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Life Cycle Assessment of the Byåsen tunnel in Trondheim, Norway

Assessing emissions from traffic and infrastructure

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Abstract:

The Byåsen tunnel is a tunnel proposed by the Norwegian Public Roads Administration (NPRA), and an infrastructural element in an environmental programme (Greener Trondheim) initiated by the Trondheim municipality, Norway. Among the main goals is an overall decrease in CO_2 emissions from traffic.

This study assesses the environmental impacts (expressed in greenhouse gases) induced by the construction of the tunnel and emissions from traffic in operation. Additionally, the study gauges its coherence with goals set in the Trondheim municipality's environmental programme.

The study utilizes LCA methodology, including regional traffic data and parameters pertaining to routes travelled by vehicles included in the study.

The project's environmental impacts are between 73.738 – 77.851 thousand ton CO_2-eq/year, depending on tunnel design (length), and 80.516 thousand ton CO_2-eq/year for the reference scenario, with no tunnel constructed. Net GHG-emissions related to the excavation and operation of a tunnel in excess of 2 km proves to be between 3106-5509 ton CO_2-eq/year depending on design, which is about 6% of yearly emissions from traffic. A simulation of traffic volume (after excavating the Byåsen tunnel) without tolling reveals an increase of 7715-8040 ton CO_2-eqs/year. This is a 10% increase in traffic emissions from tolled tunnel alternatives.

The results found in this study shows that the construction of the Byåsen tunnel leads to a net decrease of 2665-6778 ton CO_2-eq/year. That is a net decrease of 3.3-8.4% over the reference alternative. This study does also show the importance of including traffic in operation when assessing infrastructure as well as the significant effect tolling stations has on traffic volume and yearly GHG-emissions.

Keywords:

1. Life Cycle Assesment
2. Traffic emissions
3. Infrastructure
4. Tunnel

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«Den lange, lange sti over myrene og ind i skogene hvem har trakket op den? Manden, mennesket, den første som var her. Det var ingen sti før ham.»

- Knut Hamsun, Markens grøde.

Preface

This thesis concludes my education at the Norwegian University of Science and Technology (NTNU), within the international master’s programme of Industrial Ecology. The thesis, this study, was conducted in collaboration with Greener Trondheim and the National Public Roads Administration (NPRA). Greener Trondheim and the NPRA has supported the study with data material and project documents pertaining to the Byåsen tunnel and the new Sluppen Bridge project. The thesis is worth 30 credits.

Rolf André Bohne has been the main supervisor throughout the thesis. Helge Brattebø, Thomas Jonsson and Jardar Lohne have been acting as co-supervisors. I want to thank Bohne, Brattebø, Jonsson and Lohne for their excellent advice and support throughout the process of writing this thesis. Their input on structure and scope of the thesis has been invaluable. I further want to thank Børge Bang and Erik Fjellheim at the NPRA. Bang has been most patient, taking the time to answer questions and support the thesis with data materials from the NPRA’s traffic analysis section. Fjellheim has been the study’s main contact person within the NPRA, putting me in contact with experts within the NPRA organization.

I also want to thank Roar Norvik and Odd André Hjelkrem at SINTEF for their advice on vehicle fuel consumption and for alerting and instructing me in the use of the SEMBA model. I further owe gratitude to Irina Jonsson at the NPRA and Pål Johannes Bruhn at Opplysningsrådet for Veitrafikken AS for their supply of statistics on average speeds and regional vehicle stock composition.

Lastly, I would wholeheartedly like to thank my family and my friends for their support and good company during my five years at NTNU.

Per Olav Fremo Kalvå

10.06.2015

Abstract

The Byåsen tunnel is a tunnel proposed by the Norwegian Public Roads Administration (NPRA), and an infrastructural element in an environmental programme (Greener Trondheim) initiated by the Trondheim municipality, Norway. Among the main goals is an overall decrease in CO_2 emissions from traffic, an overall reduction of traffic noise and inner city traffic volume.

This study assesses the environmental impacts (expressed in greenhouse gases) induced by the construction of the tunnel and emissions from traffic in operation, assuming a 20 year analysis time horizon. Additionally, the study gauges its coherence with goals set in the Trondheim municipality's environmental programme.

