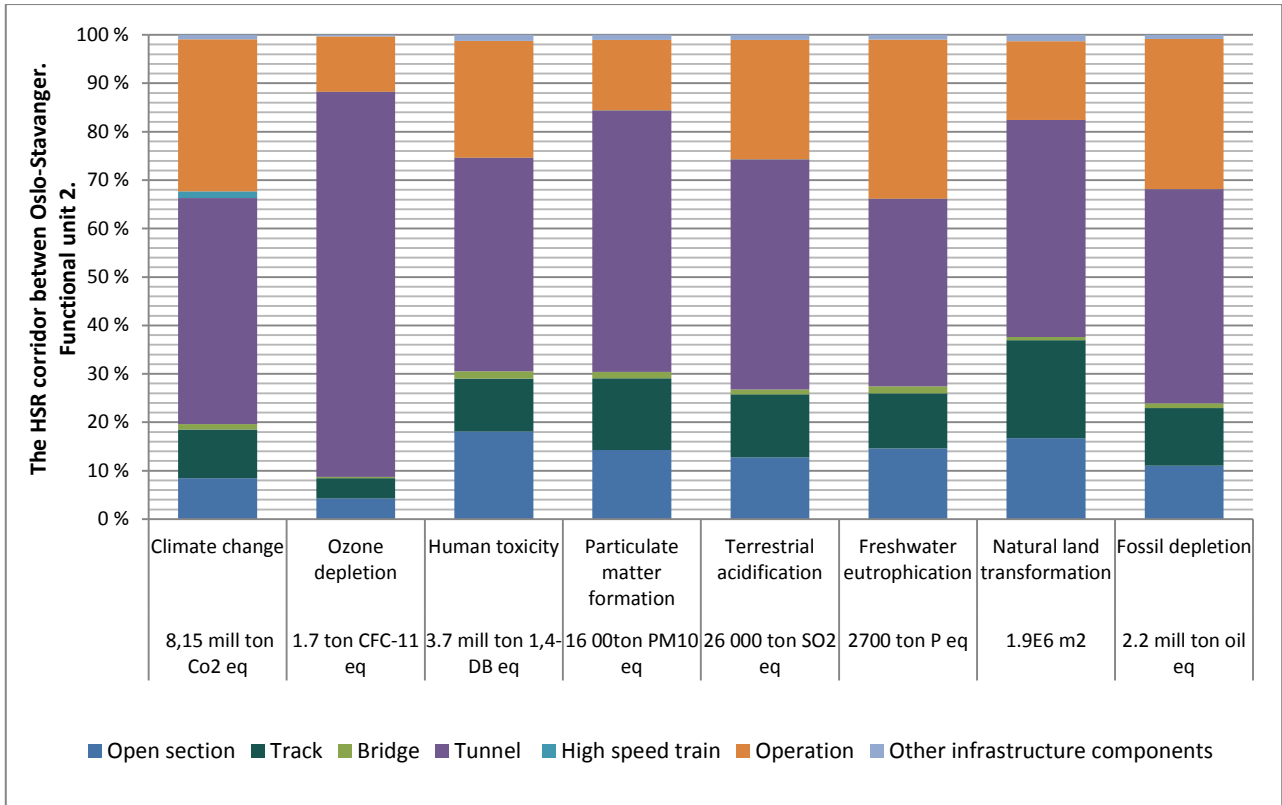


Figure 18 Baseline results, functional unit 2. The figure presents the share of environmental impact for the different railway components of our baseline results for the corridor between Oslo-Stavanger (250km/h). The “High speed train” and “Operation” represent the operation phase. The remaining labels indicate the different infrastructure components, were “Other infrastructure component” refers to platforms, passing loops and rail switches. Both the construction and maintenance phase over the life cycle of 60 years.

## 6.2 IMPACT OF TECHNOLOGICAL AND GEOLOGICAL CHANGE FOR FUNCTIONAL UNIT 1: ONE METER OF TUNNEL AND TUNNEL TRACK

In this section, we present the environmental consequence of a change in technology or geology dissimilar from our baseline results for the functional unit 1, which we presented in Figure 17. We begin with our results obtained for the application of slab track in tunnels and for bridges, followed by a presentation of our results for the three tunneling technologies. We present the technologies first for a tunnel estimated for 250km/h followed by a tunnel estimated for 330km/h. Next, we briefly discuss some uncertainties in our results of the tunneling technologies. Subsequently, we present our results of the different level of support work and grouting levels. Lastly we discuss the impact of our results for the additional tunnels.

### 6.2.1 TRACK TECHNOLOGY

In a recently finished student project, Lia (2011) investigate the environmental impact of several track designs for high-speed rail. Two of these technologies; the ballasted track NSB 95 and the slab track RHEDA 2000 are chosen for this assessment

In Lia (2011) the comparison between these designs resulted in only small differences for climate change and freshwater eutrophication. However, the differences were greater for ozone depletion and terrestrial acidification. The report concludes with an emphasis on the interconnection between the component service life, steel and the transportation of material waste, as the major influencing factors for the total results. The ballasted track of the report constitute relatively more material waste, thus the waste transportation constitute a differencing factor between the two designs. Figure 19 presents the relative impact from the two track designs included in this study.

Figure 19 presents a fairly dissimilar result compared to the student project. The reason is that we have removed the hydraulic bonded layer, as we discussed in section 3.1.

The most important difference between the two designs is the level of emission, as a result of waste transportation. Because of the relatively higher level of material turnover for the ballasted track are also the transportation requirements higher. The amount of material waste is a consequence of the calculated service life of the track components. The technical service life is thus an important factor which will be discussed in detail later.

The different materials in the graph are each denoted by their own color. The darker of a specific color indicate the construction phase, and the lighter, the maintenance phase, also labeled with an "(m)". Steel represents the material with the relatively highest emission level and includes reinforcement, rail and the rail fastener.

The relevance of the amount of steel is particularly important for the impact categories human toxicity and terrestrial eutrophication. The volume of concrete has the comparatively highest impact for climate change, and gravel for natural land transformation. Since the RHEDA do not include gravel, this category represents the relative largest difference between the two designs of approximately 17.5%.

For climate change, the decrease in CO<sub>2</sub> eq. by applying the slab track for tunnels and bridges represents about 3%. This is a total reduction of about 400 kg CO<sub>2</sub> eq. per meter. The RHEDA 2000 includes about three times the volume of concrete as the NSB 95, but because of the vast amounts material transported, the result is a lower environmental impact for the slab track. For human toxicity

a 3% decrease of emission is associated with the installation of the slab track in tunnels and on bridges.

Our conclusions emphasize the interdependence between the service life and material waste, and a relatively high impact from steel for rails, is in line with the results obtained by Lia (2011). Further, they present a higher sensitivity for the transportation length for the ballasted track, and the greatest environmental benefit from increasing the assumed service life of rail.

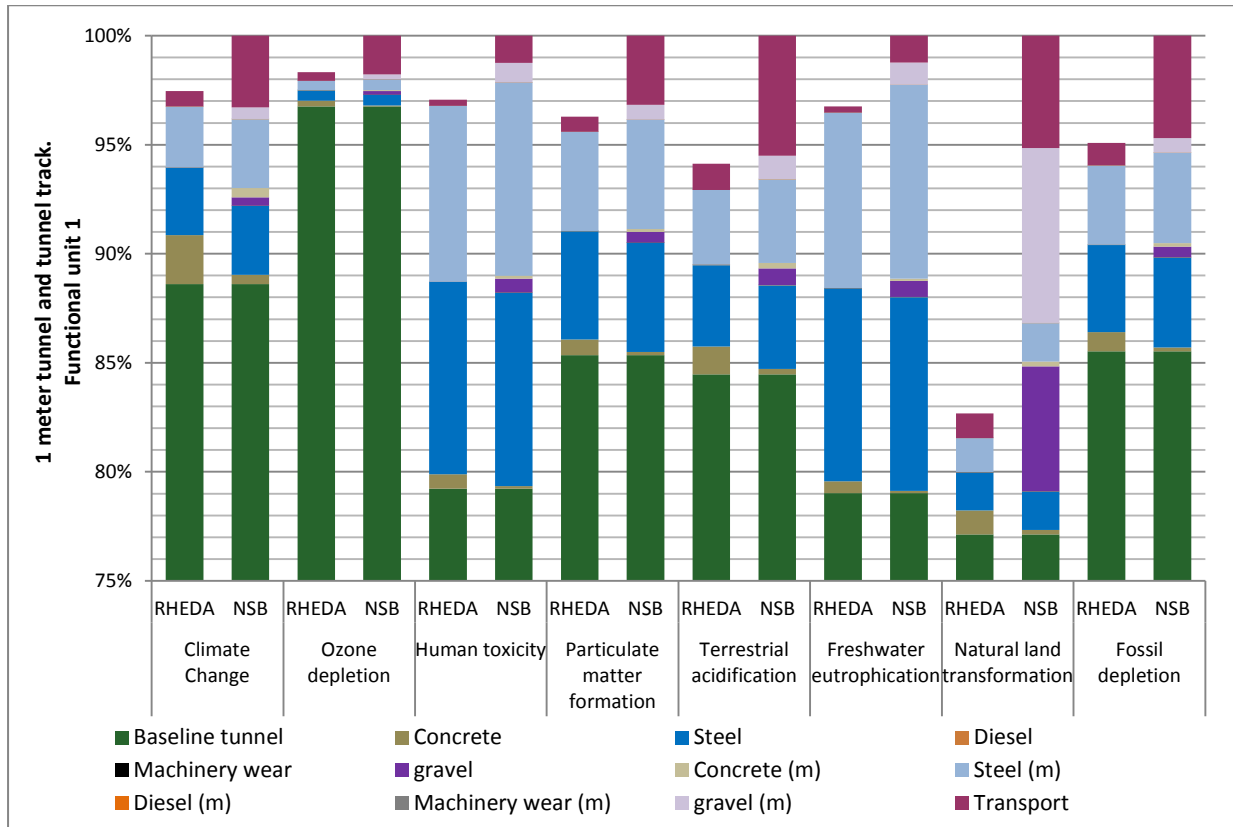


Figure 19 Comparing ballasted and slab track design. The figure present a comparison of the materials applied for one meter tunnel and track, applying the NSB95 and the slab track, RHEDA 2000. Both the construction and the maintenance phase are included where the latter is indicated with (m). The process "Transport", represents the activity of transporting waste materials to deponi.

### 6.2.2 TUNNELLING TECHNOLOGIES

We have illustrated the material requirements for the construction of the three tunnelling methods, the Norwegian, the European and the TBM in Figure 20. Our baseline scenario consist of the Norwegian tunnelling technology, our results are thus normalized to this method.

Figure 20 presents a dissimilar distribution of impact between the different impact categories as a result of different material composition. It is however, the materials cement and steel which results in the relative highest impact for almost all categories. The statement made by Bergsdal et al. (2010), of the importance of these materials for a railway construction, is thus supported by our results.

In the graph, orange and red represent diesel and electricity respectively. Different shades of blue indicate components made from cement, while green represents emission associated with the production of steel. Purple labels explosives and black, XPS.

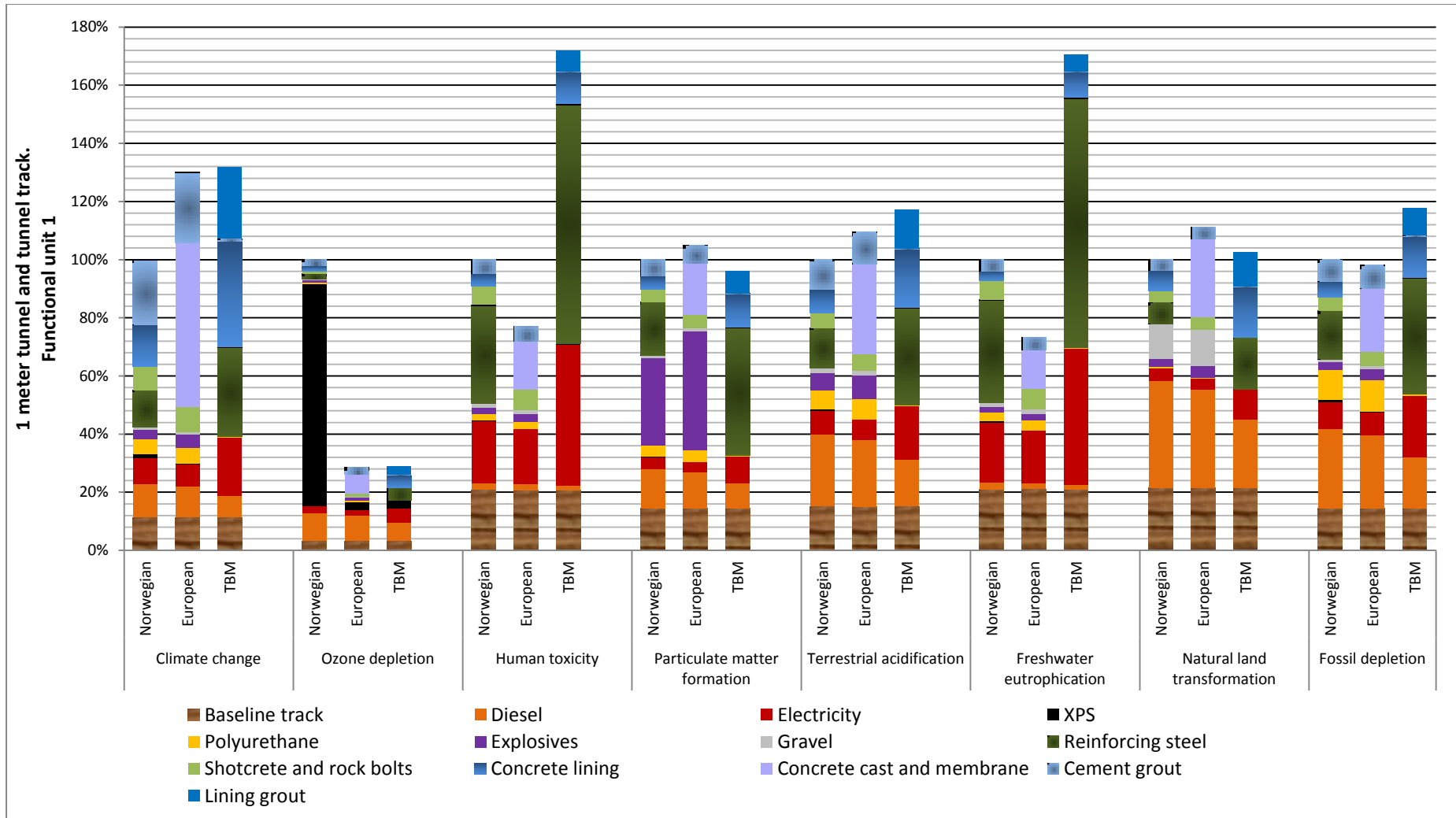


Figure 20 Compare the relative impact of the construction materials for the three assessed tunneling methods for the estimated life cycle phase of 60 years. The graph is normalized to the Norwegian method, as this represent the baseline tunneling method. Included in the graph is the baseline track, the NSB95.

Concrete has a comparatively high impact on climate change leading to a higher emission level for the European tunneling method compared to the Norwegian method. The main reason is the concrete cast which ultimately leads to a 34% higher emission level which constitutes approximately 4.7 ton CO<sub>2</sub> eq. per meter tunnel (including both directions). The total increase in emission for the TBM constitutes of about 4.9 ton CO<sub>2</sub> eq. per meter tunnel. Ozone depletion potential is highly influenced by the use of XPS. However, since only small amounts of this substance are used through the entire process of the tunnel construction, what do exist will present misleadingly high impacts. By normalizing the results for ozone depletion, the XPS presents marginal results, confirming the statement.

The impact on human toxicity and freshwater eutrophication is similarly to the results presented in Figure 19, highly sensitive to the amount of steel, and in this case, electricity. Because of the absence of reinforcement steel in the European tunneling method, the impact on the mentioned environmental categories are comparatively lower than for the TBM and the Norwegian method, which both include reinforcement steel. The result is a reduction of about 31% which amounts to about 1 ton CO<sub>2</sub> eq. for the European method. Because of the large amount of reinforcement steel in the lining for the TBM, this method results in an increase of about 74% compared to the Norwegian method.

The use of explosives has the comparatively highest affect on the environmental category particulate matter formation. The result is a comparatively lower emission level for the TBM method of about 4%. The only category that is significantly influenced by the amount of gravel in this graph, is natural land transformation indicated by the gray color. The use of diesel has an impact on all categories, ranging between 4–40% of total impact were the comparatively highest impact is for natural land transformation, fossil depletion and terrestrial acidification.

### **Tunnel Technology for 330km/h**

The results we presented in Figure 20 represent a tunnel estimated for a speed of 250 km/h. In the high-speed rail assessment, two sets of corridor speed were assessed, 250km/h and 330km/h. In Figure 21 we illustrate our results of the impact assessment for a tunnel designed for 330km/h, for each of the tunnelling methods included in this study. We have maintained the same use of colours as in Figure 20.

The main difference compared to our results calculated for a tunnel designed for 250km/h, is the relatively smaller impact from the European method for all categories. This is a result of the tunnel dimensions, presented in Table 4. Compared to the cross section for a tunnel of 250km/h, the dimension for the European method for 330km/h presents a thinner tunnel wall and thus a reduced requirement for materials. The reason may be explained by the varying thickness of the concrete cast and profile. The specific tunnel dimensions were used in the NHSRA, and are thus included in this thesis, the results should nevertheless be interpreted with caution

It is however interesting to note that if the thickness of the tunnel walls were maintained, the relative relation between the three tunnelling methods would be similar to that presented in Figure 20.

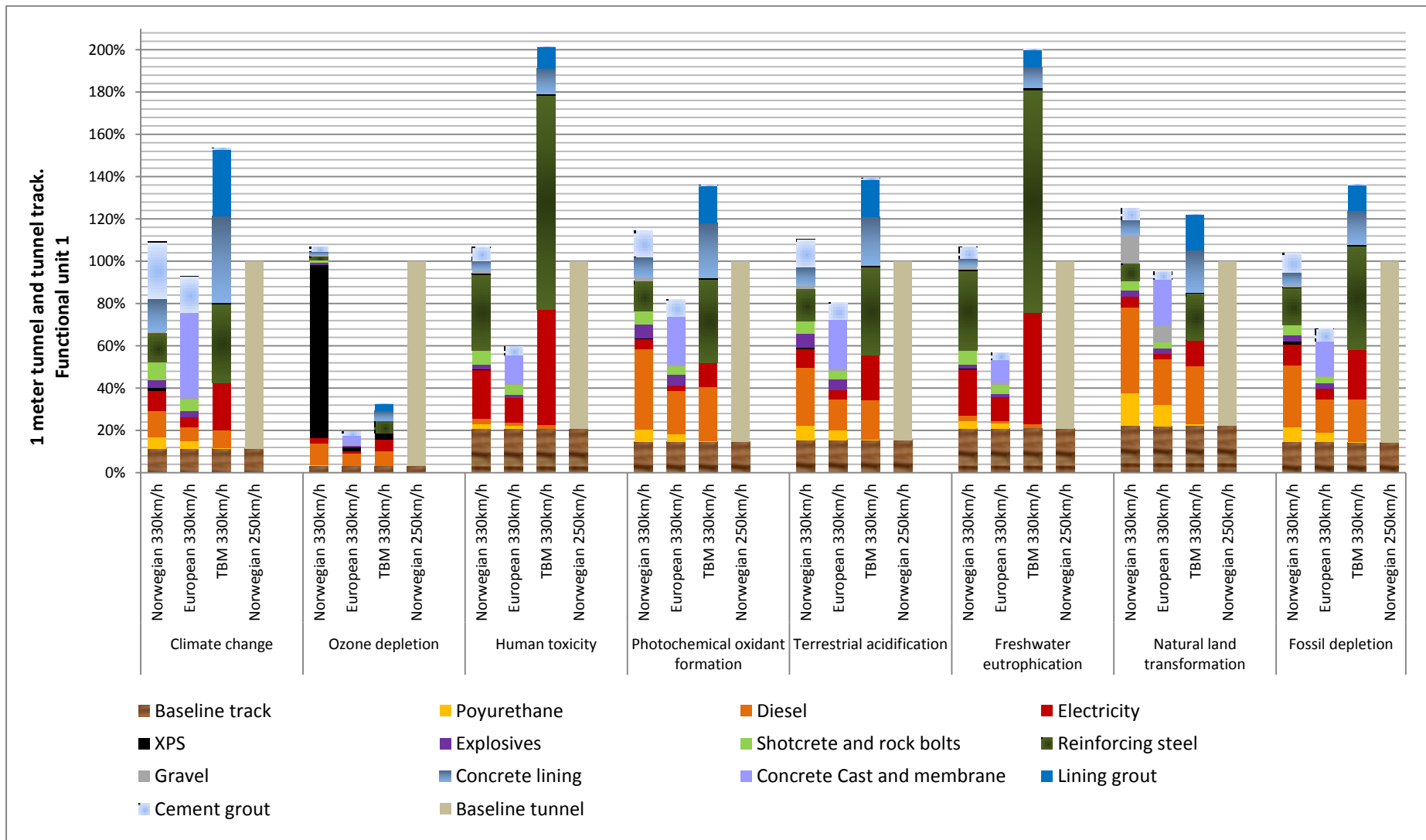


Figure 21 Comparing one meter of tunneling technology 330km/h. The figure presents a comparison of the material requirements for the double shielded tunnel boring machine, the Norwegian and the European method, estimated for 330km/h. The results are normalized to our baseline results estimated for 250km/h

## Tunnel Technology and Uncertainties

Several assumptions are made to obtain the results presented in Figure 20. Some of the most influential are the maintenance of the Norwegian tunnelling method and the size and installation of the concrete segments for the tunnel boring machine.

### I. Tunnel service life: Norwegian med 50 years service life

The Norwegian tunnelling method is estimated for a service life of 50–70 years while the European and the TBM tunnel are estimated for 100 years (Gammelsæter 2012). According to the method for calculation of service life assumed for this report, if 50 years were assumed for the tunnel lining, the calculations would include a total exchange of this lining. The work and energy required to first hack down the existing lining is not included in the assessment. Figure 22 presents the relative impact from the different tunnelling methods, including a total shift of lining for the Norwegian tunnelling method after 50 years indicated by the tan colour.

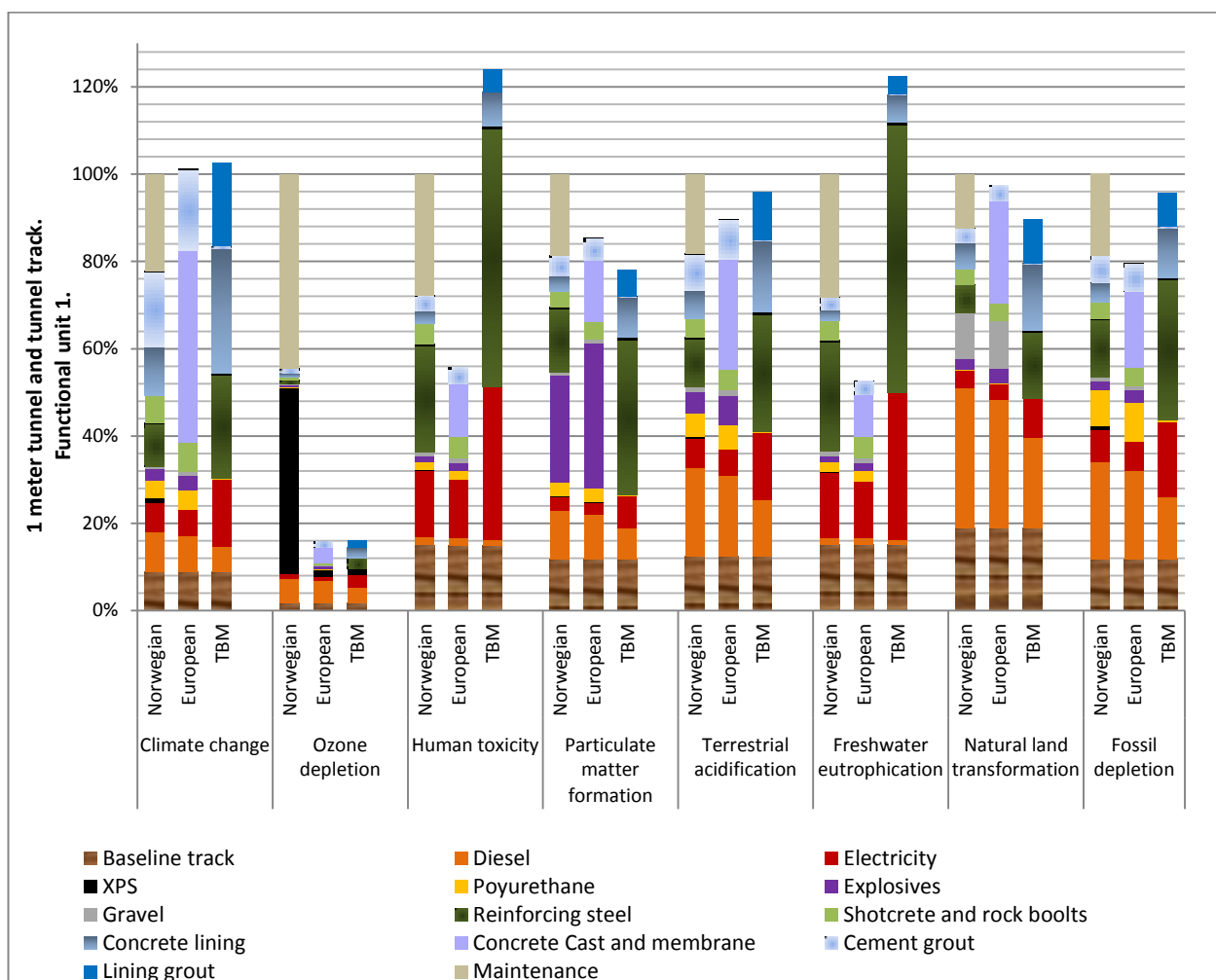


Figure 22 Comparing tunnel maintenance. The figure presents a comparison between the three tunneling methods when estimating the Norwegian method for a service life of 50 years. This adds a total shift of lining for the Norwegian tunneling method indicated by the tan color.

The result is an increase in emission level for the Norwegian method of 20–42% of total emission level. Following this assumption, the Norwegian tunneling method represent an increase in emission level compared to the European method for all impact categories except climate change. Because of



the large amount of concrete included in the European tunnel, will this method still have a relative higher impact compared to the Norwegian technology.

## II. TBM tunnel – Segments

The tunnel boring machine assessed in this study install concrete segments for the entire length of the tunnel. Since the TBM creates less damage to the rock compared to the D&B method in the excavation process, there is a possibility that there might not be necessary to install these segments for the entire tunnel length. Figure 23 presents a comparison between one meter of TBM tunnel with and without concrete segments. In addition to the concrete segments, also, the concrete grouting used to seal the segments together and fill out the space behind the segments are included in the graph columns.

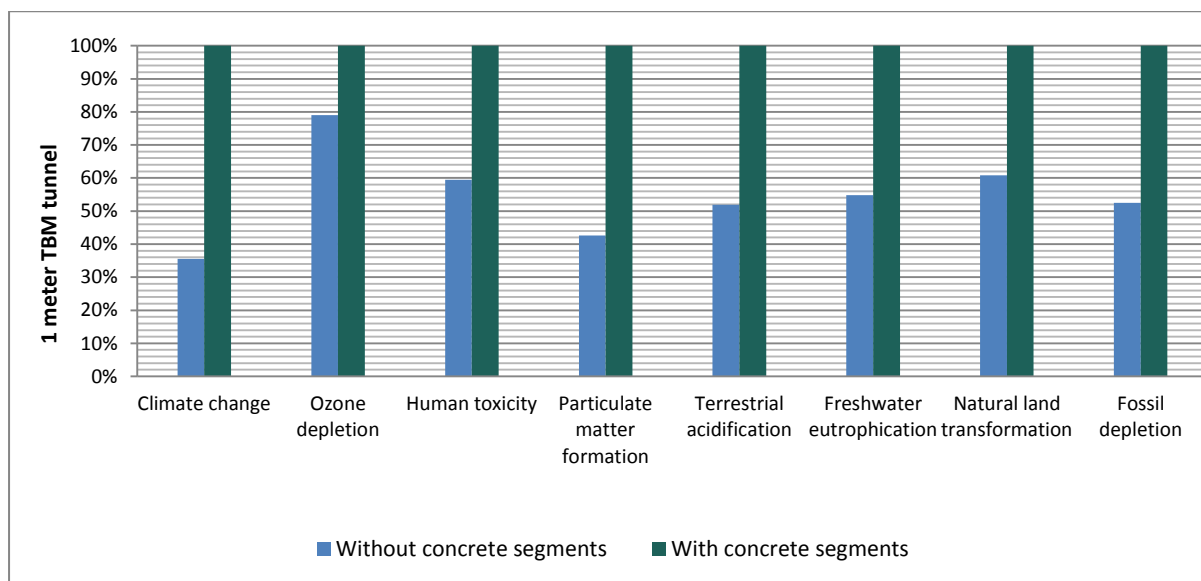


Figure 23 TBM lining. Comparison of a scenario which includes the reinforced segments for the double shielded TBM to a scenario that does not apply the segments. The lining grout used to seal the segments is also included in the graph.

The segments consists of both cement and steel and thus have a considerably impact for all environmental categories. For climate change, the result of not including the concrete segments represents a decrease of total emission by 64%. This gives a total reduction of 12 ton CO<sub>2</sub> eq. Similar; the reduction for human toxicity represents a decrease of 40%, which is 4 ton 1.4-DB eq.

The columns presenting a result that do not include the concrete segments may be representative for the use of a different tunnelling machine, the main beam tunnel boring machine (see section 3.2.2 on page 16 for description). The main beam applies the same methods for support work as the drill and blast method instead of the concrete segments. The reduction of materials per meter tunnel (calculating for support work equal that of the drill and blast method), would reduce the total emission level to about 7 ton CO<sub>2</sub> eq. per meter, (including both directions). This would ultimately result in the TBM would be the preferable method in a climate perspective.

Further, the segments applied vary within the range 40–60cm. The environmental consequences of the different sizes are presented in Figure 24. The thickness included in this assessment is that of 40 cm. The increase of 10 cm represents an increase of about 12% or 2 ton Co<sub>2</sub> eq. per meter tunnel. Because of the increase in reinforcement steel, the impact is about similarly important for the other impact

categories except ozone depletion as the TBM lining do not affect the category ozone depletion to any particular degree.

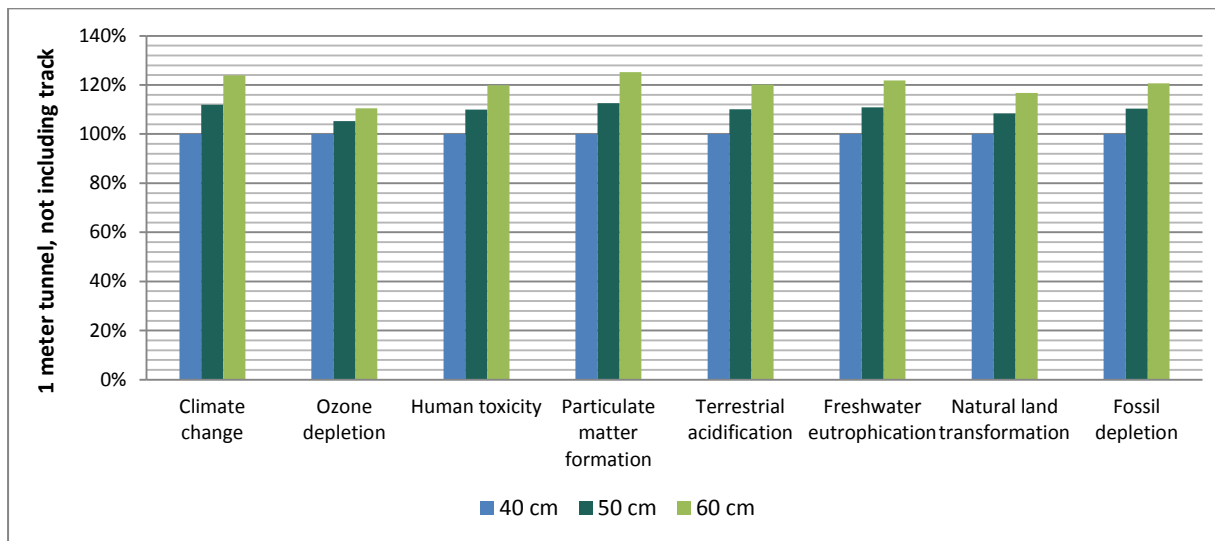


Figure 24 TBM segment size. Comparing the environmental impact from different possible thicknesses of reinforced concrete segments applied for 1 meter of tunnel constructed with a double shielded tunnel boring machine.

### 6.2.3 GEOLOGICAL CONDITIONS AND REQUIREMENTS – THE Q-METHOD

To evaluate the different geological conditions, we have calculated material volume for five securing levels based on the rock quality categories of the Q-method. In Figure 25, we indicate the environmental impacts associated with each of these categories.

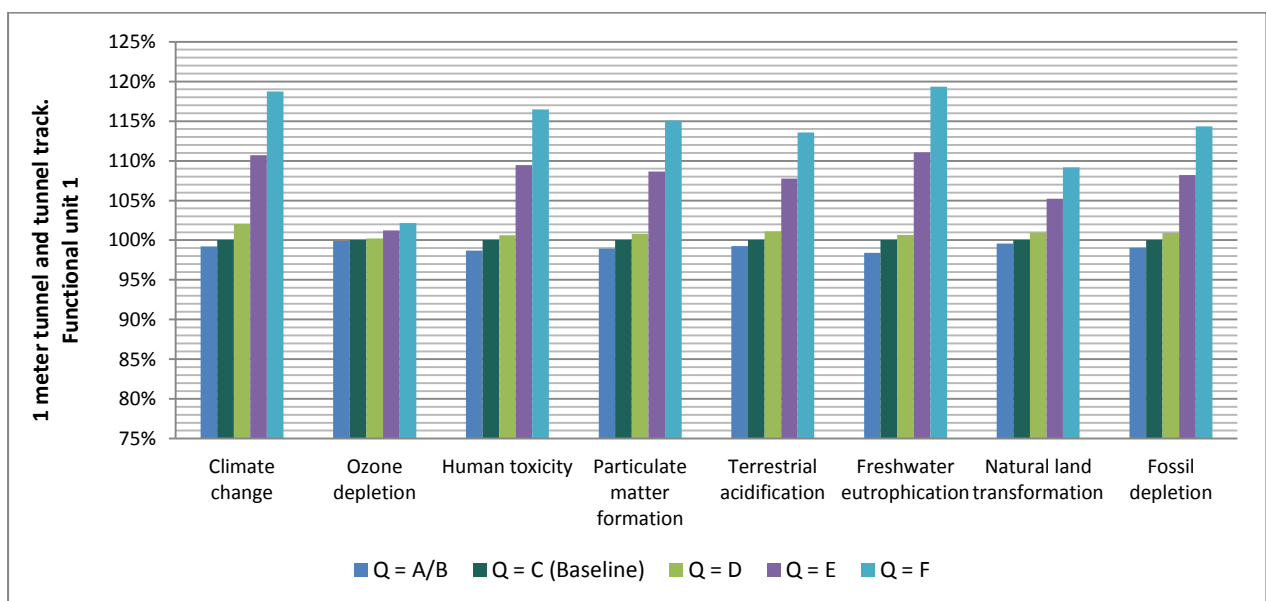


Figure 25 Level of support work FU1. The image presents our results of the five analyzed securing levels based on the five first categories of the Q-method. Results are normalized to the category C, which represent the category applied for our baseline results.

The inventory for the categories of the Q-method constitutes of steel and concrete and has therefore little effect on ozone depletion compared to the other seven categories. The largest effect on total emission level is however for climate change and freshwater eutrophication.

The baseline inventory constitutes the category “C”, which is the second lightest level of support work of the five categories. A securing level equal that of the category C is further the most used level for railway tunnels in Norway because of stable rock and since engineers strategically seek to place the tunnels in order to avoid applying securing similar to the level F or worse (Gammelsæter 2012). The difference between A/B and C is a slight increase in the number of bolts per meter and equal a difference of about 1%. Moving from securing level C to D includes an increase of an extra 20 mm of shotcrete and about 2% increase in emission per meter. The total increase is about 0.3 ton CO<sub>2</sub> eq. and about 46 kg 1.4-DB eq.

The comparatively largest increase in emission occurs when moving to category E and F. The reason is the application of reinforced ring beams. Such an increase in support work compared to the baseline category C, would result in 2 or 3 ton increase in CO<sub>2</sub> eq. for the category E and F respectively. For human toxicity, the same increases would give a 0.7 and 1 ton increase of 1.4-DB eq.

#### 6.2.4 GEOLOGICAL CONDITIONS AND REQUIREMENTS – GROUTING

For grout, we divided this into five different levels, as described in Table 5. In Figure 26 we present the comparison of our calculations for the environmental impact because of applying the five grouting levels. The grout is made from cement, a change in grouting level, has therefore the relatively highest impact for climate change followed by terrestrial acidification.

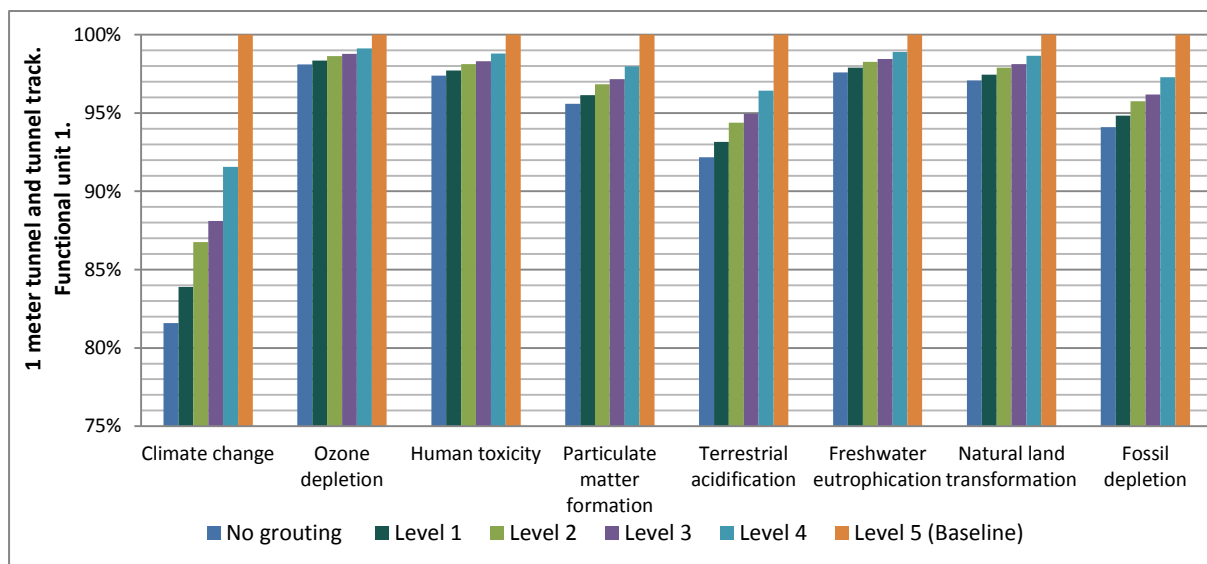


Figure 26 Level of grouting FU1. The image presents the comparison of our five estimated levels for grouting. The results are normalized to level 5 since this is the level applied for our baseline results.

The level of grout applied for our baseline in this thesis is the level five, which amount to 96kg cement per m<sup>2</sup> of the tunnel. The largest environmental difference between the grouting levels occurs between level 4 and 5. The reason is a comparatively larger increase in cement per kg compared to the remaining categories. A reduction from the baseline scenario to the level 4 would result in a decrease of 1 ton CO<sub>2</sub> eq. and approximately 60kg 1.4-DB eq. The total difference between level 1 and 5 represent approximately 17% or close to 2 ton CO<sub>2</sub> eq. and about 3% or 0.1 ton 1.4-DB eq. per meter tunnel.

### 6.2.5 ADDITIONAL TUNNELS

Figure 27 presents the impact of including additional tunnels for each of the tunneling methods. The comparatively largest impact occurs from the additional tunnels for the TBM method, which in this analysis represent the method with the highest density of additional tunnels (see Table 7 on page 39). The material applied for the tunnels mainly consist of concrete and therefore consequently has the highest impact for climate change, and terrestrial acidification. Further, the construction of these tunnels all require the use of explosives, which in turn as an increasing effect of the category particulate matter formation.

As presented in Figure 27, does the highest impacts for the additional tunnels, occurs for the tunnel boring machine. This is in conflict with what was initially expected from the description of the TBM in section 3.3. The anticipated result was fewer additional tunnels for the TBM, which is the opposite of what is presented in the inventory of density of additional tunnels in Table 7. Neither working halls nor an access tunnel is included for other technologies than the TBM. The total impact of the tunnels are however, not very significant, with a total of 2% of total CO2 level for the D&B method and about 4% for the TBM tunnel.

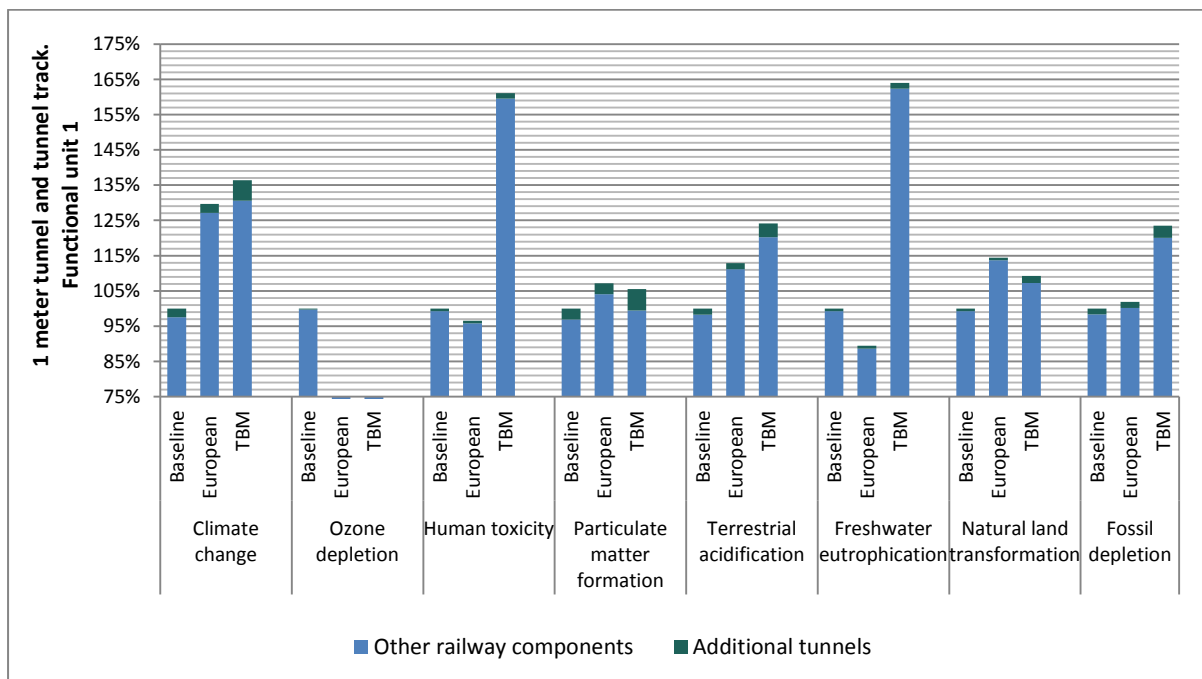


Figure 27 Additional tunnels FU1. The image presents the relative impact of additional tunnels such as adits and escape tunnels for each tunneling method. The results are normalized to the Norwegian tunnel, which represents our baseline results.