The study utilizes life cycle analysis methodology, including regional traffic data and parameters pertaining to routes travelled by vehicles included in the study. The National Public Roads Administration has provided traffic volume for three scenarios; a reference scenario with no tunnel constructed (0-alternative), tunnel constructed with tolling stations present and tunnel constructed with no tolling stations present. Traffic emissions pertaining to each scenario is calculated using a dedicated traffic emissions model.

The project's environmental impacts are between 73.738 – 77.851 thousand ton CO_2-eq/year, depending on tunnel design (length), and 80.516 thousand ton CO_2-eq/year for the reference scenario, with no tunnel constructed. Net GHG-emissions related to the excavation and operation of a tunnel in excess of 2 km proves to be between 3106- 5509 ton CO_2-eq/year depending on design, which is about 6% of yearly emissions from traffic. A simulation of traffic volume (after excavating the Byåsen tunnel) without tolling reveals an increase of 7715-8040 ton CO_2-eqs/year. This is a 10% increase in traffic emissions from tolled tunnel alternatives.

The results found in this study shows that the construction of the Byåsen tunnel leads to a net decrease of 2665-6778 ton CO_2-eq/year. That is a net decrease of 3.3-8.4% over the reference alternative. The tunnel's mitigating effect on net yearly GHG-emissions is however declining as the analysis time horizon increases, due to a larger amount of tunnel life-cycle emissions being allocated to the project. Lastly, this study does show the importance of including traffic in operation when assessing infrastructure as well as the significant effect tolling stations has on traffic volume and yearly GHG-emissions.

Sammendrag

Byåsentunnelen er en tunnel foreslått av Statens Vegvesen, som et infrastrukturelement i Trondheim kommunes miljøprogram, Miljøpakken. Blant de viktigste målene i Miljøpakkens program er en nedgang i CO_2-utslipp fra trafikk, en samlet reduksjon av trafikkstøy og trafikkvolum i bysentrum.

Denne studien vurderer miljøkonsekvensene (uttrykt i utslipp av klimagasser) indusert ved bygging og drift av tunnelen, samt utslipp i fra trafikk. Studien analyserer de årlige klimagassutslippene fra seks ulike tunnelalternativ over en analyseperiode på 20 år. Av de seks tunnelalternativene er halvparten enkeltløpstuneller, og de resterende tre er dobbeltøps tuneller. I tillegg vurderer studien tunnelens bidrag til oppnåelse av målene i Miljøpakken.

Studien benytter livssyklusanalyse-metodikk og en dedikert trafikkutslippsmodell som beregner årlige utslipp fra trafikk. Trafikkutslippsmodellen benytter data fra trafikkanalyser, regional statistikk og et utvalg av ruter som antas påvirket av den ferdig byggede tunellen. Statens Vegvesen har beregnet trafikkvolumet i tre scenarier; et referansescenario uten tunnel (0-alternativ), bygget tunnel med bomring og tunnel bygget uten bomring i Trondheimsområdet.

Prosjektets miljøpåvirkning er mellom 73 738 til 77 851 tonn CO2-ekvivalenter/år, avhengig av tunnelalternativ, og 80 516 tonn CO2-ekvivalenter / år for referansealternativet, uten tunnel. Årlige klimagassutslipp knyttet til bygging og drift av en tunnel i overkant av 2 km er mellom 3106- 5509 tonn CO2-ekvivalenter / år, avhengig av alternativ. Dette tilsvarer ca. 6% av årlige utslipp fra trafikk. Scenarier med tunnelen bygget, uten bomstasjoner, viser en netto økning på 7715-8040 tonn CO2-ekvivalenter/år. Dette er en 10% økning i trafikkutslipp sammenlignet med scenarier med bomring.

Resultatene i denne studien viser at byggingen av Byåsentunnelen medfører en netto nedgang i klimagassutslipp i størrelsesorden 2665-6778 tonn CO2-ekvivalenter / år. Dette er en netto reduksjon på 3.3-8.4% i forhold til referansealternativet, uten tunnel. Reduksjonen i utslipp vil dog reduseres i takt med en økende analysetidshorisont, hvilket vil allokere en større andel av tunnelenes livssyklusutslipp til prosjektet. Studien viser videre viktigheten av å inkludere trafikk, og endringer i trafikkmengder, ved vurderingen livssyklusanalyser av infrastruktur, samt den betydelige effekten bomstasjoner har på trafikkmengde og årlige klimagassutslipp fra trafikk.