### 6.3 ENVIRONMENTAL IMPACT FOR THE FUNCTIONAL UNIT 2: THE CASE CORRIDOR BETWEEN OSLO AND STAVANGER

In this section, we present the environmental consequence of a change in technology or geology dissimilar from our baseline results for the functional unit 2, which we presented in Figure 18. We begin with our results obtained for the application of slab track in tunnels and for bridges, followed by a presentation of our results for the three tunneling technologies. We present the technologies first for a tunnel estimated for 250km/h followed by a tunnel estimated for 330km/h. Subsequently, we present our results of the different level of support work and grouting levels. Lastly we discuss the impact of our results for the additional tunnels.

#### 6.3.1 THE USE OF SLAB TRACK IN TUNNELS AND ON BRIDGES

Reviewing Figure 17 in the previous section, the graph presents a general reduction per meter for all impact categories when installing the slab track in tunnels and on bridges. The reason is mainly the reduced transportation requirements due to a lower material turnover for the slab track. The component service life is however an uncertain factor which have great influence on total results.

Figure 28 presents the results from installing the slab track for all tunnels and bridges on the case corridor. As expected do the introduction of slab track result in a similar decrease in total emission level as Figure 17. The difference is slightly lower however, because of the many other influencing components included in the calculations of the functional unit 2.

The total reduction varies within the range of 2-9%. For climate change the 2% reduction represent just above 100 000 ton CO<sub>2</sub> eq. and for human toxicity about 1% which represent 25 000 ton 1.4-DB eq.

The comparatively largest difference occurs for natural land transformation, because of the gravel used for the ballasted track. Since the slab track does not include gravel, the difference is therefore relatively larger. Also for terrestrial acidification is the difference significant. This is a result of the reduced transportation requirements for the slab track design. The track in general has the relative smallest impact on ozone depletion, which is because of the high impact leading from the use of XPS in the Norwegian tunnelling method.

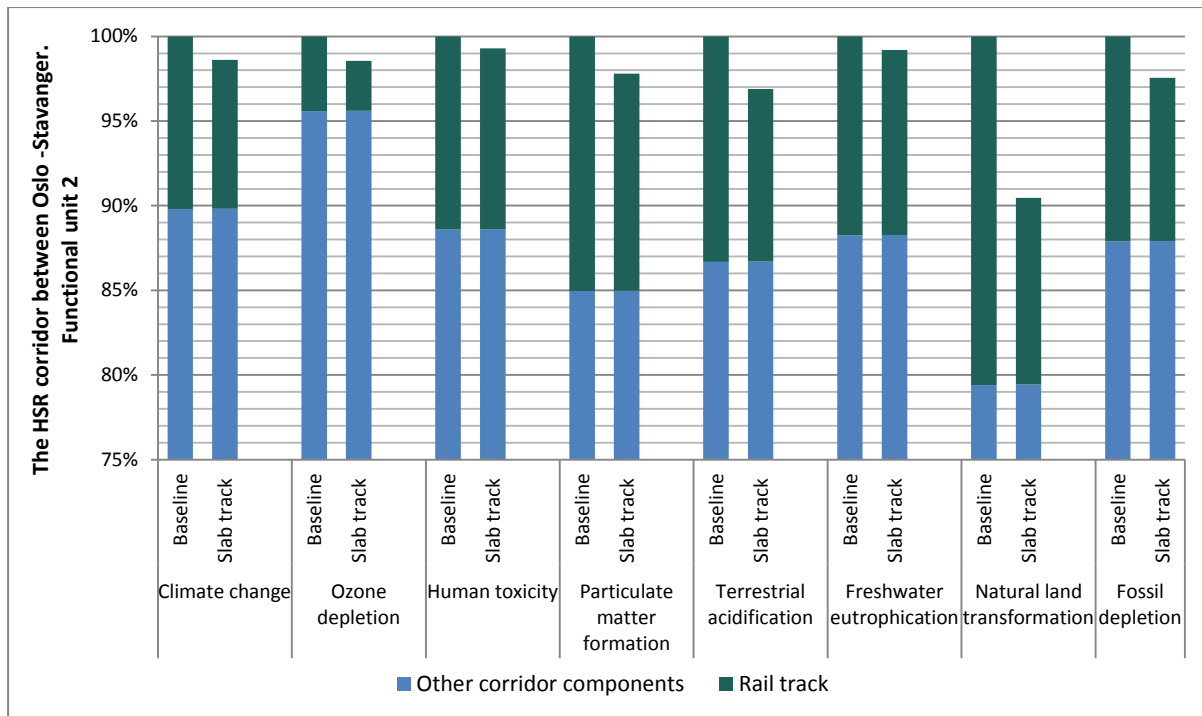


Figure 28 Track design FU2. The image presents the relative impact of the two track designs, the ballasted track NSB 95 and the slab track RHEDA 2000 for the total corridor. For the slab track scenario, the RHEDA 2000 is applied for tunnels and bridges, while the NSB 95 is used for the open sections. The baseline scenario consists of the NSB95 for the entire corridor.

### 6.3.2 TUNNELLING TECHNOLOGIES

The tunnel length of the case corridor represents about 50% of the total corridor length. Variations in the tunnel therefore, have a great impact on the total emission level for the functional unit 2.

Figure 29 illustrates the relative impact of the three tunnelling methods on the total emission level for the case corridor. In general, tunnels have the comparatively highest impact for particulate matter formation (not including ozone depletion potential because of the unrealistically high impact from the XPS as discussed for Figure 19). The reason is the relative high impact from the use of explosives. The TBM tunnel does not use explosives, but because of the high amount of steel, the emission level is not significantly reduced compared to the other methods.

The impact on climate change and terrestrial acidification from the tunnel constructions is significant and represent 40-50% of total emission level for the case corridor. The difference from baseline, (the Norwegian method) is a result of higher volume of cement applied for the TBM and the European method.

Reviewing Figure 20, the similar pattern is present in Figure 29, only uncovering a slight reduction in relative differences between the tunnelling methods.

The baseline result for climate change is estimated to approximately 8.15 million ton CO<sub>2</sub> eq. A change in tunnelling technology to the European method would result in an increase of 12%, which represents just above 1 million ton CO<sub>2</sub> eq. and about 1.3 million ton CO eq. increase if applying the tunnel boring machine. The European tunnelling method does however not include reinforcement steel, the total emission level for human toxicity is as a consequence lower compared to the baseline, the Norwegian method. To install the European would therefore decrease total emission level with

about 300 000 1.4-DB eq. To construct the tunnel using the boring machine would however increase total emission with approximately 800 000 1.4-DB eq. due to the vast amount of reinforcing steel.

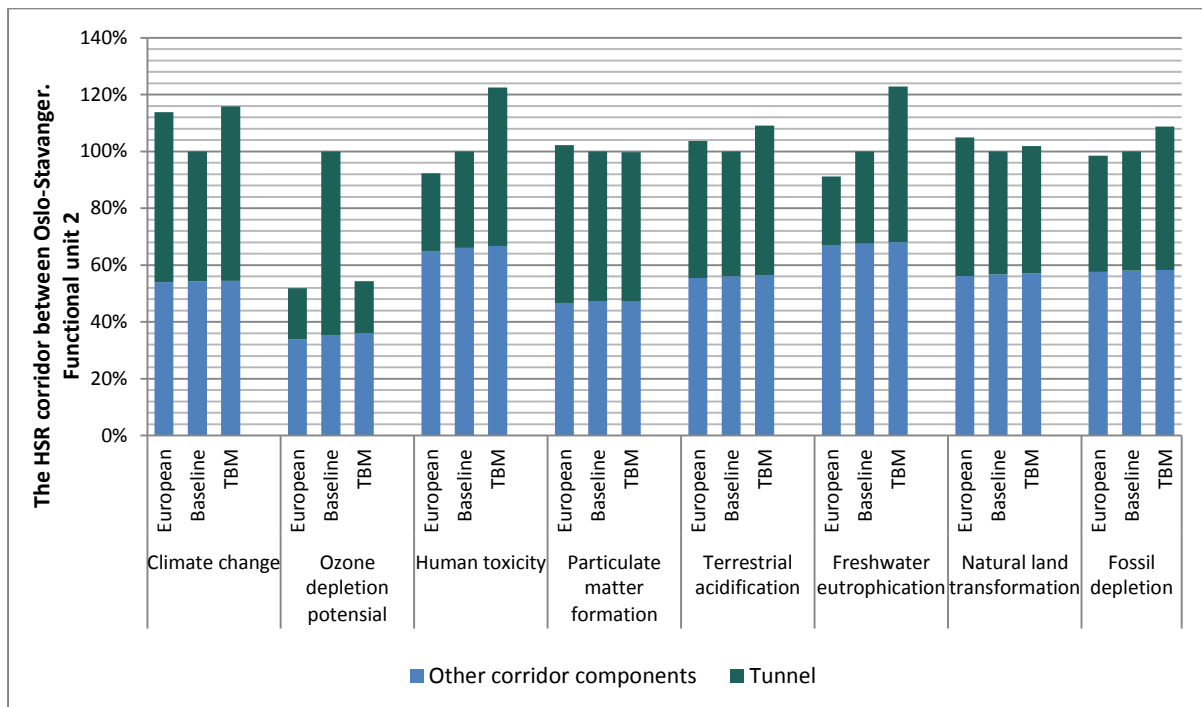


Figure 29 Tunneling methods, FU2. The figure presents the relative impact of the different tunneling methods on the case corridor. The results are normalized to the Norwegian method, which constitute our baseline result. The graph includes all activities within the estimated 60 years life cycle phase.

### Tunnel Technology for 330km/h

Figure 30 illustrates the relative difference in emission level between the three assessed tunnelling methods for a railway corridor designed for a speed of 330km/h. These results are evaluated against the baseline scenario indicated by the light green colour. The graph presents a shift in the relative relation between the three tunnelling methods, resulting in reduced impact from the European method for all impact categories.

The reason for the comparatively reduced emission level for the European method is an assumption in the tunnel dimensions estimated for 330km/h, that the materials for the tunnel walls can be reduced significantly. Based on this assumption, the reduction by construction a tunnel for 330km/h applying the European method, would reduce total emission level for climate change by approximately 4% or 340 000 ton CO<sub>2</sub> eq. and about 9% or 300 000 ton 1.4-DB eq. for human toxicity.

The results however, must be interpreted with caution because of this uncertainty and should be a topic for further investigation. If the method in question were to maintain the same thickness of the tunnel walls for the increase in speed, the results would present a similar ranking between the three tunnelling methods as illustrated in Figure 29.

The TBM and the Norwegian method are both increased similarly maintaining the relative relation between the two methods. Compared to the baseline, the TBM and Norwegian tunnel estimated for a speed of 330km/h results in significantly higher environmental impact. For the impact category climate change, the increased speed would result in a 7% increase of emissions, which represent about 580 000 ton CO<sub>2</sub> eq., and for the TBM, an increase of approximately 25% or 2 million ton CO<sub>2</sub> eq.

The increase of the Norwegian tunnel is however, an estimate we produced for this thesis, and may thus constitute some level of uncertainty.

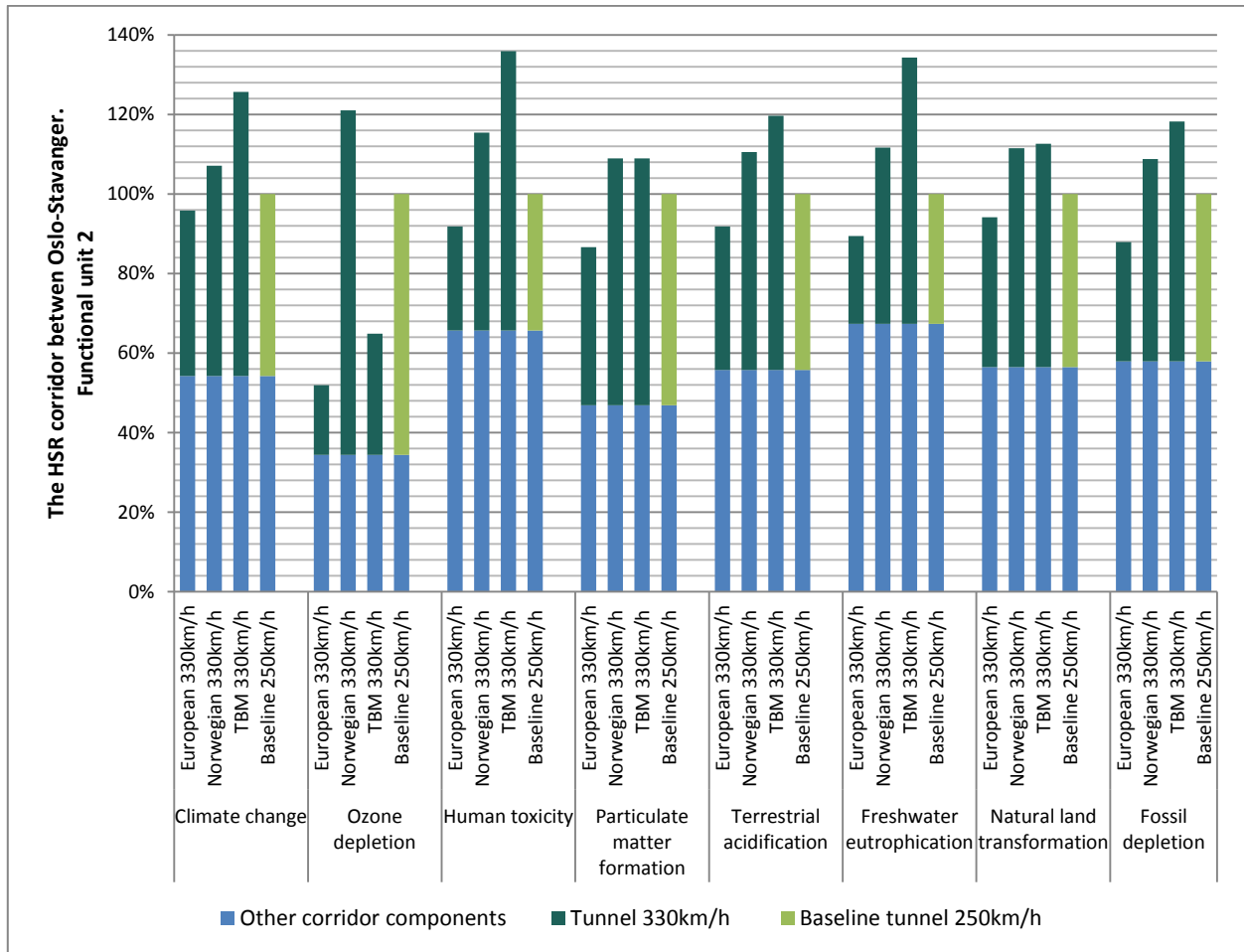


Figure 30 Tunneling technology 330km/h. FU2. The figure presents the relative impact of the Norwegian, the European and the double shielded tunneling technology for 330km/h for the total emission level normalized to our baseline results. The results for the European method presented in this figure are based on dimensions which indicate a reduction of the tunnel wall compared to a tunnel of 250km/h. The result should therefore be interpreted with caution.



### 6.3.3 GEOLOGICAL CONDITIONS AND REQUIREMENTS – Q-METHOD

In Figure 31 we illustrate the relative impact of the different support work categories based on the Q-method, relative to the total impact of the case corridor. The support work consists of steel and concrete, where the latter constitute the larger part. The high level of concrete results in a comparatively higher impact on climate change from a potential change in securing level. For the first three securing levels, only small changes in impact are presented, similar to the results presented for functional unit 1 in Figure 25. The largest difference in impact occurs when assuming a change in securing level equal to the categories E and F.

Our baseline result represents about 8.15 million ton CO<sub>2</sub> eq. presented by the category C. An increase in securing level equal to category E and F would result in an increase of about 6 and 10% or 450 000 and 800 000 ton CO<sub>2</sub> eq. For the impact category human toxicity, such an increase would lead to a 170 000– 300 000 ton 1.4-Db eq.

The total difference between the category A and F represent slightly higher than 10% or 830 000 ton Co<sub>2</sub> eq. for the category climate change.

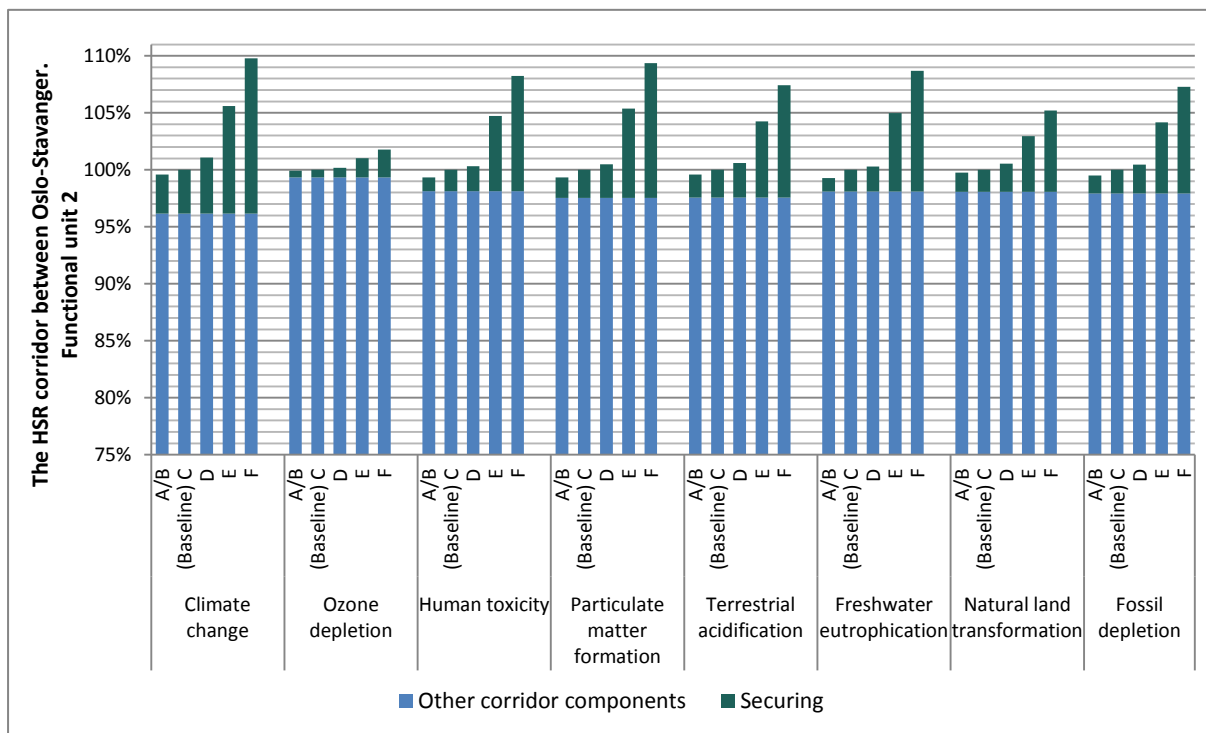


Figure 31 Level of support work FU2. The image presents the impact of the five securing levels based on the five first categories of the Q-method relative to the impact from the case corridor. Results are normalized to the category C, which represent the category applied for our baseline.

### 6.3.4 GEOLOGICAL CONDITIONS AND REQUIREMENTS – GROUTING

In Figure 32 we present the impact of the different levels from our calculations for grouting. Because of the material assumed for the grout, climate change represents the category comparatively most influenced by the injection level. The differences between the grouting levels present a relatively largest difference between level 4 and the baseline level 5. Except for terrestrial acidification which is somewhat effected by a change in injection level, is the impact on the remaining categories limited to a few percent.

The total difference between level 1 and 5 is about 9% or 760 000 ton CO<sub>2</sub> eq. for climate change and about 1% or 46 000 ton 1.4-DB eq. for human toxicity.

The largest relative difference between the levels of injection cement is as mentioned between the level 4 and 5. A reduction of the cement equal to that of level 4 would result in a reduction of approximately 400 000 ton Co<sub>2</sub> eq. and 24 000 ton 1.4-DB eq.