Part I: The process report

1. Introduction

This study is divided into two parts, Part I: The process report and Part II: The article. The process report considers the workings upon the article, included in part II, “Life Cycle Assessment of the Byåsen tunnel in Trondheim, Norway –assessing emissions from traffic and infrastructure.” The article, in its purest form an extract from the process report, is included in part II. For future reference, “Life Cycle Assessment of the Byåsen tunnel in Trondheim, Norway –assessing emissions from traffic and infrastructure”, is hereby referred to as “the article.”

Part I of this study, the process report, is an elaborating document, describing and outlining the progress towards the article. The process report does further address parts of the study not included in the article, as well as sections describing workings not fit within the format of a scientific article. The purpose of this process report is furthermore to close the gap between an article based and a traditional master’s thesis and to present moments not discussed in the article. The process report does further describe, among others, context, literature assessed, inventory data and methodology in detail.

Certain sections, such as the context of this study, is similar to the introduction presented in the article. This also goes for the research questions presented in the context section, which are the same for both the process report and the article. This is considered necessary in order to provide a readable and well-structured introduction to the process report.

Part II, the article, is an extract of the most contextually relevant findings within this study. It is a densified document, an extract of the process report, containing a fraction of the theory, methodology, results and discussion provided in the process report.

1.1. Thematic background

Year 2014.

This study is a continuation of a project work undertaken in the autumn of 2014. The project work resulted in study assessing the life cycle impact of the Byåsen tunnel in Trondheim, Norway, using life cycle assessment methodology. The life cycle analysis (LCA) was undertaken by the signatory, in part collaboration with Tonje Buø, who performed a life cycle assessment of a projected bridge in Sluppen, Trondheim, Norway. For future reference, the projected bridge is hereby referred to as the new Sluppen Bridge.

The signatory and Tonje Buø were introduced to the Byåsen tunnel, the new Sluppen Bridge and Greener Trondheim by Rolf André Bohne, Helge Brattebø and Thomas Jonsson, who were the academic supervisors throughout the project work and this study. Bohne, Brattebø and Jonnson are in addition co-authors of the article, presented in part II of this study.

The project work study was performed in part in collaboration with Tonje Buø, as the new Sluppen Bridge and the Byåsen tunnel are closely connected, meaning that the completion of the projected bridge is a premise for the tunnel being constructed. The inlet of the tunnel is furthermore parallel to the exit of the new Sluppen Bridge. The Byåsen tunnel and the new Sluppen Bridge are in several ways closely connected, being located in the same area and with relatively similar traffic volumes traveling through each of them. This lead to the assumption that the two projects could affect routes travelled in the Sluppen and western Trondheim area in a similar fashion.

A life cycle inventory was compiled in The Life Cycle Considerations of EIA of Road Infrastructure (LICCER) model, which was further utilized in the study to assess the environmental impact, expressed in greenhouse gas emissions, for each available tunnel design alternative. The study did also include an assessment of traffic emissions pre and post the construction of the tunnel, employing average values on fuel consumption found in literature, and traffic volume from traffic analyses by the National Public Roads Administration (NPRA). During the project, a dedicated Excel model was developed for calculating traffic emissions and for the compilation of reference alternative life cycle inventories.

Year 2015.

In January 2015, the early workings on this study began. Sadly, Tonje Buø went on to pursue another study, which meant that the main assessor of the new Sluppen Bridge was no longer available for the workings of this study.

The signatory, Per Olav Fremo Kalvå, had mainly been assessing the Byåsen tunnel, and it was further decided to continue with a study on the Byåsen tunnel solely. This meant that the study could still focus on the life cycle impact from constructing the Byåsen tunnel, employing the same life cycle tunnel inventory as compiled in the project work, whilst improving other aspects of the project work study.

In the project work study, traffic emissions were, pre and post tunnel, found to be the largest contributors to yearly GHG-emissions. The methodology employed for calculating traffic emissions was however somewhat primitive. It was decided, after consulting the SINTEF researchers Roar Norvik and Odd André Hjelkrem, to enhance the methodology employed in the project work's study on transport emissions. Hjelkrem and Norvik gave most welcome advice on matters such as fuel consumption and fuel consumption models. Hjelkrem did also give an introduction to SEMBA, which is a Python model designed for calculating vehicle fuel consumption, to the signatory.

The project work's study had utilized only the most basic methods of estimating emissions from transport, with average values on passenger car and heavy duty fuel consumption averaged over a traffic volume. Parameters, such as incline and average speeds, were not included in the project work study. However, with the introduction of SEMBA model and the ARTEMIS project, vehicle stock statistics could be combined with SEMBA and ARTEMIS model functions to calculate fuel consumption and traffic emissions in greater detail. Detailed traffic emission models had been found to be lacking in literature reviews performed in the project work study, and furthermore even in the project work study itself.

During the months that followed, several Matlab and Python scripts were designed for calculating traffic emissions. The Python scripts calculated heavy duty vehicle fuel consumption, and the fuel consumption data were compiled into matrices in Excel. Excel was further employed to calculate emissions from electric vehicles and for compilation of passenger car fuel consumption matrices.

The amount of matrices involved in the study made the shift from calculating traffic emissions in Excel to Matlab necessary. The Excel model compiled in the project work was however still in use, although only serving as a database for traffic volume data and route parameters. Additionally, another route of traffic was introduced, a route travelling through the city centre via the new Sluppen Bridge to Byåsen. This route was included to assess if the tunnel could affect traffic volumes in the city Centre.

Lastly, a turning point in the process of writing this study presented itself when Bohne, Brattebø and Jonsson suggested that the master's thesis, this study, should in part be written as a scientific article. The proposal was accepted, and the process of densifying the contents of this study began. This meant the welcome introduction of Jardar Lohne, who was introduced to the project as a fourth advisor. Lohne has been contributing, throughout the process of writing the article, most welcome advice on article structuring and the overall presentation of the article.

Division of work

The division of work throughout the workings of this study, process report and article included, has been as follows:

The signatory has conducted the fraction of the study, including the literature review, data collection, calculations and calculation model design, design of tables and layout, redacting and writing the process report as well as the article.

Bohne, Brattebø and Jonsson have been the main advisors associated with the study. Bohne has contributed with reviewing and an introduction to the statistical analysis and graphing software SigmaPlot, which this study utilizes. Brattebø has contributed with giving advice on compilation of life cycle inventories as well as giving an introduction to LICCER. Jonsson has contributed with expert advice on traffic related matters and reviewing. Lohne has contributed with expert advice on article structure, presentation and clever wordings. Overall, the advisors have all contributed with welcome advice on research questions, scope and academic reviewing of the article.

1.2. Context, scope and research questions

Reducing transport emissions through investments in infrastructure used for transportation, encouraging a shift in mode of transportation and avoiding journeys are all means suggested by the Intergovernmental Panel on Climate Change (IPCC) in an effort to mitigate emissions from transport (R. et al., 2014). The need for mitigation of transport emissions is further emphasized by the IPCC, stating that a further increase in transport emissions alone could outweigh the energy use from other end-use sectors by 2050.

This highlights the importance of mitigating measures taken in an effort to reduce global greenhouse gas emissions from transport, and further improve local air quality and local pollution through municipal programmes such as Greener Trondheim.

32% of total Norwegian CO_2 emissions stem from transport, where passenger cars hold the majority of transport emissions (Miljødirektoratet, 2015). The Norwegian government has not currently set any quantified targets for the reduction of inland transport emissions (Nenseth, 2013).

The Trondheim municipal has set a number of targets pertaining to local emissions resulting from transport through their environmental programme "Greener Trondheim".

Out of Greener Trondheim's 10 politically approved goals, the following goals are found to be most relevant in the context of this study:

- Reducing travel by passenger car and a 20% cut in CO_2-emissions from traffic in 2008 to 2018
- Reducing NO_x and particulate matter emissions.
- Reducing traffic noise.

Measures adopted for reducing traffic emissions employed are among others increasing the length of cycle pathways, increasing the frequency of travels by public transport and infrastructural projects aimed at reducing congestion and reducing travel length by car.

Furthermore, the municipal authorities wish to relieve traffic congestion and reduce traffic emissions through constructing a main road network that can route traffic away from low capacity road arteries found in the city Centre and roads surrounding it. As a part of this project, the Trondheim municipal and the Norwegian Public Roads Administration (NPRA) are currently working on a zoning plan that incorporates a tunnel towards Byåsen in the western Trondheim area. The NPRA estimates the cost of the Byåsen tunnel to be between 0.8 – 1.4 billion NOK depending on design (Statens Vegvesen, 2012).