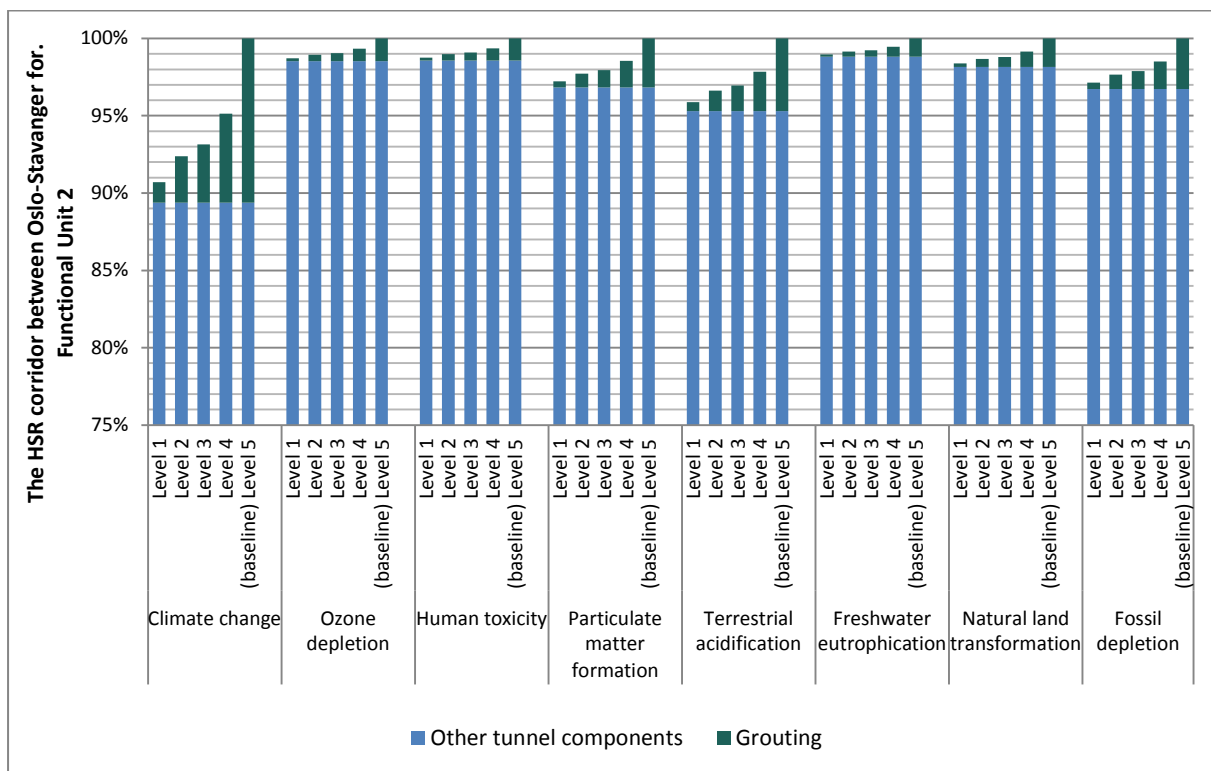


Figure 32 Level of grouting, FU 2. The image presents comparison of the relative impact of the five estimated levels for grouting compared to the total emission level of the corridor. The results are normalized to level 5, since this is the level applied for our baseline results.

### 6.3.5 ADDITIONAL TUNNELS

The additional tunnels, as previously mentioned, mainly have an impact on climate change, terrestrial acidification and particulate matter formation, because of the use of concrete for support work and explosives for excavation. Figure 33 presents the environmental impact from including the additional tunnels for the case corridor for each of the three assessed tunnelling methods.

For climate change, the additional tunnels represent about 200 000 ton CO<sub>2</sub> eq. for the baseline corridor. The European method results in a similar amount, while the additional tunnels for the TBM represent about 500 000 ton CO<sub>2</sub> eq. The additional tunnels thus represent about 3% for the drill and blast methods and about 5% for the double shielded boring machine.

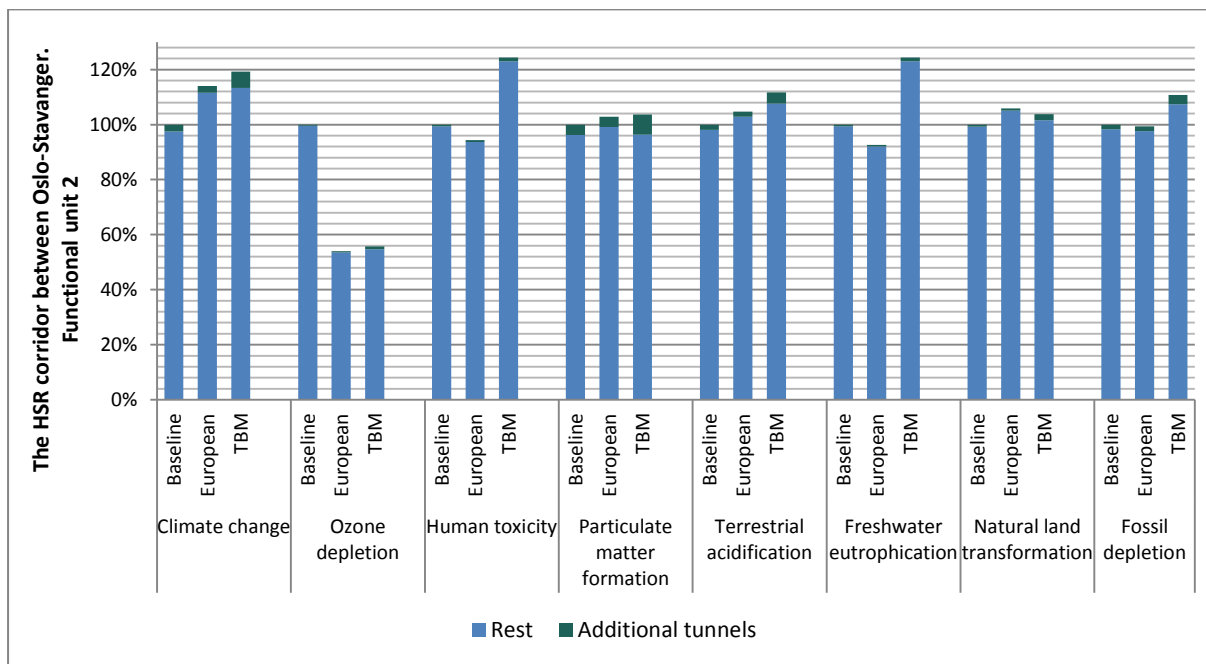


Figure 33 Additional tunnels, FU2. The image presents the relative impact of additional tunnels such as adits and escape tunnels for each tunneling method relative to total impact from the corridor. The results are normalized to the Norwegian tunnel, which represent the baseline.

## 7. INTERPRETATION

The following section represents phase 4 in the life cycle assessment, as illustrated in the LCA framework, presented introductory in Figure 2. According to the ISO 14040: 2006, the interpretation phase should analyse the obtained results in order to draw meaningful conclusions in accordance with the goal and scope (Standard Norge 2006). We have thus structured the following section in order to meet these requirements.

In this section, we begin with a comparative analysis, where our results obtained in section 6, are compared for relative importance. Following, we present a system path analysis where we identify the major sources of the total emission level for each of the tunnelling technologies assessed in this thesis.

We have chosen the impact categories climate change and human toxicity to represent the environmental impact for the interpretation phase. The choice is based on the relative difference between the two environmental categories, for impact, from the applied materials. Whereas the production of cement has a high impact on climate change, steel has the relative higher impact for human toxicity.

### 7.1 COMPARATIVE ANALYSIS

Given our assumptions in this thesis, our results from the impact assessment was presented in section 6, from page 40 and onwards. In Figure 34 we present two of our baseline results from Figure 17 for the functional unit 1, which constitute one meter of tunnel and tunnel track.

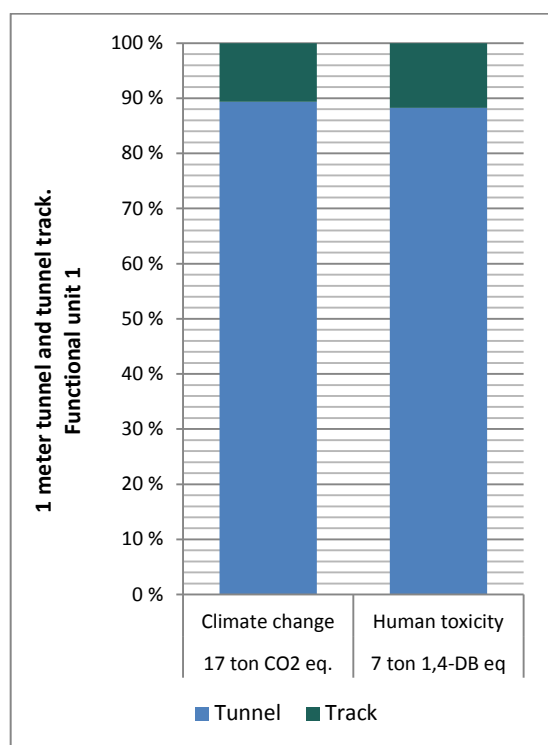


Figure 34 Comparative results, FU1. The figure presents a selection of the baseline results from Figure 17. The figure presents our baseline results of comparison for the variables in the table to the right.

Variables		Climate change	Human toxicity
Track design	Ballasted track	Baseline	Baseline
	Slab track in tunnels and bridges	-3%	-3%
Tunnelling method	Norwegian	Baseline	Baseline
	European	+30%	-23%
	TBM	+32%	+74%
Securing level	Q = A/B	-1%	-1%
	Q = C	Baseline	Baseline
	Q = D	+2 %	+1%
	Q = E	+11 %	+9%
	Q = F	+19 %	+16%
Cement grout	Injection level 1	-16%	-2%
	Injection level 2	-1 %	-2%
	Injection level 3	-11%	-2%
	Injection level 4	-8.4%	-1%
	Injection level 5	Baseline	Baseline
Increased speed	Norwegian 250km/h	Baseline	Baseline
	Norwegian 330km/h	+6%	+6%
	European 330 km/h	-14%	-40%
	TBM 330 km/h	+50%	+99%

Table 9 Comparative results, FU1. The table presents a summary of four most important results obtained in Section 6. The white squares indicate baseline (100 %) and the point of normalizing, while the red color indicates an increase and the green, a decrease compared to our baseline results. The results for 330km/h should be interpreted with some caution as discussed in Section 5.2.1.

In Table 9 we present our results of the different technological and geological alternatives presented in section 6, compared to our baseline results for the functional unit 1. In the table, the white rows

represent the baseline from which the variables are normalized. The red squares represent an increase in emission level compared to baseline, and the green colour, a reduction.

Despite of the differences in material influence for the two impact categories, the similarity between the two in terms of colour pattern is almost identical. The difference in relative deviation from baseline however, varies depending on the specific process. Variables, which include steel and cement, change more similarly between the two impact categories compared to a variable, which consist only of cement. The variable tunnelling methods is an example of this where the change from the baseline, the Norwegian method, to the European, results in an increase of the CO<sub>2</sub> level, though the level for human toxicity is reduced. The TBM represent an increase for both categories because of the reinforced concrete segments. The change in method to the tunnel boring machine therefore represents one of the variables which results in the comparatively highest impact compared to baseline, only exceeded by the variable; increase in speed. The statement is supported by the results in Figure 45 in the appendix, which presents the same variables for the total corridor.

The European tunnel constitutes a comparatively lower impact for increased speed. If the assumptions, which these results are based upon (see section 5.2.1), are technically realistic, this method would be preferable in an environmental perspective, without further investigation however, the results are evaluated as unsecure. The remaining alternative for a corridor of increased speed is the Norwegian method, which results in a much lower increase in emission compared to the TBM

The installation of slab track for bridges and tunnels is a positive measure in an environmental perspective, and reduce total emission level by approximately 3% for both impact categories. The impact on the total corridor, range between 1-2% of the total emission level, presented in Figure 45 in the appendix.

The relative difference between the five levels for the variables supports work and cement injection are similar for climate change. This means that an increase in level for both of the mentioned variables will result in about an equal increase of emission. For human toxicity, the results are more diverse due to cement injection, which only constitute cement and thus have only a small effect on this category.

The most important difference between the two is however, that the level applied for the baseline is in separate ends of the ranking scale for the two variables. For the support work, the baseline is represented by the category C, which is a comparatively low securing level. For cement injection however, the baseline level is the highest of the estimated levels, level five.

Similarly for both however, is that the relatively largest increase of emission occurs for the two highest levels. This indicates that the marginal change in emission is considerably higher for cement injection compared to the support work by a shift of one level. If the securing level was altered by one level, to A/B or D, the difference in impact represent about 0-2% for functional unit 1.

A comparison of all the variables indicates that the increase of speed and especially the alternation of design for the tunnel boring machine. Further, the European method results in comparatively lower impact on human toxicity, while the Norwegian has lower impact on climate change. The increase in securing level represent a significant impact for both impact categories if support work was escalated to category E or F, while the impact of decreasing the cement injection would provide a significant environmental benefit. In addition, the installation of slab track in tunnels represents a positive impact for both emission categories.

## 7.2 SYSTEM PATH ANALYSIS OF THE THREE ASSESSED TUNNEL TECHNOLOGIES

Similar to what has been stated in earlier reports such as by Bergsdal et al. (2012) and in the environmental project for the Follo Line (Korsmo & Bergsdal 2010), materials such as cement and steel constitute important contributors to the total emission level of a railway corridor. This statement is supported by our results in this thesis.

In section 6, which constitute results and impact analysis, the impact of the different railway components was investigated for the functional unit 1. The purpose of this section is to perform the same analysis for the entire infrastructure system of the case corridor, and thus make visible the different components, which was aggregated into one element in the calculation of functional unit 2. The approach further aims at facilitating a streamline understanding of the major emission flows that occur when undertaking a major railway construction project.

Only the main paths of the infrastructure are included in this section. Similar to previous section is climate change and human toxicity selected to reflect the environmental impact of the system. For climate change, the materials cement and steel are identified as the main sources of emission and the analysis is thus reserved for these materials. For human toxicity, the analysis is focused on the main contributors' steel, copper, and electricity.

Figure 35 presents the emission system for the baseline scenario for the impact category climate change. The total emission level for the system is presented in the top label of the figure.

The construction represents the major bulk of the emission, constituting of approximately 83 % of total impact. 60% is a result of the construction of tunnels. The track constitute of about 5 % were the rails are the major source of emission. In addition, the transportation of material waste is an important factor.

For the tunnel construction, the major emission source is the lining that constitutes both concrete and steel. In addition, the cement grouting used to seal the rock before blasting is a considerable contributor, remembering that the highest injection level is assumed for this study. Aggregated, steel, cement and transportation of waste materials amount to 47% of total emission level. The remaining share is made up of comparatively smaller amounts divided between several processes such as electricity and diesel among others.

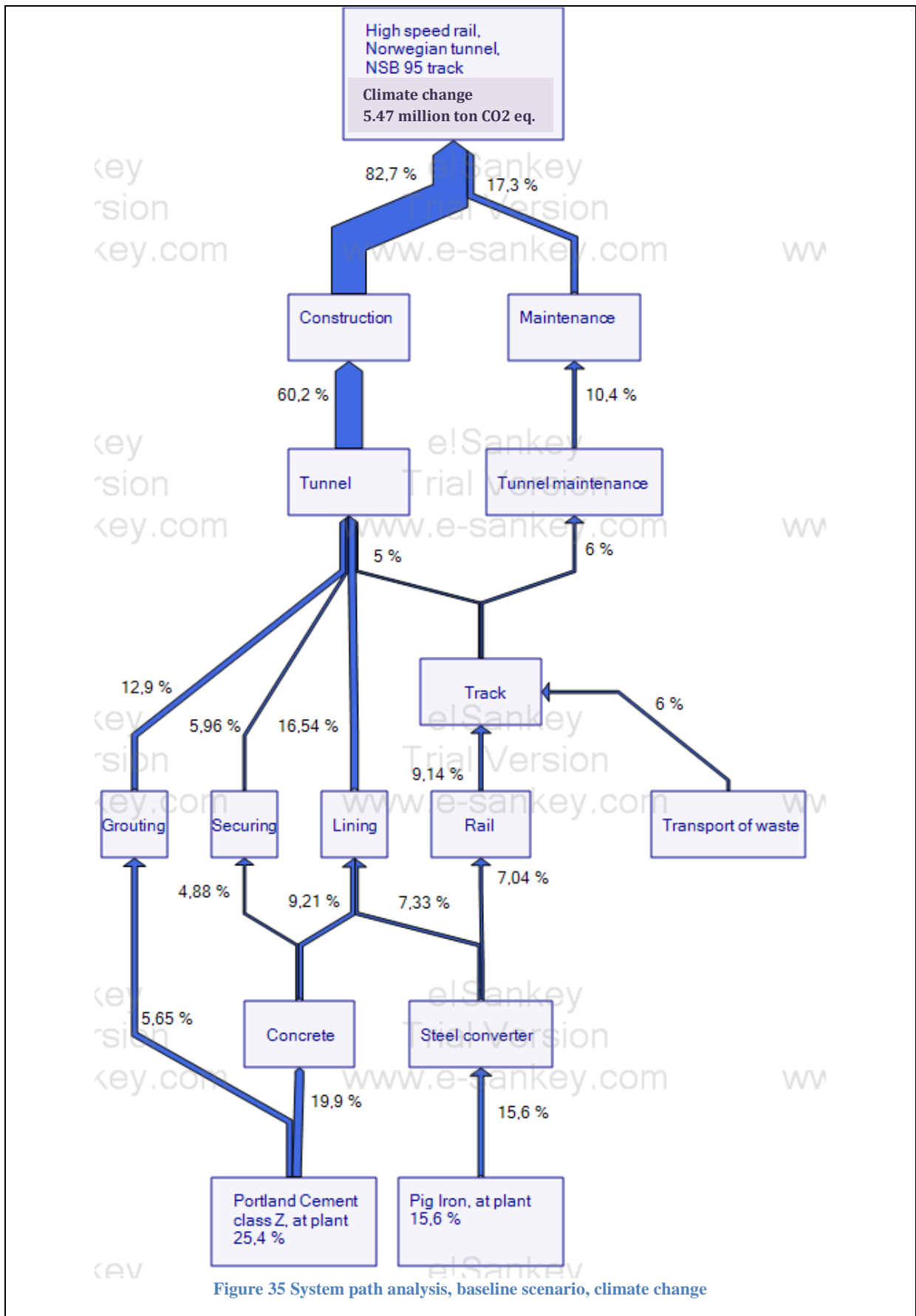


Figure 35 System path analysis, baseline scenario, climate change

Figure 41 in the appendix, illustrates the emission system for climate change for the European tunnel technology. Since this method also is a drill and blast method, the two systems are similar. Materials for support work and track is equal to that of the Norwegian tunnelling method. The main difference is the concrete cast, which constitute about 24% of total impact, which equal that of the entire cement production for the Norwegian tunnel. The cast is thus the main reason for the comparatively high emission level for the European method compared to the baseline. Cement production for the European tunnel therefore represent more than 41% of total emission level and steel only that of the production of steel for rail and reinforcement for the concrete sleepers. Aggregated the cement and iron represent almost 51% of total impact.

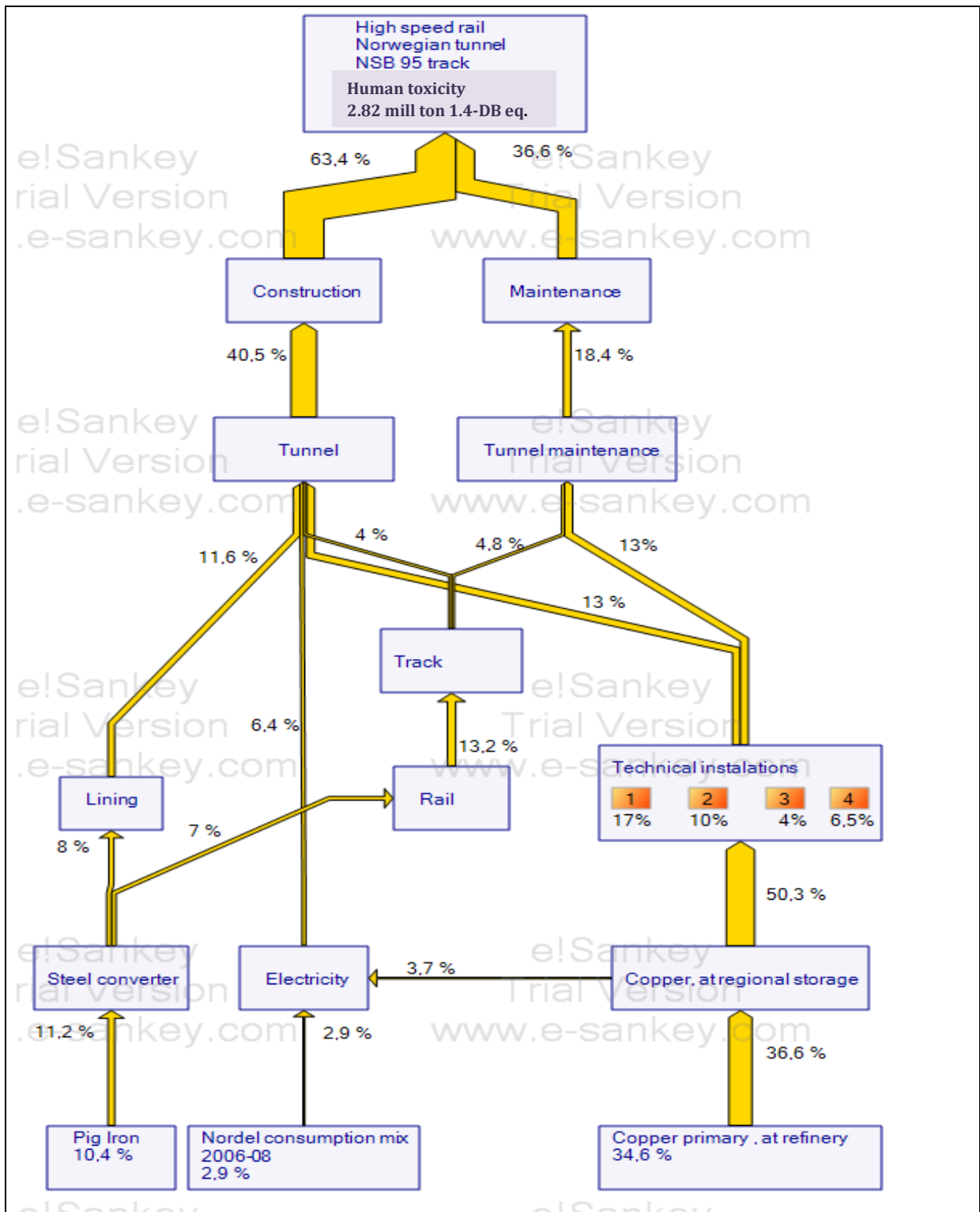
Figure 42 in the appendix presents the emission system for the tunnel boring machine, also for climate change. The Tunnel boring machine, for this study, installs reinforced concrete segments of 40 cm. The segments, in addition to the grouting required for sealing the segments together amount to more than half of the total emission of the corridor. This makes the lining the major component of the track corridor. Aggregated, cement and iron represent 55% of total CO<sub>2</sub> eq. Compared to the Norwegian tunnel, about 25% more of the total emission may be traced back to the cement and steel.