The tunnel connects with the proposed new Sluppen Bridge, of which the older version has been a cause of congested traffic for decades due to its low capacity. Congestion has been especially prominent during rush hour times, causing travellers to choose a variety of routes to circumvent the traffic jammed bridge.

The tunnel is expected to function as a shortcut for traffic travelling to and from Byåsen, and further relieve traffic on smaller low-capacity road arteries found in the western Trondheim area.

Traffic analyses is performed by expert NPRA personnel for the following scenarios:

- No tunnel constructed (reference scenario)
- Tunnel constructed, with tolling stations present
- Tunnel constructed, no tolling stations present

To explore the environmental impacts of the tunnel, this study will employ LCA methodology to assess yearly GHG-emissions over an analysis time horizon of 20 years, pre and post construction of the tunnel.

The LCA inventory includes NPRA provided traffic data for the above-mentioned scenarios and NPRA handbooks on road and tunnel construction. This permits for, in the opinion of the authors, a more reliable LCA than is common within the literature.

Moreover, standard LCA methodology utilized for assessing GHG-emissions from early-phase projects commonly employ average values for fuel consumption. Other studies, such as (Treloar et al., 2004) include average energy use or fuel consumption assumed valid for an entire region's vehicle stock. A lesser amount of LCA of infrastructure include the actual use of the infrastructural projects assessed, mostly focusing on the environmental impact from constructing and operating a project over a given time.

Improving infrastructure typically leads to an increase in traffic emissions through induced demand or decreasing it by shortening the length travelled. This study will show the importance of including traffic emissions from constructing new infrastructure. Additionally, it will show how LCA methodology can assess the environmental impact of infrastructural projects within Greener Trondheim, when combining early-phase LCA tools with detailed traffic data, regional vehicle stock data, local gradients and vehicle speeds. More precisely, the study aims to address the following questions:

1. Using LCA methodology, what are the net life cycle environmental impacts (expressed in GHG emissions/year) of the Byåsen tunnel?
2. Compared to a reference scenario with no tunnel, how will the Byåsen tunnel affect yearly GHG-emissions from traffic?
3. What effect will removing local road tolling stations have on yearly GHG-emissions from traffic?
4. What are critical factors for minimizing life cycle environmental impacts?

1.3. Greener Trondheim

Greener Trondheim is an intra-municipal infrastructural transport programme proposed and adopted by the Trondheim municipality. It consists of 10 goals, which follow the guidelines for transport politics in the Norwegian government's climate agreement from 2008. A key measure in Greener Trondheim's vision is environmentally friendly growth in traffic, meaning a growth in, among others, the share of cyclists and pedestrians and no growth in passenger car traffic. Of further relevance, in the context of this study, is reducing local air pollution in the city centre, and lowering traffic emissions by routing through-traffic away from the city centre.

Envisioned effects of the measures proposed by the Greener Trondheim programme are reduced greenhouse gas emissions from traffic, less congestion and traffic noise, and an overall increase in cyclists and use of public transportation (Miljøpakken, Unknown year). Moreover, Greener Trondheim targets reducing CO_2 emissions from traffic, having set a target of a 20% cut in CO_2-emissions from traffic in 2008 to 2018 (Trondheim Bystyre, 2008).

Funds are budgeted towards Greener Trondheim by the regional county council, the Trondheim municipal authorities and the Norwegian government through governmental transport plan documents. Greener Trondheim does also divert funds from toll stations along selected routes in the municipality. The Greener Trondheim programme was in the year 2012 estimated to have an overall cost of 7 billion NOK (Trondheim kommune, 2012).

1.4. The process of preparing the research questions

The research questions posed in this study relate to the Byåsen tunnel as a case study, both assessing changes in traffic resulting from constructing it and the life-cycle impacts related to the construction of the tunnel itself. As the Byåsen tunnel is a part of a Greener Trondheim, assessing whether the tunnel can prove mitigation of transport emissions or not is a vital inspiration for the study. The research questions pertaining to net life-cycle greenhouse gas emissions and emissions from changes in traffic are carried over from the project work study. The study has over the course of this year improved in several ways, which lead to their inclusion in order to provide results considered more reliable than its predecessor.

Secondly, in the traffic analyses data received from the NPRA, a trend in increasing traffic volume resulting from removing tolling stations is observed. This lead to the inclusion of scenarios where a tunnel with and without tolling assessed. Traffic volume typically fluctuates with the cost of travel and, among others, the time gained by travel, which can be described by the concept of price elasticity and induced demand. The effect of these concepts could now, however to an unknown degree compared to other projects, be assessed in a case study. Throughout the study's literature review, no article had analysed and quantified the effect of tolling stations Additionally, in the context of this study, it would be important assess whether removing tolling stations could impair progress towards achieving a cut in CO_2-emissions towards 2018 or future emission targets.

Studies like (Strand et al., 2009) emphasize the effect induced demand has on traffic volume, when travel times are reduced through improvements to infrastructure. With this effect in mind, it was in the beginning stages of this study felt that this could be further assessed through a sustainability impact analysis (SIA). This type of analysis is suitable to unravel indirect effects of infrastructure projects, such as an increase in car travel or an overall higher traffic volume.

However, of the main objects of this study is to provide a life cycle assessment of the tunnel alone and changes in traffic arising from it. Within the temporal boundaries of this study such an assessment would be too consuming. The idea of an SIA was abandoned to allow improvements to the study's methodology.

Lastly, the inclusion of the SEMBA module and fuel consumption data from (Joumard et al., 2007) meant that the mitigating effects of increasing average speeds and simulating congestion could be tested. Traditional scenarios, such as a shift in vehicle stock and increasing the share of electric vehicles, is also included. This lead in turn to the comparison of the included scenarios in an effort to identify critical factors for reducing transport emissions, and further discussion of the included scenarios.

1.5. Outline

This study is divided into two parts, part I and part II. Part I is the process report, which considers the workings until the article "Life Cycle Assessment of the Byåsen tunnel in Trondheim, Norway –assessing emissions from traffic and infrastructure." Part I, the process report, is divided into the following sections:

The first section will present the study's thematic background, context, research questions and structure. The study's theoretical framework is presented in the second section, whereas the third section presents methodology utilized in the study. The fourth section presents the case assessed in this case study. In the fifth section, results and findings from the study are provided. The sixth section provides an elaborate discussion of the findings from the study as well as an assessment of the study's strengths and weaknesses. Conclusions from the study are listed in the seventh section, and the eight section delivers recommendations for further work. The sections' structure are based roughly on the work order employed throughout this study.

Part II, the article, is divided into the following sections:

The first section of the article provides case context, background for the study and study research questions. A very brief insight is given into the methodology utilized in the article is provided in the second section. In the third section, the theory section, an overview is given of the current landscape within life cycle assessment of infrastructure and, among others, research within the field of fuel consumption. Results and findings are presented in the fourth section and further discussed in the fifth chapter. Lastly, the sixth section provides conclusions based on findings in the study.

2. Theory

This section considers the study's theoretical framework, which is findings from the literature review, data collection and life cycle assessment, an introduction to traffic analysis methodology and the theoretical background for methodology employed throughout the study. Additionally, an introduction to issues surrounding transport emissions and global warming is provided. The section aims to provide an overview over contextually relevant research within life-cycle assessment, infrastructure and transport research. This section is furthermore more elaborate than the theoretical framework presented in the article. Reasons for not including literature reviewed in the process report into the article are discussed in section 2.5. *Literature reviewed.*

Altogether, the section consists of the following: Transport emissions and global warming, life cycle analysis, EFFEKT, LICCER, literature reviewed, data collection, traffic analysis, The National Transport Plan and the NPRA decision process.

2.1. Transport emissions and global warming

The IPCC identifies CO_2 emissions resulting from human activities, such as transport, to be a key driver of future climate. During their research on climate change, the IPCC has defined a number of scenarios describing possible outcomes of future emissions of greenhouse gases. The scenarios indicate the increase in global average temperature levels due to the release of greenhouse gases. The scenarios range from no actions taken, leading to a projected increase of 2˚ C in year 2050, and approximately 0.5 ˚ in year 2050 with more stringent mitigation actions taken (IPCC, 2014).