Human toxicity is affected comparatively more by the production and use of steel and electricity compared to cement. Figure 36 illustrates the emission system for the baseline scenario when assessing human toxicity potential. Similar to the emission system for climate change, the major mission is a result of the tunnel construction. The steel is primarily used to reinforce the tunnel lining, but has an almost identical share going to the production of rail. A new metal however becomes visible in this emission system. This is the copper used for the technical installations for the infrastructure. The copper represents nearly 35% of the total emission level, which makes it a determining material for the total environmental impact.

From the regional storage, the copper is distributed between several sources. Nearly 4 % is used for the distribution network for electricity. 50% of total impact for the human toxicity potential is distributed among different technical installation, where the major bulk is divided in different wires and cables. According to the calculation method applied for this thesis an equal amount of technical equipment is divided between the construction and the maintenance phase.

Figure 43 in the appendix, presents the emission system for the European tunnel for the impact category human toxicity. The system is similar to that of the Norwegian, but differs in the reduced amount of steel. The result is an increased importance of the copper for the total emission level. Steel is only the result of rail and sleeper reinforcement production. The distribution between the different technical installations is the same as before and therefore follow the same pattern. The tunnel boring machine is the only system where the copper does not represents 50 % or more of total emission level. The reason is the high level of steel in the concrete lining. Figure 44 preset the tunnel boring machine impact on human toxicity. Steel, copper and electricity constitute approximately 50 % of total impact for the entire case corridor for the impact category human toxicity.





- 1 = Cables and wires
- 2 = Signal equipment
- 3 = Telecommunications equipment
- 4 = Transformers

Figure 36 System path analysis, baseline scenario, human toxicity

The emission system for climate change is divided into four activities: the design of railway corridor, tunnelling technology, rail track design and material production. Each of these activities presents a decision that ultimately will influence the total emission flow out of the system. Each of these also makes an arena for discussing future reduction potentials. For human toxicity, copper make up the material that ultimately has the highest impact on total emission level. The path for the copper is however not as straight forward as the major paths for cement or steel. From regional storage, the copper is divided into several different production and use systems where the largest systems include the production of wires and cables, transformers, the electricity grid and signal and communication systems. In order to reduce this impact, an activity influencing all these small arenas would be required as they separately represent a small share, but aggregated the bulk of total emission for human toxicity.

### 7.3 SENSITIVITY ANALYSIS

#### 7.3.1 SENSITIVITY OF COMPONENT SERVICE LIFE

Our results from the impact assessment of the different track designs, presented per meter in Figure 19 and for the total corridor in Figure 28, indicate that transportation represent the factor that constitute the major difference between the slab track and the ballasted track . The reason is a comparatively higher material turnover for the ballasted track as a result of component service life.

In Lia (2011), the service lives of the different track components were emphasized as a determining factor for the total results and comparison between the track designs. The reason is the comparatively higher material turnover for the ballasted track as a consequence of material service life. To assess the impact of service life for the rail track , Lia (2011) developed a three service life scenarios basted of the ranges presented by specialists within the JBV (Jernbaneverket 2011). The scenarios are presented in Table 10 and labeled as low, high and most likely service life, where the latter constitute the service life closest to the technical service life, which is assumed for this assessment.

Railway component	Service life (SL) <sup>21</sup>	Scenario 1: Low SL	Scenario 2: Most likely SL	Scenario 3: High SL
Ballast cleansing	15 - 25	15	30	25
Tamping	3	3,3	3	5
Sleeper	15 - 50	15	30	50
Fastener	10 – 30	15	30	25
Rail	10 – 40	15	30	50
Slab	60-120	60	90	125

**Table 10 Service life of track components. Three estimated scenarios for service life, low, medium and high, based on the range for technical service life presented in the second column.**

The different scenarios are “optimized”, meaning that the service life chosen for each of the components, for the three scenarios are intentionally matched within each scenario, in order to minimize maintenance activities. Most of the railway components have an approximately linear increase of service life over the three scenarios, with the only exception being ballast cleansing and the fasteners, which decrease slightly from scenario 2 to scenario three to achieve the optimization criteria.

<sup>21</sup> Data obtained from: (Jernbaneverket 2011)

The scenarios presented in Table 10 are used to investigate the impact of track service life for the case corridor between Oslo and Stavanger for this thesis. Our results obtained from this calculation are presented in Figure 37. Similarly to the results obtained by Lia (2011), do the relative largest reduction of emission occur when the service life is lengthened from a low to the most likely scenario. The emission reduction from extending the service life further, is limited to a few percent. This may be explained by the few components which do not have a linear increase in SL. As mentioned, this does apply both for ballast, rail and fasteners. Reviewing Figure 19, the importance of steel is undisputed, thus the reason for the comparatively smaller gain from increasing the service life beyond “most likely” may be a result of the rails. In Table 11, the total difference between the scenarios is presented.

From this brief discussion, it is possible to conclude that the greatest emission reduction potential for both track designs, when only assessing the track, is an increase in service life for rails. Further, if assuming the given scenarios, “most likely”, represents the optimal use of track as the comparatively largest possible gain is obtained at this level, give the limitations provided by the ranges from the JBV presented in Table 10.

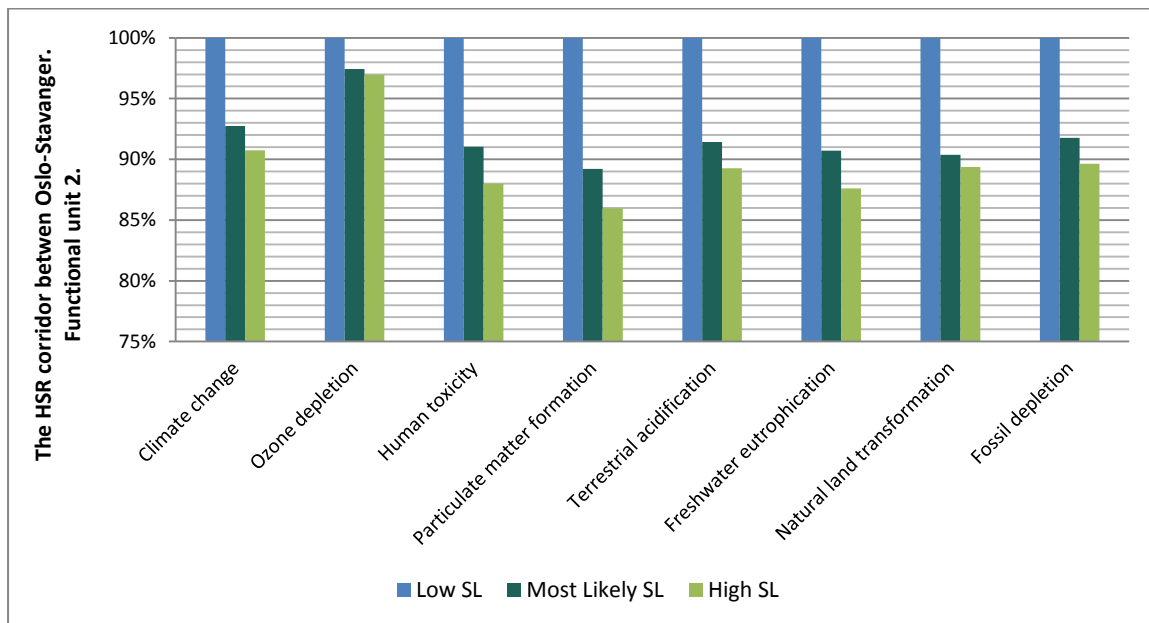


Figure 37 Service life scenarios. The figure presents the three service life scenarios presented in Table 10. SL is an abbreviation for service life. All activities, which occur the estimated 60 years of service life is included in the calculations.

	Climate change - CO <sub>2</sub> eq. (in million tons)	Human toxicity – 1.4 DB eq. (in million tons)
Low SL – Most likely SL	0.6	0.4
Most likely SL - High SL	0.2	0.1
Total	0.8	0.5

Table 11 Service life scenarios, results. The table presents the relative differences in emission level for adjusting the service life of the different track components equal to the three scenarios developed by Lia (2011). The first row presents the reduction in emission from increasing service life from low to medium. Similarly, the second row presents the reduction in emission from increasing service life from medium to high.

### 7.3.2 SENSITIVITY OF METHOD FOR SERVICE LIFE CALCULATIONS

According to the calculation method applied in the assessment by Bergsdal et al. (2012) and illustrated in Figure 10, each set of components for the railway corridor are normalized for 60 years service life, in addition an extra set of components are installed in year 60 leaving the corridor “new” at ended life cycle phase. A slightly different approach is chosen for this assessment illustrated in Figure 11. This method accounts for the total of all installations that has to be made for the track to function through the given life cycle phase of 60 years. The railway therefore can be regarded as incomplete at year 61.

Figure 38 presents the comparison of the two calculation methods, where the total difference between the methods are indicated below the category labels.

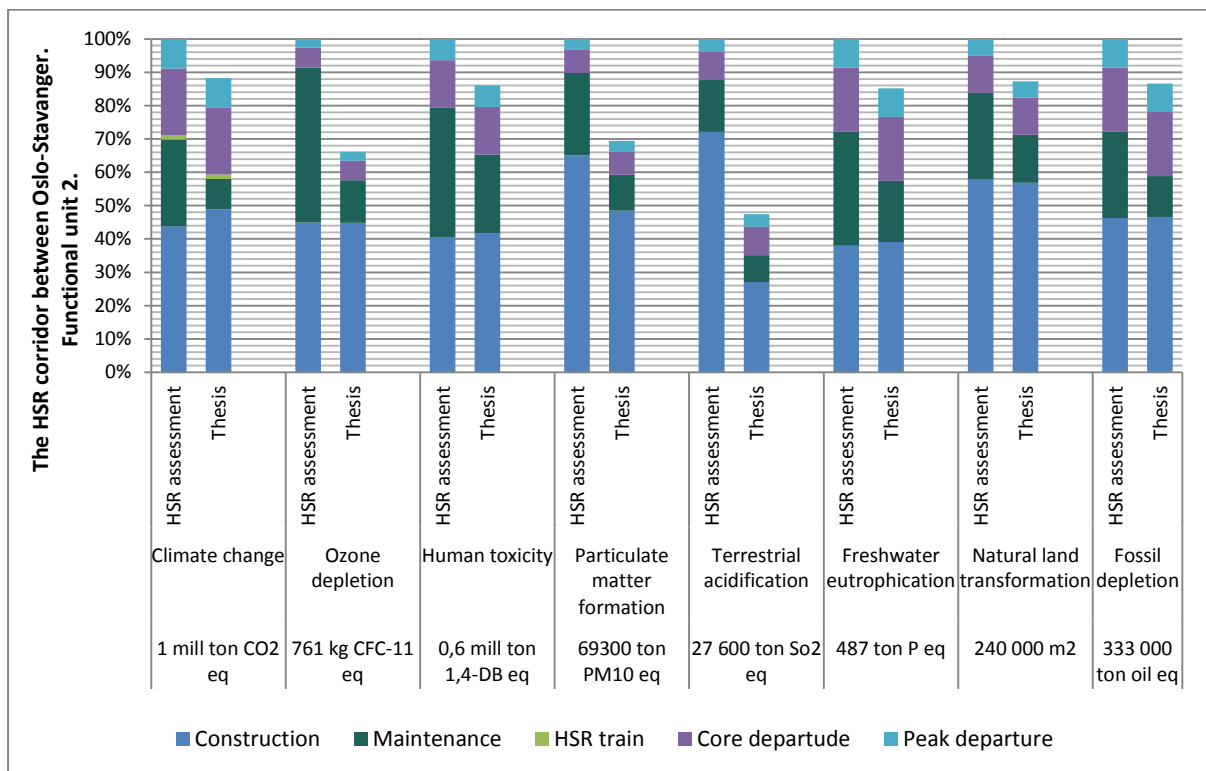


Figure 38 Sensitivity of service life calculation. The figure compare the impact from the service life calculation method used in the High speed rail assessment by Bergsdal et al. (2012), and the method applied for this thesis. The results representing the calculation method of this thesis also includes adjustments of the blasting process and the grouting level. The total reduction in emission level as a result of the different calculation method is presented below the columns.

In addition to the calculation of service life, two additional changes are applied for the inventory used in this thesis.

- 1) The level of cement grout is changed back to the original inventory established for the project in the Follo Line (Korsmo & Bergsdal 2010) as the inventory composed for the two other tunneling methods which are to be investigated are estimated for the same tunnel and geological conditions.
- 2) The inventory process for “blasting” was upgraded from the initial “tovax” process to the “slurry” process developed by MiSA to better represent the Norwegian situation.

The main difference in the results of the two methods is the expected reduction of the maintenance process as a result of the new calculation method. However the increased level of cement grout results in a slight increase of the construction phase. This is mainly visible for the climate change. The

adjusted blasting process applied for the new method represent a considerably different impact distribution compared to the original (see Figure 40 in the appendix). The result is a considerably lower emission level for particulate matter formation and terrestrial acidification and a slight increase in climate change. The main difference in the new blasting process compared to the initial, is higher amount of ammonium nitrate and naphtha for the slurry and aluminum and calcium nitrate for the tovox process.

The adjustments results in a total reduction for the category climate change of about 12%, which represent approximately 1 million CO<sub>2</sub> eq. as presented in Figure 38. The reduction in human toxicity constitute of about 14%.

## 8. DISCUSSION

The construction of a railway corridor is a vast project, which must undertake a large range of considerations. The environmental consequence of such a project is further a complex system of different sources of impact. The following section aims to facilitate the understanding of the relation between such a project and the environment by combining the theoretical background with obtained results within the system boundary and the assumptions and limitations of this thesis.

### 8.1 MODELLING SERVICE LIFE

The development of the system model constitute the second step in the procedure of performing a life cycle analysis (Standard Norge 2006), as illustrated in Figure 2. Even though based on the same goal and scope, a model may be designed in several different ways. The element of transparency in modelling is therefore important, particularly because of the possibility for benchmarking.

The system model for this thesis differs slightly from the model initially applied for the Norwegian High Speed Rail Assessment by Bergsdal et al. (2012), because of a different method for calculation service life, in addition to minor process adjustments. The result is a reduction of about 1 million ton CO<sub>2</sub> eq. for the same railway corridor.

The modelling of service life constitute a difficult task as there are many factors which may influence the technical service life of a component, such as use, climate conditions and future uncertainties.

The decision to alter the initial method of service life calculations is thus based on this uncertainty. The life cycle phase of the construction is decided for 60 years. The inventory calculated for in the High Speed Rail Assessment, Phase 3 however, is estimated to last for minimum 90 years, by including the installation of a new set of components after year 60. The method applied for this thesis, does not include this final shift in materials, thus are the maintenance reduced by approximately half and the track may theoretically be considered non-functioning in year 61. This may be a crude assumption but is rooted in the theory that the inventory should reflect all activities performed within the 60 years, and not include what occurs after. To assume what a tunnel construction process will constitute, 60 years from now, contain a significant level of uncertainty as both technological development and population migration may cause the proposed corridor to shift use and purpose over the next century. In addition, also the construction process may alter.

As presented in the results, the tunnel constitutes the comparatively largest source of emission for the case corridor, because of the large number of tunnels. This is however likely to be somewhat representative because of Norway's relatively mountainous geography. The service life of tunnels will thus have a large impact on the total emission level. This was presented in Figure 22 were the Norwegian tunnel was calculated for a service life of 50 years, and thus included a total shift of the reinforced concrete lining.

The three tunnels assessed in this study represent two different estimated service lives. The Norwegian tunnel is estimated for 50–70 years, while the European and the TBM for 100 years. For the Norwegian High-Speed Rail Assessment (Bergsdal et al. 2012), the Norwegian tunnel was estimated for 50 years and thus the tunnel maintenance included a shift of the entire tunnel lining similar to Figure 22. For this report, a minimum of 60 years in assumed for the same tunnel. This decision is based on the level of uncertainty that the process, to hack down the tunnel lining and subsequently replacing his with a new after 50 years constitute. Firstly, this implies that the tunnel will be constructed based on current methods. Secondly, the assumption, take for granted that the

tunnel still is in use according to current estimates. Several factors may contribute to alter the use of a tunnel over half a century. This includes the mentioned development in technology, transition to different means of transportation or reduced demand because of people moving. For this assessment, it is therefore decided, that to include a second installation would constitute too many uncertainties and that the relatively more realistic prospect is that the tunnel will maintain for 60 years and thus meet the requirement for a life cycle of 60 years.

## 8.2 CHOICE OF TUNNELLING AND SECURING METHODS

The traditional Norwegian tunnelling method has been developed over years of practice, and is based on good knowledge and decisions from the constructor. Lately, a discussion concerning other tunnelling options is under debate. The root of this discussion has been linked to the accident, which occurred in Hanekleivtunnelen in 2006, and the increased public fear of similar incidents (Carstens 2007). On the other hand, the debate is also claimed to be a result of the requirement for technologies that necessitate less maintenance and can withstand stronger forces (Tunmo 2011). The question is thus whether this debate is rooted in legitimate technical requirements because of increased speed, or only constitutes precautionary measures to appease travellers, or both.

According to the rock classification system, the Q-method, the European tunnelling technology represents the highest level of support work for this scale (see Table 15 in the appendix). This seems an unnecessary measure for the relative hard rock used for tunnels in Norway. The reason may therefore be explained by the increase of speed, which create a relatively higher pressure and suction power. According to a specialist from the JBV, it is however not technically impossible to apply the Norwegian method for this speed, but argue that the maintenance requirements will contribute to a shift towards the European method. He continues by stating that because of the increase in power, that follows a speed of 330km/h, the Norwegian tunnel may preferably only be applied for relatively shorter tunnels (Gammelsæter 2012). An interesting subject is therefore where the boundary between a short and a long tunnel is, and what the share for each of these constitutes for the corridors evaluated in the High Speed Rail Assessment. The total emission level could thus be influenced by combining tunnelling technologies.

In regard for the maintenance, there has however been argued that a tunnel constructed by the European method is comparatively harder to repair compared to the Norwegian, which may increase the maintenance work also for this tunnel (Seehusen 2012). There is thus no single answer for the political interest in European tunnelling methods. Instead, the answer seems to be a combination of the different arguments. The environmental impact of the construction of these tunnels differs, depending on which impact category assessed. The Norwegian method constitutes less cement and thus has a lower impact on climate change. For human toxicity the European method is preferred since this do not apply reinforcement steel. For an increase in speed from the estimated 250km/h for the baseline, to a corridor of 330km/h, the European method presents a comparatively lower emission level for both categories, also compared to the emission level of the same tunnel for a speed of 250km/h. The design and estimated dimensions for the two tunnel alternatives is however, developed by different companies, which may have separate reasons and assumptions behind their estimated structures. As indicated earlier, the level of concrete for the cast and profile may vary slightly, about 14% per m<sup>2</sup>. The total reduction in m<sup>2</sup> per meter of the tunnel estimated for 330km/h is however considerably higher. Nevertheless, these are the dimensions used for the Norwegian High Speed Rail Assessment and are thus included for this study. Assuming however that the results prove technical possible, the European would prove the best alternative, but would require a vast reduction of materials compared to what was estimated for the Follo Line tunnel by Vianova (2011a) The

different assumptions underlying these dissimilarities should therefore be a topic of further investigation.

According to Nord (2006), the third method assessed, the tunnel boring machine, applies less damage to the rock stability during excavation, which leaves the rock more solid. The expectance of less required materials for support work is however, not fulfilled. The specific boring machine in question is the double shielded machine, which is decided to install reinforced concrete segments of 40 cm for the entire tunnel length. The result is a vast requirement of materials, which ultimately contribute to the tunnel boring machine representing the technology with the highest envision level compared to baseline, for both climate change and human toxicity. The question is therefore if it is realistic to assume that these segments will be applied for all tunnels excavated by the boring machine. Figure 24 and Figure 25, illustrate the impact of not applying the concrete segments and the results from altering their size. The reduction of not including the segments decrease total emission level by 65% for climate change. A reduction in the required thickness of the segments would contribute to a significant reduced impact. Another option is the application of a main beam tunnel boring machine instead of the double shielded, which would allow for support work similar to that of the drill and blast method instead of the segments. This method however, is comparatively more vulnerable for the “soft spot” of the TBM, namely the down time that may arise if unprepared weak zones occur. This may represent a reason why this machine is not considered.

Intrusion of water may cause vast damage to both tunnel and track which is a great motivation for applying a high level of grouting for all tunnels of high use. There might however not be technical necessary to apply a high level of injection for tunnels situated away from habited areas. Following the assumption however, that the European method is applied as a precautionary measure, the high level of injection may also be applied of the same principle, which indicate that a reduction of this level may not only be based on geological condition. However, the reduction of grout does represent one of the best reduction potentials for the tunnel constructions assessed, the reduction possibilities is thus necessary to investigate further.

The level of support work included in the baseline, is represented by the category “C” in the Q-method, which also represent the average securing level for tunnel in general in Norway as constructors intentionally avoid building in rock that require heavy support work (Gammelsæter 2012). A marginal change in support work, by one level in either direction, would not have significant effect on total emission level, thus the assumption of a level C for support work proves a robust estimate for tunnels in general.