The effects of climate change and global warming are typically a higher occurrence of extreme-weather events, affecting both human and natural systems. Rising yearly average temperatures can further lead to, among others, ocean acidification, sea-level rise, heat-stress in larger cities and drought in rural areas. More intense precipitation is also commonly associated with an increase in global average temperature, which can lead to severe floods. Drought, flooding and heat-waves can lead to water shortages, ruined crops and health-damages – which again can lead to effects such food and water shortage for people living in sensitive areas (IPCC, 2014).

As for the transport sector, the IPCC maintains that this sector was in the year of 2010 responsible for approximately 23% of total energy-related CO_2 emissions worldwide. Moreover, a growth in transport emissions, despite more efficient vehicles entering the market and the adaptation of transport policies, has been documented by the IPCC (R. et al., 2014). This suggests that stringent measures for reducing transport emissions are necessary. Failing to do so can lead to a situation where transport emissions outweigh mitigation initiatives undertaken in other energy end-use sectors. The effects of climate change are well known, and organizations, such as the IPCC urges that immediate actions must be taken to reduce emissions that contribute to global warming.

In order to reduce transport emissions, which hold a considerable share of worldwide yearly GHG-emissions, there is need for a methodological framework analyzing and iterating strategies pertaining to emissions from constructing and operating infrastructure. Strategies intended to mitigate traffic emissions can be formed using assessment methodologies such as life cycle assessment.

Moreover, there is a need for a connection between life cycle assessment and traffic analyses, in order to communicate the benefits from projects or programmes. This is especially the case for initiatives or programmes seated in mitigation of transport emissions through improvements of infrastructure. Greener Trondheim, a prime example of where such assessments are in place, can utilize asssessments of project life cycle impacts through workings such as this study. This enables the mitigating effect of each project to be seen in advance, and if faced with several designs. Secondly, this enables the choosing of the best available design or concept suited for mitigation of transport emissions. In this manner, regional programmes as well as larger programmes can all contribute efficiently to the mitigation of transport emissions, as so urgently required by the IPCC.

2.2. Life Cycle Analysis (LCA)

Environmental life cycle analysis aims to assess a product's life cycle impact, typically expressed in CO_2-emissions, through life-cycle stages such as cradle to grave or cradle to factory gate. In ISO1404, which is an international standard for life cycle assessment, an LCA is defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". The ISO does furthermore define the life cycle as "consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal" (ISO, 2011).

Life cycle assessments can however deviate from the ISO standard. Such analyses are typically labeled as non-standard, and in some cases streamlined LCAs, tailored for early-phase decisions on design. The life cycle assessment presented in this study is an example of this, considering solely greenhouse gas emissions from each tunnels life cycle and traffic. Non-standard life cycle assessments are envisioned for use in decision making, by i.e. choosing the tunnel design with the least emissions and further assessing the effect constructing a tunnel has on emissions from traffic in the western Trondheim area.

Conducting a life cycle assessment
Performing an LCA consists of four phases: defining the goal of the analysis, scope, impact assessment and interpretation of the results. The scope of the analysis is a method of determining how the analyst wants to perform the study, which means determining system boundaries and a functional unit. Without a system boundary, an infinite amount of inputs can be attributed to each input that goes into the production of the item assessed. The system boundary limits the amount of periphery inputs and sets the level of detail included in the system. An inventory analysis involves data collection for every life cycle stage.

Impact assessments are performed after data collection is completed, where inputs collected for each life cycle stage are associated with their respective emission factors. Finally, the interpretation of results is an iterative process, guiding potential improvements within the system.

Improving one aspect of the system may feed back onto other stages within the system, and thus affecting every phase included in the LCA (Brattebø et al., 2013b). The figure below illustrates the four stages of life cycle assessment.

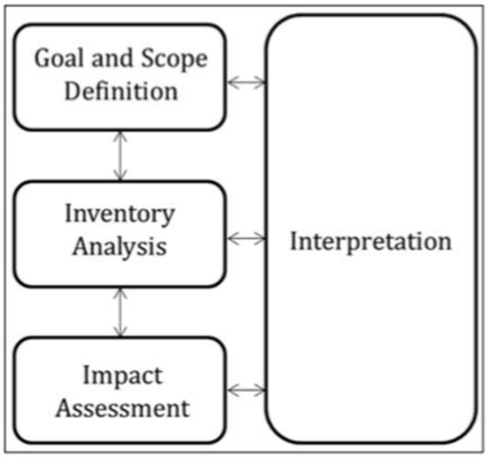

Figure 1: The four stages of life cycle assessment illustrated (Brattebø et al., 2013a).