## 9. CONCLUSIONS

In this thesis we have investigated the implication of adjusting the material inventory presented for the Norwegian High-Speed Rail Assessment (NHSRA) by Bergsdal et al. (2012), for different technological and geological options and requirements. Further, we chose the eight impact categories climate change, ozone depletion, human toxicity, particulate matter formation, terrestrial acidification, freshwater eutrophication, natural land transformation and fossil depletion to reflect the environmental impact from the case corridor and the different variables for track and tunnel design. Our findings are as follow:

- *When performing a life cycle analysis, several relevant impact categories should be included in order to reflect the dissimilarities in impact for, the range of applied materials.*

The different impact categories are affected by dissimilar production processes, of the materials applied in this thesis the distribution between the impact categories of this thesis is as follows:

- Cement has a relatively higher impact for climate change and Terrestrial acidification
  - XPS make up almost the total emission level for ozone depletion.
  - Production of steel and copper has the comparatively largest effect for human toxicity, freshwater eutrophication and fossil depletion.
  - Impact on particulate matter formation is influenced by the use of explosives and of the production of steel.
  - Natural land transformation is affected by the production of diesel, and is the only category where the use of gravel has a significant impact.
- *A general rule for the method of service life calculations should be decided for projects, which are to be used for benchmarking purposes. .*

The strategy selected for service life calculations, has proved through this thesis, a determining factor for the total emission level of both track and tunnel constructions. The method we have used for this thesis, differs from what is used by Bergsdal et al. (2012) for the NHSRA. The result of this dissimilarity is a reduction of about 1 million ton CO<sub>2</sub> eq. The importance of developing a general rule for calculation methods for potential benchmarking is thus illustrated.

- *The length of tunnels are determining for the total emission level for all of the eight environmental impact categories assessed in this thesis.*

The NHSRA by Bergsdal et al (2012), emphasise the relative importance of the tunnel construction for the total emission level for a railway corridor, estimated for climate change. This statement is supported through this thesis, and further expanded to include the categories: ozone depletion, human toxicity, terrestrial acidification, freshwater eutrophication, natural land transformation and fossil depletion. For these categories, the tunnels of the case corridor constitute approximately 45-80% of total emission level. For climate change, the total impact of the tunnels thus equal about 5 million ton CO<sub>2</sub> eq.

- *The Norwegian tunnelling method is the preferred methods (of the three assessed technologies), in a climate perspective, while the European has the relative lowest emission level for human toxicity.*

Of the three tunnelling methods, the Norwegian method (the baseline), results in the comparatively lowest emission level for a speed of 250km/h for climate change. Compared to baseline for the functional unit 1, the European constitutes an increase of 30% and the boring machine a 32% higher emission level. For human toxicity however, the European represent a decrease of 23% compared to baseline because the method do not apply reinforcement steel. The boring machine however, represents an increase of 74%.

- *A shift in tunnelling method and the increase in speed, or both, relative to the baseline, constitute the variables, which has the comparatively highest effect on the emission level.*

Between the six different variables assessed in this thesis, the shift of tunnelling method and the increase in speed or both represent the potential highest increase in emission level compared to baseline, both per meter tunnel and for the case corridor. For a railway estimated for 330km/h the application of the double shielded tunnel-boring machine would increase total emission level by 50% for climate change and 99% for human toxicity, for the functional unit 1. The results for the European tunnelling method however, presents a decrease in emission for both categories compared to baseline. The reason is the proposed dimensions for a tunnel with full cast for 330km/h, which gives a tunnel with comparatively thinner tunnel walls compared to the same tunnel estimated for 250km/h. The two tunnel designs, are however, developed by two different companies, and may thus be based on dissimilar assumptions. The dimensions for the tunnels of 330km/h were used for the economical estimated for the NHSRA and in thus included in this study. The results however, should until further investigation be interpreted with caution

- *The double shielded tunnel boring machine represents the technology that, for this thesis, results in the highest increase in emission level, compared to baseline.*

The tunnelling method, which in this assessment represents the comparatively highest emission level, is the double shielded tunnel boring machine. The main source is the reinforced concrete segments and the grouting used to seal these. Aggregated, these represent about 65% of total emission level for 1 meter tunnel calculated for climate change. Thus, a reduction in the application of the concrete segments or their size would reduce the total impact significantly.

- Cement, steel and copper represent the materials, which constitute the highest emission source of the corridor.

Cement and steel represent the materials that according to Korsmo and Bergsdal (2010) are the materials that contribute to the highest share of total emission level for climate change, when assessing a railway corridor. The results of this thesis support this statement. For the baseline, 41% of total impact is a result of the requirement for cement and steel. For the European method, the same share represents approximately 51%. The highest share occurs for the tunnel boring machine were cement and steel represent 55% of the total emission level. Through this assessment, another material

has proven important. Copper, used for different technical equipments has a high impact for human toxicity and freshwater eutrophication, and represent about 24-35% of total emission level for human toxicity depending on the specific tunnelling method.

- *The use of copper is distributed between numerous producers and applications, and is therefore more difficult to assess, compared to the use of cement.*

For climate change, the system represents a clear path for the most influential materials, steel and cement. It is therefore easy to identify the few stages from where decisions of the downstream measures are taken. For human toxicity, the path represents a comparatively more complex system. Copper is applied in small amounts in numerous different installations. Aggregated the amount of copper represents a large impact, but because of the divided application, the specific paths are more difficult to identify.

- *The tunnel lining and the level of grout are the railway components, which constitute the highest emission source for the case corridor.*

For the corridor between Oslo and Stavanger, specific components, which depend on the tunnelling technology assessed, make up the major bulk of the total emission level for the entire railway corridor. For climate change, this is represented by the level of grout and the reinforced concrete lining for the baseline, constituting 13 and 17% respectively. For the European method, the concrete cast represent 24% of total emission for the entire corridor, and the level of grout about 12%. The reinforced concrete segment installed for the double shielded boring machine represent 44% of the total emission if installed for the entire tunnel length.

- *The slab track and level of grouting constitute the highest reduction potentials of our study*

The variables, which represent the best reduction potentials, compared to the baseline, are the reduction of cement injection and the installation of slab track in tunnels and bridges. In addition, would a reduction of the thickness of the concrete lining, result in reduced emission for all tunnelling technologies.

- *Our results of this thesis, presents a reduction in total emission level for the corridor between Oslo-Stavanger, compared to what was obtained for the same corridor in Bergsdal et al. (2012).*

Our assessment is based on the inventory developed for the NHSRA by Bergsdal et al. (2012) for the corridor between Oslo–Stavanger, estimated for 250km/h. In order to calculate our baseline for this study, we performed the following adjustments to the material inventory:

- The process for blasting is altered to the newest process developed by MiSA.
- A different method for service life calculation is applied
- Application of the NSB 95 track design for high speed rail
- Increase in level of grout similar to the tunnel included in the Follo Line
- Adjustment of tunnel dimensions, to the requirements of high speed rail, resulting in a comparatively larger tunnel

These adjustments contribute to our baseline results of this thesis. The effect is a decrease in total emission level compared to what was presented by Bergsdal et al. (2012). The reduction of approximately 9% for climate change constitutes about 750 000 ton CO<sub>2</sub> eq., which subsequently result in a comparatively shorter payback period for the assessed corridor of 250km/h between Oslo and Stavanger.

## 9.1 FURTHER RESEARCH

Several topics, which we have only briefly touched upon through this thesis, would be relevant for further research. In this section, we present the issues, which we have evaluated as the most important and interesting topics for further research. Our recommendations can be summarized as follows:

- *A study of the different types concrete, which is applied for tunnel construction.*

In this thesis, we have assumed that the different concrete components such as the concrete membrane and cast, both for the European method, and the shotcrete for support work, can be modelled with the same concrete process. This may be a crude assumption, which of, would be interesting to investigate the implications.

- *Investigate the possibility of material reduction for the tunnel lining.*

The tunnel lining constitute the component, which results in the comparatively highest impact for climate change, for all three tunnelling technologies. It would therefore be of interest to investigate the possibility of reducing the installation length and the thickness of the lining for all the methods and the implications of this measure. Further, to assess the possibility of the application of a main beam tunnel boring machine would be of value as this machine may apply support work similar to the D and B methods. For this, is also of interest to look into the differences in location of the tunnel in relation to the thickness of the lining.

- *Assess the geological requirements of grout for tunnels.*

Further, the level of grout is in this study evaluated to represent the second largest emitter for the case corridor for climate change, and thus hold a great reduction potential. An important issue would therefore be to assess the possibility of reducing this amount for a high-speed rail corridor. One possibility is to look at the relation between level of grout and location of the tunnel, in order to investigate if tunnels through inhabited areas may constitute less grout, or if political requirements state a certain level of precautionary principles. Also, if there exist potential substitutes, and the impact of applying these.

- *Analyse the application of copper in railway components.*

Through the system path analysis, we discovered that the use of copper have a high impact on human toxicity and freshwater eutrophication. It would therefore be interesting to look further into the use and application of this material throughout the railway structure.

- *Investigate further the relation between tunnel dimensions, material requirements and train speed.*

In this thesis, the dimensions of the European tunnel indicate a comparatively thinner tunnel wall for increased speed. It will be of high relevance, to further investigate this variable and the implications of the obtained results. Further, through this thesis, we have learned that the Norwegian tunnel may not be the best alternative for long tunnels with an operation speed of 330km/h. It would therefore be of value to study the limitations of the Norwegian tunnel, potential measures for improvements of this method and the specific effect on service life of the tunnel. Additionally, would it be very interesting

to look into, which length that separate a short from a long tunnel, and the relative share of each of these for the different corridors assessed in the High Speed rail assessment by Bergsdal et al. (2012).

- Analyse the relation between speed and passenger use

In this thesis, increased speed represents a larger tunnel, which in turn generates a higher demand for materials (not including our uncertain results for the European tunnel). This results in a higher environmental impact. We have not considered the relation between speed and use in this thesis. It is thus relevant to investigate if such a relation exists, if it is positive and whether it may ultimately present an environmental gain.

- *Evaluate the content of a potentially future, methodological framework for service life calculations.*

The slightly different method we applied in this thesis for calculation of service life, compared to the method applied in the report by Bergsdal et al. (2012), results in a significantly different environmental impact. Thus we have illustrated the requirement of a framework that indicate strategy for calculations, content and system boundaries, for projects to be relevant for benchmarking.

## 10. REFERENCES

- Baumann, H. & Tillmann, A.-M., 2004. *The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application*, Lund, Sweden: Studentlitteratur.
- Bergsdal, H. et al., 2012. *Environmental Analysis Climate. Norwegian High Speed Railway Project Phase 3.*, Trondheim. Available at: [http://www.jernbaneverket.no/PageFiles/17582/Climate\\_Final%20report%20Phase3\\_MiSA.pdf](http://www.jernbaneverket.no/PageFiles/17582/Climate_Final%20report%20Phase3_MiSA.pdf) [Accessed March 26, 2012].
- Bilow, D.N. & Randich, G.M., 2000. *Slab track for the next 100 years*, Skokie, Illinois: Portland cement association. Available at: [http://www.arena.org/files/library/2000\\_Conference\\_Proceedings/00047.pdf](http://www.arena.org/files/library/2000_Conference_Proceedings/00047.pdf) [Accessed August 14, 2011].
- Broch, E. & Nilsen, B., 2001. *Ingeniørbiologi - Berg*, Trondheim: Institutt for geologi og bergnetnikk, NTNU.
- Carstens, H., 2007. Derfor raste Hanekleivtunnelen. *GEO Mars*, pp.40–41.
- FHWA, 2011. Technical Manual for Design and Construction of Road Tunnels - Civil Elements. *Structures*. Available at: <http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/10a.cfm> [Accessed May 27, 2012].
- Gammelsæter, B., 2012. Tunnel dimensions, support work and service life. Personal contact through mail.29.03.12. Available at: Bjornar.gammelsaeter@jby.no.
- Geldermalsen, L.A. van, 2004. *Environmental Aspects in Tunnel Design*, Prague, the Netherlands: Civil Engineering Division of Rijkswaterstaat, Ministry of Transport, Public Works and Water Management. Available at: <http://www.ita-aites.org/fileadmin/filemounts/ovion/doc/safety/prague/LAG.pdf> [Accessed February 6, 2012].
- Goedkoop, M. et al., 2010. *Introduction to LCA with SimaPro 7*, USA: PRé Consultants.
- Goedkoop, M. et al., 2009. *Recipe 2008*, Available at: <http://www.pre-sustainability.com/content/reports> [Accessed April 20, 2012].
- Hansen, A.M., 2008. Tunnel Boring versus Drill & Blast. *NFF*. Available at: <http://www.tunnel.no/article.php?id=185> [Accessed May 7, 2012].
- Holter, K.G. & Hognestad, H.O., 2010. *Modern pre-injection in underground construction with rapid setting microcements and colloidal silica*, Switzerland. Available at: [http://www.basf-cc.cz/cs/novinky/prisadydobetonu/technologiepropodzemnistavby/Documents/moderni\\_preinjektazni\\_metody.pdf](http://www.basf-cc.cz/cs/novinky/prisadydobetonu/technologiepropodzemnistavby/Documents/moderni_preinjektazni_metody.pdf) [Accessed May 27, 2012].
- ITA WG Mechanized Tunnelling, 2000. Recommendations and Guidelines for Tunnel Boring Machines. *Recommendations and Guidelines for Tunnel Boring Machines*, pp.1–118.
- Jernbaneverket, 2012a. Ballast. *Teknisk Regelverk*. Available at: <https://trv.jbv.no/wiki/Overbygning/Prosjektering/Ballast>.

Jernbaneverket, 2012b. Ballastfritt spor. *Teknisk Regelverk*. Available at: [https://trv.jbv.no/wiki/Overbygning/Prosjektering/Sporkonstruksjoner#Avslutning\\_av\\_ballastfritt\\_spor](https://trv.jbv.no/wiki/Overbygning/Prosjektering/Sporkonstruksjoner#Avslutning_av_ballastfritt_spor) [Accessed March 3, 2012].

Jernbaneverket, 2010a. Hovedplan Follobanen, enkeltspor tunnel, hastighet 250km/h, frostfri sone. Available at: Obtained from Bjørnar Gammelsæter, Jernbaneverket [Accessed May 31, 2012].

Jernbaneverket, 2012c. InterCity kan planlegges og bygges på ti år. *Nyheter*. Available at: <http://www.jernbaneverket.no/no/Nyheter/Nyhetsarkiv/2012/InterCity-kan-planlegges-og-bygges-pa-ti-ar/> [Accessed March 20, 2012].

Jernbaneverket, 2011. *Nytt dobbeltspor Oslo-Ski. Veileder for utarbeidelse av miljøbudsjett*, Oslo. Available at: Obtained from Johan Pettersen, MiSA.

Jernbaneverket, 2010b. *Slik bygges jernbanetunneler*, Available at: <http://jernbaneverket2.no-ip.org/Documents/Brosjyre%20-%20Slik%20bygger%20vi%20tunneler%20mars%202010.pdf> [Accessed March 26, 2012].

Jernbaneverket, 2012d. Underbygning/prosjektering og bygging/tunneler. *Teknisk Regelverk*. Available at: [https://trv.jbv.no/wiki/Underbygning/Prosjektering\\_og\\_bygging/Tunneler#Full\\_utst.C3.B8ping](https://trv.jbv.no/wiki/Underbygning/Prosjektering_og_bygging/Tunneler#Full_utst.C3.B8ping) [Accessed February 13, 2012].

Jernbaneverket, 2008. *Vurdering av drivemetode for tunnelene på Follobanen - rapport på utredningsnivå*, Available at: <http://www.jernbaneverket.no/PageFiles/7292/Rapport%20vurdering%20av%20drivemetode%20for%20tunnelene%20p%C3%A5%20Follobanen%2001.09.2008.rev01Adoc.pdf> [Accessed May 27, 2012].

Kellenberger, D. et al., 2007. *Life Cycle Inventories of Building Products*, Dübendorf: Swiss Centre for Life Cycle Inventories.

Kiani, M.R., Parry, T. & Ceney, H., 2007. Slab track. Life-cycle energy study of railway track beds. *Britpave*.

Korsmo, A. & Bergsdal, H., 2010. *Miljøbudsjett for Follobanen, Infrastruktur*, Oslo, Norway. Available at: <http://www.jernbaneverket.no/PageFiles/17959/Milj%C3%B8budsjett%20Follobanen%20%28Infrastuktur%29.pdf> [Accessed March 5, 2012].

L2B, 2012. EBRD`s first private transport deal in Serbia. Available at: <http://blog.linked2balkan.com/financial/ebrd%E2%80%99s-first-private-transport-deal-in-serbia>.

Lia, A.M., 2011. *Life Cycle Assessment of Infrastructure for High-Speed Rail in Norway*, Trondheim: NTNU.

Løhren, A.H., 2011. Track design in Norway. Personal contact by mail. Available at: [alf.helge.lohren@jbv.no](mailto:alf.helge.lohren@jbv.no).

Moen, K., 2008. Geologiske forhold og bolting. Available at: <http://www.tekna.no/ikbViewer/Content/746432/06-Moen.pdf> [Accessed February 3, 2012].



NGI, 1997. *Engineering Geology. Practical Use of the Q-Method*, Oslo, Norway. Available at: <http://www.ngi.no/upload/6700/Practical%20use%20of%20the%20Q-method.pdf> [Accessed March 3, 2012].

NGI, 2008. Q-metoden. Available at: <http://www.ngi.no/no/Innholdsbokser/Referansjeprojekter-LISTER-/Referanser/Q-metoden/> [Accessed March 3, 2012].

Nilsen, F., 2011. Norsk tunnelteknologi. *Nettavisen for geomiljøet GEO365*. Available at: <http://www.geoportalen.no/anleggsbransjen/tunnelteknologi/> [Accessed March 3, 2012].

Norconsult, 2011a. To enkeltsportunneler sprengt tverrsnitt. Available at: Obtained from Johan Pettersen, MiSA.

Norconsult, 2011b. To enkeltsportunnelerTBM tverrsnitt. Available at: Obtained from Johan Pettersen, MiSA.

Nord, G., 2006. TBM versus Drill and Blast, the Choice of Tunneling Method. In International Conference and Exhibition on Tunneling and Trenchless Technology. Selangor, Malaysia. Available at: <http://www.ita-aites.org/fileadmin/filemounts/general/pdf/ItaAssociation/Organisation/Members/MemberNations/Malaysia/S3-4.pdf> [Accessed February 6, 2012].

Ogilvie, N. & Quante, F., 2001. *Innovative Track Systems. Criteria for their Selection*, Available at: [http://www.promain.org/images/council/08\\_Selection\\_of\\_Tack\\_Systems.pdf](http://www.promain.org/images/council/08_Selection_of_Tack_Systems.pdf) [Accessed September 5, 2011].

Palmstrøm, A., Blindheim, O.T. & Einar Broch, 2002. *Q-systemet - muligheter og begrensninger*, Available at: [http://www.rockmass.no/files/misc/q\\_systemet.pdf](http://www.rockmass.no/files/misc/q_systemet.pdf) [Accessed February 20, 2012].

Pedersen, K.B., Kompen, R. & Kveen, A., 2010. *Arbeider foran stuff og stabilitetssikring i vegtunneler*, Oslo: Statens vegvesen. Available at: [http://www.vegvesen.no/\\_attachment/155750/binary/269125](http://www.vegvesen.no/_attachment/155750/binary/269125) [Accessed March 26, 2012].

Pöyry et al., 2011. *High speed rail assessment, phase II. Technical and Safety Analysis.*, Norwegian National Rail Administration. Available at: <http://www.jernbaneverket.no/PageFiles/13670/Technical%20and%20Safety%20Analyses.pdf> [Accessed August 20, 2011].

RAIL.ONE GmbH, 2011. RHEDA 2000. Ballastless track system. Available at: [http://www.railone.com/fileadmin/dateien/03\\_Broschueren/EN/Rheda2000\\_EN\\_2011\\_ebook.pdf](http://www.railone.com/fileadmin/dateien/03_Broschueren/EN/Rheda2000_EN_2011_ebook.pdf) [Accessed May 7, 2012].

Ramsland, R., 2011. Volume and maintenance of ballast. Personal contact by mail. Available at: [roy.ramsland@jbv.no](mailto:roy.ramsland@jbv.no).

Robbins, 2012a. For projects with difficult ground that still demand the speed of a Main Beam TBM. Available at: <http://www.robbinstbm.com/our-products/tunnel-boring-machines/double-shield/> [Accessed March 26, 2012].

Robbins, 2012b. In hard rock nothing bores faster than a Main Beam TBM. Available at: <http://www.robbinstbm.com/our-products/tunnel-boring-machines/main-beam/> [Accessed March 3, 2012].

Seehusen, J., 2012. Frykter at vi mister vår tunnelkompetanse. *Teknisk Ukeblad*. Available at: <http://www.tu.no/bygg/2012/01/24/-frykter-at-vi-mister-var-tunnelkompetanse?service=print> [Accessed May 9, 2012].

SSB, 2012. Statistisk sentralbyrå: - Befolkning - temaside. Available at: <http://www.ssb.no/befolkning/> [Accessed May 22, 2012].

Standard Norge, 2006. *Environmental management. Life cycle assessment. Principles and framework (ISO 14040:2006)*.,

Statens Vegvesen, 1999. *Fjellbolting*, Vegdirektoratet. Available at: [http://www.vegvesen.no/\\_attachment/69898/binary/34568](http://www.vegvesen.no/_attachment/69898/binary/34568) [Accessed February 13, 2012].

Statens Vegvesen, 2004. *Injeksjon - Erfaringer fra Lunnertunnelen*, Available at: [http://www.vegvesen.no/\\_attachment/61917/binary/15139](http://www.vegvesen.no/_attachment/61917/binary/15139) [Accessed May 28, 2012].

Statens Vegvesen, 2012. Slik bygger vi tunneler. Available at: <http://www.vegvesen.no/Vegprosjekter/e6alta/Fakta/Tunnelbygging> [Accessed May 28, 2012].

Stillesby, T. & Botnen, L.K., 2012. Oppsummering:Hovedkonklusjoner. *Høyhastighetsutredningen*. Available at: <http://www.jernbaneverket.no/no/Prosjekter/Hoyhastighetsutredningen/Nyhetsarkiv/Oppsummering-Hovedkonklusjoner/> [Accessed February 14, 2012].

Strande, M., 2009. Vil bore rekordtunnel Oslo-Ski. *Teknisk Ukeblad*. Available at: <http://www.tu.no/bygg/2009/04/22/vil-bore-rekordtunnel-oslo-ski> [Accessed May 9, 2012].

Tempo, 2012. Høyhastighetstog. *Transport og miljø*. Available at: <http://www.transportmiljo.no/tema/jernbane/hoyhastighetstog/> [Accessed May 27, 2012].

Tunmo, T., 2011. Vil helstøpe tunneler. *Teknisk Ukeblad*. Available at: <http://www.tu.no/bygg/2011/02/14/vil-helstope-tunneler> [Accessed May 9, 2012].

Vianova, 2011a. *Follobanen tunnelstrekning. Underbygning. Sprengt løsning. 250km/t*, Available at: Obtained from Johan Pettersen, MiSA [Accessed March 30, 2012].

Vianova, 2011b. *Follobanen tunnelstrekning. Underbygning. TBM-løsning.250km/h*, Available at: Obtained from Johan Pettersen, MiSA.

Vianova, 2011c. Miljømengder til miljøbudsjett for Follobanen. Available at: Obtained from Johan Pettersen, MiSA.

# APPENDICES

## APPENDIX I – DENSITIES

Density for concrete is obtained from the Ecoinvent report PartIII “concrete for sole plate and foundation” (Kellenberger et al. 2007).

The density of gravel is obtained from the inventory estimated for the Follobanen project (Korsmo & Bergsdal 2010), which also indicated the density of diesel

Material	Density kg/m cu
Gravel <sup>22</sup>	2200
Concrete <sup>23</sup>	2387
Diesel <sup>22</sup>	885

**Table 12, Density of materials**

---

<sup>22</sup> (Korsmo & Bergsdal 2010)

<sup>23</sup> (Kellenberger et al. 2007)

## APPENDIX II – CALCULATION OF THE VOLUME OF GRAVEL FOR A DOUBLE TRACK

Calculations of the volume of ballast are obtained by applying the dimensions in the table below and subtract the volume of applied sleepers. An extra 50mm is added for the sub ballast to make it applicable for high speed rail. Further, the density from Table 12 is applied to estimate total masses.

Calculation of ballast for a double track <sup>24</sup>		
Top ballast	Width	97 dm
	Height	3 dm
Sub ballast	Width	92 dm
	Height	3.1 dm
	Extra HSR ballast	0.5 dm

Table 13, Calculation of ballast volume for a double track

---

<sup>24</sup> (Ramsland 2011)

### APPENDIX III – RELEVANT IMPACT CATEGORIES FOR A TUNNEL PROJECT

Table 14 presents the aspects of which was evaluated as affected by the construction of a tunnel project by Geldermalsen(2004). The environmental issues indicated with an arrow at the top of the list are the ten aspects evaluated as the most important environmental impacts.

Environmental issue	Environmental effects/aspect	Feasibility study	Conceptual design	Outline design	Detailed design	Realisation	Exploitation
⇒ Emissions	Air pollution (traffic during exploitation)	■	■	■	■	■	■
⇒ Living conditions	Noise & vibrations during exploitation	■	■	■	■	■	■
⇒ Energy	Traffic during exploitation	■	■	■	■	■	■
⇒ Cultural quality	Visual design and landscape values	■	■	■	■	■	■
⇒ Environmental quality	Groundwater level during realisation	■	■	■	■	■	■
⇒ Environmental quality	Soil stability during realisation	■	■	■	■	■	■
⇒ Habitat	Fragmentation of habitats	■	■	■	■	■	■
⇒ Habitat	Degradation of habitat	■	■	■	■	■	■
⇒ Habitat	Disturbance of fauna	■	■	■	■	■	■
⇒ Cultural quality	Historical and cultural heritage	■	■	■	■	■	■
⇒ Energy	Installations	■	■	■	■	■	■
⇒ Living conditions	Noise, vibrations & dust during realisation	■	■	■	■	■	■
Emissions	Waste water	■	■	■	■	■	■
Emissions	Pollution of ground and groundwater	■	■	■	■	■	■
Materials	Primary building materials	■	■	■	■	■	■
Materials	Secondary building materials	■	■	■	■	■	■
Materials	Reusable excavated material	■	■	■	■	■	■
Materials	Chemical products	■	■	■	■	■	■
Materials	(Dangerous) waste material	■	■	■	■	■	■
Environmental quality	Quality of soil and groundwater	■	■	■	■	■	■
Emissions	Pollution of excavated material	■	■	■	■	■	■
Cultural quality	Archaeological values etc.	■	■	■	■	■	■
Materials	Renewable materials	■	■	■	■	■	■
Emissions	Pollution of surface water	■	■	■	■	■	■
Cultural quality	Demolition of real estate etc.	■	■	■	■	■	■
Energy	Production of building materials	■	■	■	■	■	■
Energy	Transport of building materials	■	■	■	■	■	■
Energy	Construction equipment	■	■	■	■	■	■
Environmental quality	Air quality	■	■	■	■	■	■
Environmental quality	Surface water quality	■	■	■	■	■	■
Emissions	Air pollution (explosives/rock tunnel)	■	■	■	■	■	■

Table 14 Relative importance of environmental aspects. The table presents the collection of environmental impacts assumed for a tunnel construction project, gathered Geldermalsen (2004). The ten most important aspects are indicated by the arrows at the top of the table.

## APPENDIX IV – THE Q-METHOD

The Q – method is a classification system for rock quality developed by the Norwegian Geotechnical Institute (NGI), the following introduction to the method is therefore based on publications by the NGI (1997).

The Q-method uses a set of six parameters to determine a value between 1 and 10 whereas a high Q – value indicates good stability, and low values, poor stability.

The ranges of Q values subsequently are matched with one of 6 categories which determine the rock quality and present a recommendation for which of the securing methods presented above that should be applied and to which extent as presented in Table 15 in the appendix.

Bergmasse klasse	Bergforhold Q-verdi <sup>(1)</sup>	Sikringsklasse Permanent sikring
A/B	Lite oppsprukket bergmasse. Midlere sprekkeavstand > 1m. Q = 10 – 100	<b>Sikringsklasse I</b> - Spredt bolting - Sprøytebetong B35 E700 tykkelse 80 mm, ned til 2 m over såle
C	Moderat oppsprukket bergmasse. Midlere sprekkeavstand 0,3 – 1 m. Q = 4 – 10	<b>Sikringsklasse II</b> - Systematisk bolting (c/c 2 m), endeforankrete, forspente, gyste - Sprøytebetong B35 E700, tykkelse 80 mm, sprøytes ned til såle
D	Tett oppsprukket bergmasse eller lagdelt skifrig bergmasse. Midlere sprekkeavstand < 0,3 m. Q = 1 – 4	<b>Sikringsklasse III</b> - Sprøytebetong B35 E1000, tykkelse 100 mm eller mer. - Systematisk bolting (c/c 1,5 m), endeforankrete, endeforankrete som gyses i ettertid, eller gyste
E	Svært dårlig bergmasse.  Q = 0,1 – 1	<b>Sikringsklasse IV</b> - Forbolting ved Q < 0,2, ø25 mm, maks. c/c 300 mm - Sprøytebetong B35 E1000, tykkelse 150 mm. - Systematisk bolting, c/c 1,5 m, gyste - Armerte sprøytebetongbuer ved Q < 0,2, buedimensjon E30/6 ø20 mm, c/c 2 – 3 m, buene boltes systematisk, c. 1,5 m, lengde 3 – 4 m. <sup>(2)</sup> - Sålestøp vurderes
F	Ekstremt dårlig bergmasse.  Q = 0,01 – 0,1	<b>Sikringsklasse V</b> - Forbolting, c/c 200 – 300 mm, ø32 mm eller stag (selvborende). - Sprøytebetong B35 E1000, tykkelse 150 – 250 mm. - Systematisk bolting, c/c 1,0 – 1,5 m, gyste. - Armerte sprøytebetongbuer, buedimensjon D60/6+4, ø20 mm, c/c 1,5 – 2 m, buene boltes systematisk, c. 1,0 m, lengde 3 – 6 m. <sup>(2)</sup> - Armert sålestøp, pilhøyde min. 10 % av tunnelbredden.
G	Eksepsjonelt dårlig bergmasse, stort sett løsmasse, Q < 0,01	<b>Sikringsklasse VI</b> - Driving og permanent sikring dimensjoneres spesielt.

<sup>(1)</sup> Q-verdiene er gitt for uniaxial compressive strength, UCS = 100 MPa

<sup>(2)</sup> For krav til materialer, metoder og løsninger henvises til Teknologirapport nr. 2538: Arbeider foran stoff og stabilitetssikring i vegtunneler.

Table 15 The Q - system<sup>25</sup>

<sup>25</sup> Table obtained from: (Pedersen et al. 2010)

Calculation of the Q-value:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

Where the six parameters are:

RQD = Rock Quality Designation

$J_n$  = Joint set number

$J_r$  = Joint roughness number

$J_a$  = Joint alternation number

$J_w$  = Joint water reduction factor

SRF = Stress Reduction Factor

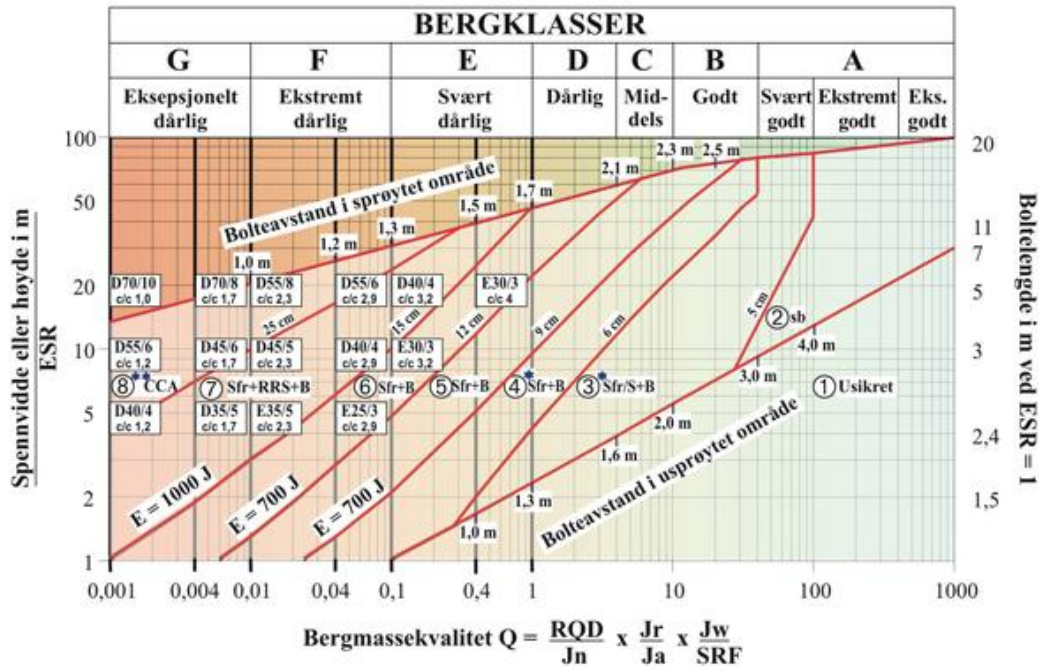
The individual parameters are obtained from geological examinations and give the three important factors:

$$\frac{RQD}{J_n} = \text{Degree of jointing}$$

$$\frac{J_r}{J_a} = \text{Joint friction}$$

$$\frac{J_w}{SRF} = \text{Active stress}$$

The Q-value are determined by three main factors; degree of jointing, joint friction and active stress. The degree of jointing is determined by the joint pattern. This parameter is calculated from the number of joints per m<sup>3</sup> divided on the number of joint sets in the area (which refer to the number of more or less parallel joints). The joint friction depends on the character of the joint wall described by the joint roughness number where the degree of smoothness and undulating conditions is given a specific number. The “joint infill” is further important for the joint friction. The joint alternation number describes the joint infill where the joint thickness and mineral composition represent important determinants for the number presented. The active stress factor is determined by the joint water reduction factor and the stress reduction factor. The former of the two is based on the level of leakage into the cavern while the SRF describe the “relation between stress and rock strength around a cavern”(NGI 1997, p.20).



**SIKRINGSKATEGORIER**

- |                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>1) Usikret</li> <li>2) Spredt bolting, sb</li> <li>3) Systematisk bolting og uarmert eller fiberarmert sprøytebetong, 5-6 cm, Sfr/B+S</li> </ul> | <ul style="list-style-type: none"> <li>4) Fiberarmert sprøytebetong og bolting, 6-9 cm, Sfr+B</li> <li>5) Fiberarmert sprøytebetong og bolting, 9-12 cm, Sfr (E700) +B</li> <li>6) Fiberarmert sprøytebetong og bolting, 12-15 cm, Sfr (E700) +B</li> <li>7) Fiberarmert sprøytebetong &gt; 15 cm + armerte ribber av sprøytebetong og bolting, Sfr (E1000) +RRS+B</li> <li>8) Betongutstøpning, CCA eller Sfr (E1000) +RRS+B</li> </ul> |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Boltene er 20 eller 25 mm i diameter

E) Energiabsorpsjon i fiberarmert sprøytebetong ved 25 mm nedbøyning i platetest

$\left[ \begin{matrix} D45/6 \\ \text{etc } 1,7 \end{matrix} \right]$  = RRS (sprøytede buer) med 6 armeringsjern i dobbelt lag, i 45 cm tykke buer med senter/senteravstand 1,7 m. Hvert rektangel er relatert til Q-verdien i venstre sidekant av rektangelet. (Se tekst for nærmere forklaring)

- \* ) Opptil 10 cm ved store spennvidder
- \*\* ) Eller Sfr+RRS+B

Figure 39 Q-method, classification of rock quality<sup>26</sup>

Figure 39 presents an illustration of the Table 15 above. In addition the illustration indicate the length of bolts for the different categories and more specific the variations within each of the categories of the Q-system.

<sup>26</sup> Illustration obtained from:(NGI 2008)



## APPENDIX V – VOLUME OF CEMENT INJECTION AND ROCK QUALITY

Table 16 presents the cases obtained from Statens Vegvesen (2004), which are divided into categories based on applied cement per m<sup>2</sup> of a tunnel as presented in the table below. Subsequently, the average of each of these categories is used to develop five levels of grout injection. These level are ultimately applied in the assessment

Volume of cement for pre-injection per m <sup>2</sup> of a tunnel									
0-15 kg		16-30 kg		31-40 kg		41-70 kg		71kg -	
Gneiss	14.2	Phyllite	26	Gneiss/Shale	35.3	Grit/Conglomerate	51	Rhombus porphyry	81.5
Granite	12.4	Lime	26	Rhombus porphyry	33.3	Hornfels	68.4	Syenite / Jointed rock	118.3
Quartz porphyry	9.5	Shale/Lime	26.3	Basalt	31	Nodule lime/Day mudstone	46.1		
		Limestone	28.3	Volcanic rock	36	Rhombus/ Quartz porphyry /Basalt	42		

**Table 16 Volume of cement for grouting. The rock types are organized in groups based on similar grouting volume per m<sup>2</sup><sup>27</sup>.**

<sup>27</sup> Volumes obtained from (Statens Vegvesen 2004)

## APPENDIX VI – VOLUME OF MATERIALS FOR SUPPORT WORK

### *Properties of the Borstagbolt*

The borstagbolt is presented in Statens Vegvesen (1999), as a bolt applicable for pre-bolting. In addition does dimensions presented in Figure 17 agree with the requirements of the pre-bolts described in the Q-method. The specific bolt is thus assumed for this assessment.

Borstagbolt	
Length	2-6m
Bolt	ø30-ø70
Weight	2,5-6,9kg

**Table 17 Properties of the Borstagbolt**

### *Calculation of materials for reinforced ring beams*

Reinforced concrete ring beams consist of steel arches and shotcrete. The steel wires are placed with pre-decided intervals over the entire tunnel lining and are subsequently covered with shotcrete (Pedersen et al. 2010). The single ring beam for category E is described as: E30/6 c/c 2, which indicate reinforcing steel of 30 cm thickness, 6 pieces placed next to each other making one ring beam, several of these are placed subsequently with a 2m center distance. For a double ring beam, the properties is presented as D60/6+4 c/c 1,5, the values indicate the same factors as presented for the single ring beam.

The amount of weight per m<sup>2</sup> is calculated from the weight per meter given in the Table 18 multiplied with the number of wires per meter. Subsequently, the volume of concrete is calculated from the information in the same table, were the steel is ultimately subtract to obtain volume of shotcrete per m<sup>2</sup> tunnel.

Reinforced ring beams <sup>28</sup>			
		Single ring beam	Double ring beam
reinforcing steel		ø20	ø20
	cross section	314mm <sup>2</sup>	314mm <sup>2</sup>
	Weight	2,47kg/m	2,47kg/m
	Nb. bars	6	6+4
Concrete	Depth	240	470
	Width	670	670 (450 on outer layer)

**Table 18 Properties of ring beams**

<sup>28</sup> Data is obtained from: (Pedersen et al. 2010)

## APPENDIX VII – COMPARING THE SIMAPRO PROCESS FOR BLASTING

Figure 40 presents the difference in environmental impact between the two blasting methods relevant for this thesis. The “China process” was initially used for the Norwegian High-Speed Rail Assessment by Bergsdal et al. et al. (2012), but was later adjusted (Norway process) by MiSA to better suit Norwegian conditions and renamed. The latter is used for this assignment. The figure presents a significant difference for the eight impact categories.

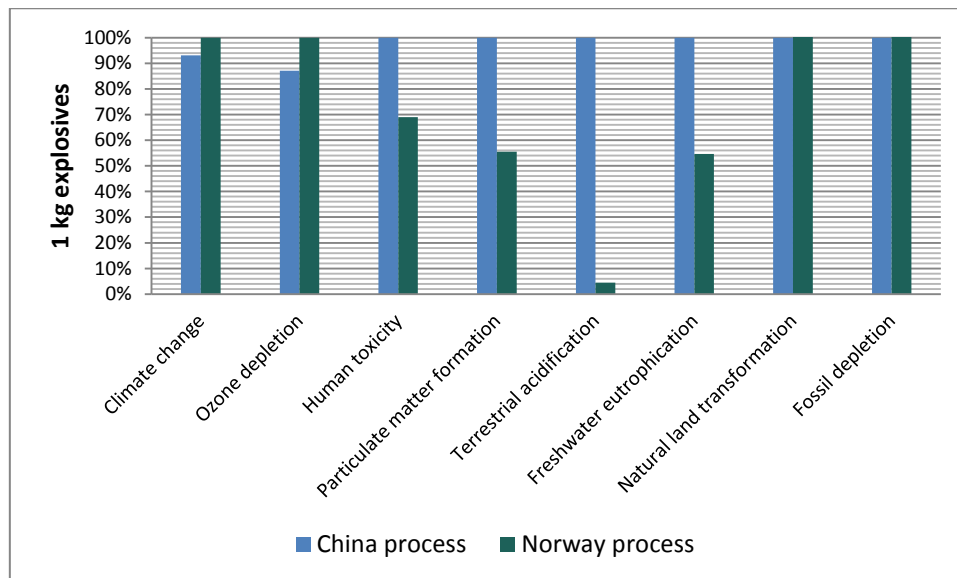


Figure 40 Process for blasting. The figure presents a comparison of the environmental impact from the two different processes for explosives applied for railway projects. The “China process” was used for the High Speed Rail Assessment by Bergsdal et al. (2012). The “Norway process” was later developed by MiSA to better present the Norwegian conditions. We have therefore decided to use this process for this thesis.

The main difference in the new blasting process compared to the initial, is higher amount of ammonium nitrate and naphtha for the Norwegian process and aluminum and calcium nitrate for the China process.

APPENDIX VIII – SYSTEM PATH ANALYSIS OF THE DOUBLE SHIELDED TBM AND THE EUROPEAN TUNNELING METHOD

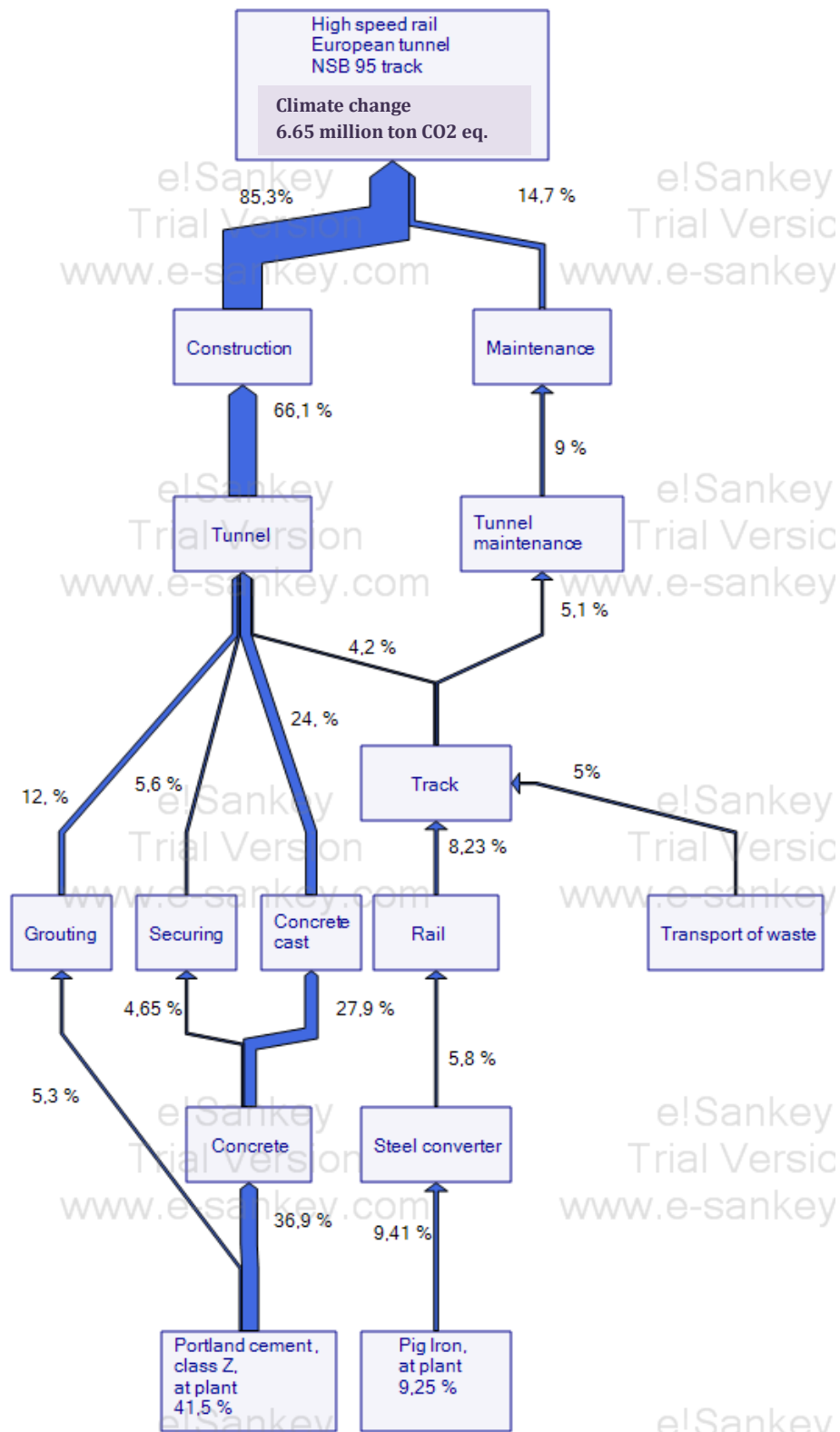


Figure 41 System path analysis, European tunnel technology, climate change

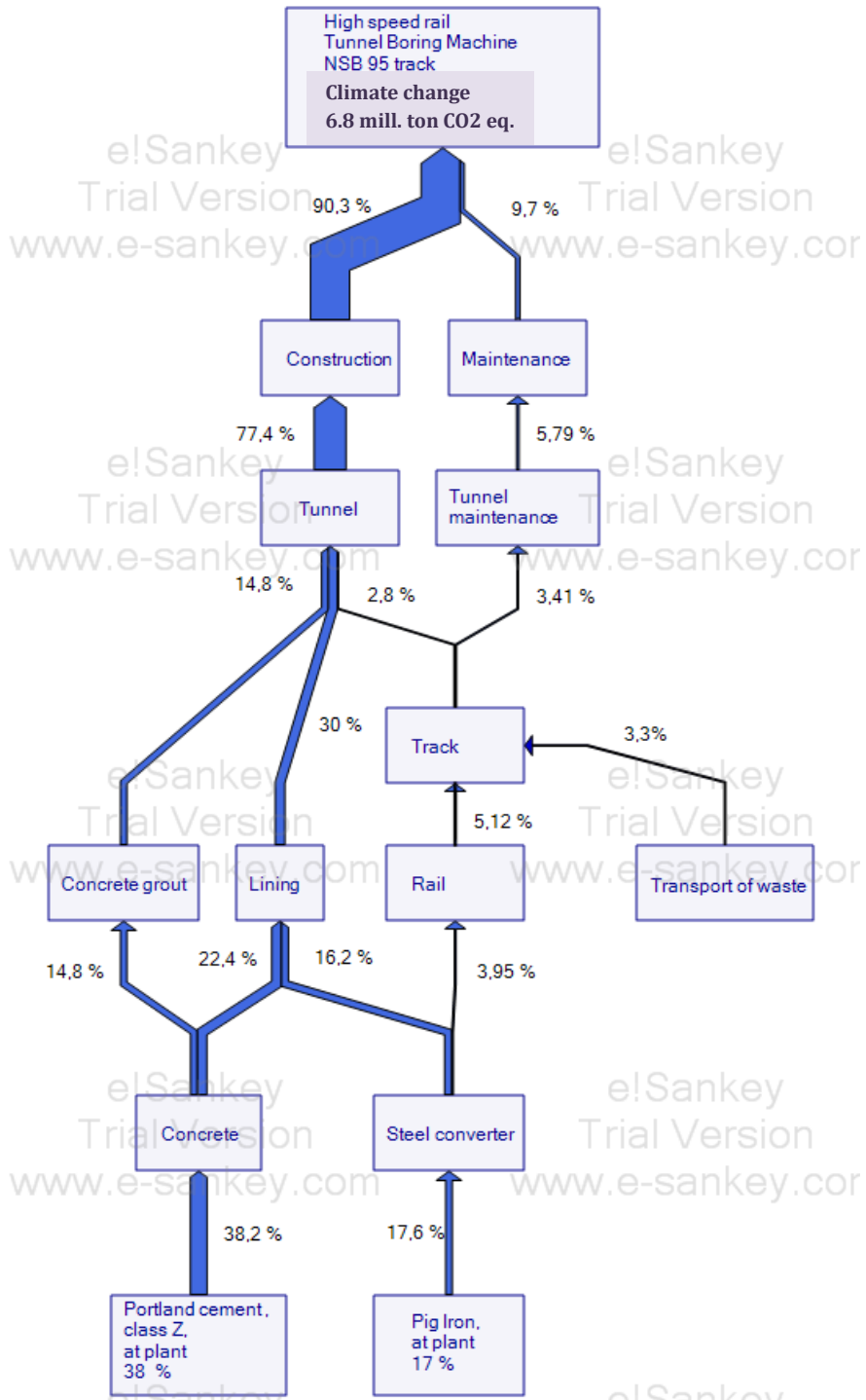


Figure 42 System path analysis, double shielded tunnel boring machine, climate change

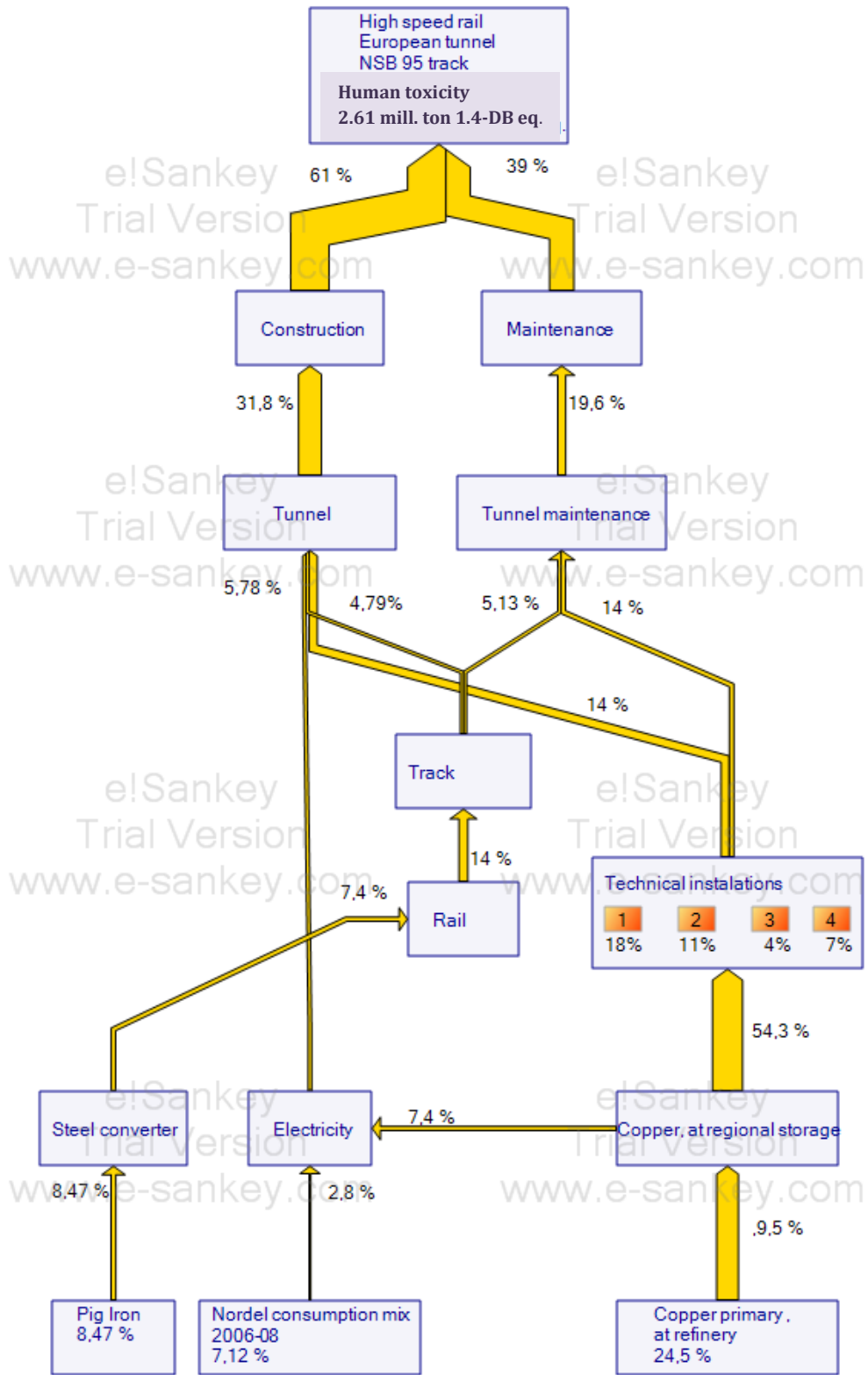


Figure 43 System path analysis, European tunnel technology, human toxicity

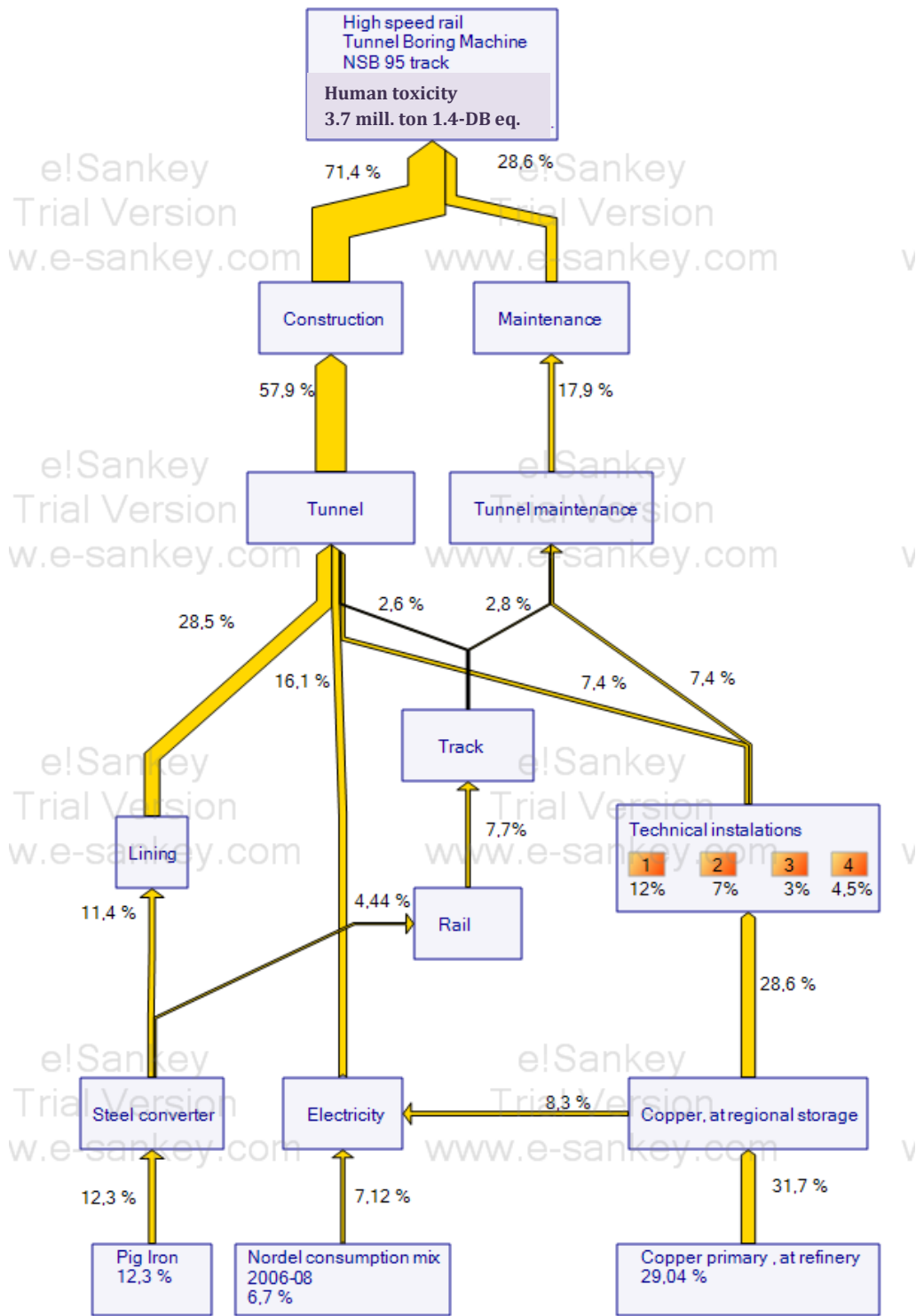
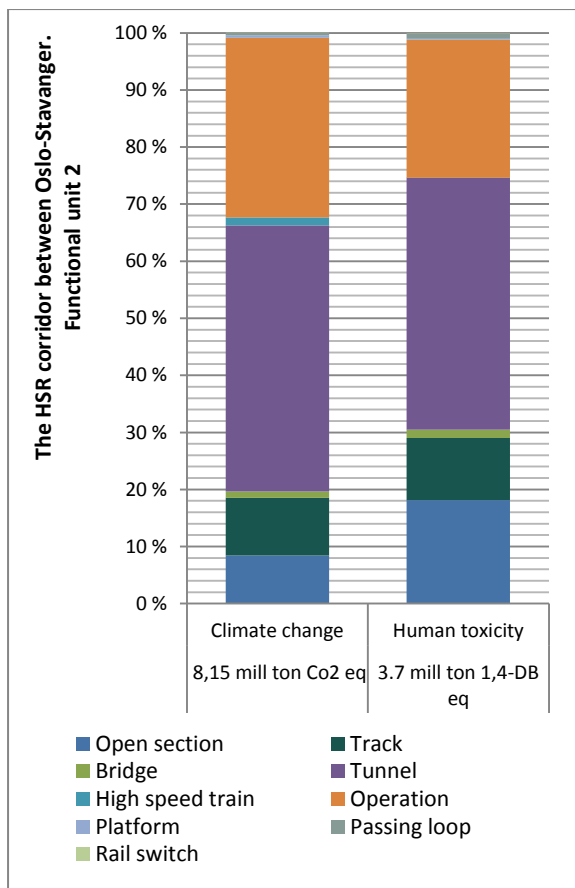


Figure 44 System path analysis, double shielded tunnel boring machine, human toxicity

## APPENDIX IX – COMPARATIVE ANALYSIS, FUNCTIONAL UNIT 2

Figure 45 presents the two selected impact categories for baseline for the functional unit 2, which was included in the comparative analysis. The numbers presented in Table 19 present a similar result as was discussed for the functional unit 1 in section 7.1. The relative differences from baseline are slightly decreased as a consequence of the remaining infrastructure and the operation phase included in the functional unit 2.



		Climate change	Human toxicity
Track design	Ballasted track	Baseline	
	Slab track in tunnels and on bridges	-2%	-1%
Tunnelling method	Norwegian	Baseline	
	European	+14%	-9%
	TBM	+16%	+22%
Securing level	Q = A/B	Baseline	
	Q = C	-0,4%	-0,7%
	Q = D	+1%	+0%
	Q = E	+6%	+5%
	Q = F	+10%	+8%
Cement grout	Injection level 1	-9%	-1%
	Injection level 2	-8%	-1%
	Injection level 3	-7%	-1%
	Injection level 4	-5%	-1%
	Injection level 5	Baseline	
Increased speed	Norwegian 250 km/h	Baseline	
	Norwegian 330 km/h	+7%	+15%
	European 330 km/h	-4%	-9%
	TBM 330 km/h	+25%	+35%

Figure 45 Comparative results, FU2. The figure presents a selection of the baseline results from Figure 18. The figure presents our baseline results of comparison for the variables in the table to the right.

Table 19 Comparative results, FU 2. The table presents a summary of four most important results obtained in Section 6. The white squares indicate baseline (100 %) and the point of normalizing, while the red color indicates an increase and the green, a decrease compared to our baseline results. The results for 330km/h should be interpreted with some caution as discussed in Section 5.2.1.



## APPENDIX X – LIST OF PARAMETERS FOR THE SIMAPRO MODEL

The following list presented by Table 8, present an overview of the parameters developed for the model which constitute the base for calculation of the impact results for this thesis.

List of parameters applied for the SimaPro model		
Input parameters	Value	Comment
Newtrack	1/0	Insert the track designs, NSB95 for all corridors and makes the RHEDA 2000 available
LifeCyclePhase	years	The life cycle used to calculate number of maintenance activities
ServiceLifeTamping	years	Insert technical service life of component
ServiceLifeCleansing	years	
ServiceLifeSleepers	years	
ServiceLifeRails	years	
ServiceLifeFasteners	years	
ServiceLifeSlab	years	
SlabItunnel	percent	
SlabonBridge	percent	Insert the share of total tunnel length were the slab track is applied
Tunnel_Euprofile	m2	Insert the blasted cross section of the European method
Tunnel_Eu_normalprofile	m2	Insert the cross section for the normal profile for the European method
TBM_profile	m2	Insert drilled profile
TBM_normalprofile	m2	Insert normal profile
Length_tunnel	km	Insert total length of tunnels in km
Length_opensection	km	Insert total length denoted as open section in km
is_1	Share of length	Insert the percent of the preferred level of cement injection. Leave remaining rows with "0"
is_2	Share of length	
is_3	Share of length	
is_4	Share of length	
is_5	Share of length	
QAB	Share of length	Insert the percent of the preferred level of support work. Leave remaining rows with "0"
QC	Share of length	
QD	Share of length	
QE	Share of length	
QF	Share of length	
Share_TBM	Share of length	Insert share of total tunnel length using the TBM tunnelling method
Share_Cast	Share of length	Insert share of total tunnel length using the European tunnelling method
Share_ruralsection	Share of length	Insert share of total length of the open section calculated as "rural"
nb_short_bridges	Nb	Number of bridges shorter than 50m
nb_short_bridges	Nb	Number of bridges of the length 50 - 100m
nb_short_bridges	Nb	Number of bridges longer than 100m
Singletunnel	1/0	Insert "1" to activate, remember to remove "Doubletunnel"
Topopstunnel	1/0	Insert "1" to activate, remember to remove "Ettlopstunnel"
Nb_passingloops	Nb	Number of passing loops for the track (double)
Nb_platforms	Nb	Number of platforms

Nb_rail_switches	Nb	Number of switches
Maintenance_no	1/0	Insert "1" to include the substitution of the lining for the Norwegian tunnel
Share_tbm_lining	Share of length	Insert share of total tunnel length that requires a lining of concrete segments
Tbm_segments	Thickness in meter	Insert the thickness of TBM segments, varies usually between 0,4-0,6cm
BallastTamping	Share of total volume	Percentage of total ballast volume added for each tamping
BallastCleansing	Share of total volume	Percentage of total ballast volume shifted for each cleansing
Additional Tunnels	1/0	Insert "1" to include additional tunnels per meter of tunnel (ex water tunnel, cross sections etc)
No_blastedprofile	m2	Insert the m2 for the blasted profile of the Norwegian tunnelling method
No_normalprofile	m2	Insert the m2 for the normal profile of the Norwegian tunnelling method
Calculated parameters		
Name	Expression	Comment
TBMlength	Track_length*share_TBM	Calculates total length for TBM tunnelling method
sprengt_ts	Tunnel_Euprofile-Tunnel_Eu_normalprofil	calculates the cross section of materials for the D&B tunnel
TBM_ts	TBM_profile-TBM_normalprofile	calculates the cross section of materials for the TBM tunnel
Track_length	Length_tunnel*(Doubrack*Singtrack)	Total length of tunnel, calculated for double or single corridor.
injectioncement	(is_1*0,012)+(is_2*0,027)+(is_3*0,034)+(is_4*0,052)+(is_5*0,096)	Will insert the chosen amount of injection cement
Doubrack	1=1	Multiplication factor for the calculation of total length of tunnel
Singtrack	1+(Doubletunnel=1=1)	Multiplication factor for the calculation of total length of tunnel
Share_No	1-(Share_cast+Share_TBM)	Share of total tunnel length with the Norwegian tunnelling method
Lcs	Length_tunnel*(singtrack*doubrack)*0,14*1000	Length of cross sections, calculated as 14% of total tunnel length
La	Length_tunnel*(singtrack*doubrack)*0,14*1000	Length of audits, calculated as 14% of total tunnel length
Lesc	Length_tunnel*(singtrack*doubrack)*(1-share_utstopt)*(1-Share_tbm)*0,02*1000	Length of escape tunnel, calculated as 20% of total tulle length
Lwt	Length_tunnel*(singtrack*doubrack)*((share_cast)+(share_tbm))*0,02*1000	Length of water tunnel, calculated as 2% of the total length for the European and TBM tunnels
Lad	Length_tunnel*(singtrack*doubrack)*(share_tbm)*0,05*1000	Length of arrival tunnel, calculated as 5% of total length for the TBM
Larb	Length_tunnel*(singtrack*doubrack)*(share_tbm)*0,05*1000	Length of work tunnel, calculated as 5% of total tunnel length for TBM tunnel
castLength	Track_length*share_cast	Length of European tunnelling method
noblased_ts	(No_blastedprofile-No_normalprofile)	Calculate material cross section for the Norwegian tunnelling method

Table 20 List of parameters developed for the parameterized SimaPro model applied for this thesis.