The goal and scope definition in an LCA study entails setting a functional unit. The functional unit defines the product to be delivered to a user within the system boundary. The system boundary and functional unit must relate to dimensions such as natural, spatial, temporal and technical boundaries. In order to reflect geographical differences in production or technology used for producing steel or electricity, where the product is produced and in which quantity is important factors for referencing or comparison between products. Examples of functional units include 1 m^3 of concrete produced in Trondheim, Norway and 1 kWh of electricity generated by hydropower in Gandak, Nepal.

Life Cycle Impact Assesment

Impact assessment is in its most basic form employing a relationship between the life cycle inventory and stressors associated with producing these items. Stressor data can be found in LCA databases such as ecoinvent, where the environmental science community has developed a relationship between certain stressors and the environment for a number of items. A life cycle impact assessment (LCIA) is typically divided into four steps:

- Classification
- Characterization
- Normalization
- Valuation

Classification is performed by separating each stressors into their rightful class, such as global warming potential or human toxicity, and further employing a characterization factor in order to define the impact resulting from the life cycle inventory.

Normalization and valuation is commonly applied to an LCIA for decision making and comparison of emissions from certain products, or even nations when normalized and expressed as yearly kg CO_2 per capita (Graedel and Allenby, 2015).

2.3. The EFFEKT greenhouse gas emissions module

The EFFEKT greenhouse gas emissions module is an Excel model developed for assessing the greenhouse gas emissions and energy use in the early-phase of infrastructure projects. The model is developed by SINTEF for the Norwegian Public Roads Administration (NPRA). The model is typically employed as a stand-alone module. The EFFEKT model in its entirety is typically employed by the NPRA to perform cost/benefit assessments and to compare the environmental performance of projects faced with several designs or concepts. The NPRA has issued a handbook on the use of the model, handbook V712 ""Brukerveiledning – EFFEKT 6" (Vegdirektoratet, 2008).

The EFFEKT greenhouse gas emissions module includes the following phases:

- Construction
- Use and maintenance
- Transport

Road elements included in the module are roads in the open, tunnel (onshore and under water), bridge (concrete and steel) and transport by ferry.

The module's database includes the most common building materials employed in infrastructure projects. Among these are concrete, rebar and diesel used for transportation on the site. Empirical data from built NPRA projects make up the majority of material consumption parameters included in the model (Straume, 2011). The parameters are typically expressed as X amount of steel/m or Y amount of cubic meters diesel per transported loose matter.

When using the model, the analyst plots his chosen analysis period, annual average daily traffic (AADT), percentage of traffic increase per year, service life of the infrastructural elements analyzed and the length of each element. The analyst must also choose the county the infrastructural element is constructed in, as the model corrects for differences in material consumption in colder climates. Using the plotted input data, the model will calculate yearly greenhouse gas emissions. Transport emissions are in the model calculated by plotting AADT and element length, where the model calculates the emissions employing average fuel consumption and fuel specific emission coefficients.

2.4. LICCER

The LICCER model is an LCA Excel model that assesses the environmental impact of infrastructure projects in an early stage of planning. The model aims to inform decisions, using LCA methodology in early phase planning when faced with several design alternatives. The model contains regional material consumption data for Norway, Sweden, Denmark, the Netherlands and Europe. The majority of Norwegian material consumption data is collected from the EFFEKT model (Brattebø et al., 2013b).

The LICCER model provides a quantitative analysis of life cycle impacts within the system. The model calculates the greenhouse gas (GHG) emissions in CO2-equivalents per year as well as the energy consumption, expressed as GJ/year.

The model supports infrastructural elements such as single and double-shafted tunnels, steel and concrete bridges, new road and expansions of existing road. This enables the comparison of proposed alternatives or concepts in an early stage with relative ease, as the model in its most basic form only requires element length and appropriate parameters for i.e. driving lane layer thickness. The analyst can choose to enter project specific variables pertaining to among others material consumption, tunnel cross-section area and regional vehicle mix. The LICCER model's structure is illustrated in the figure below.

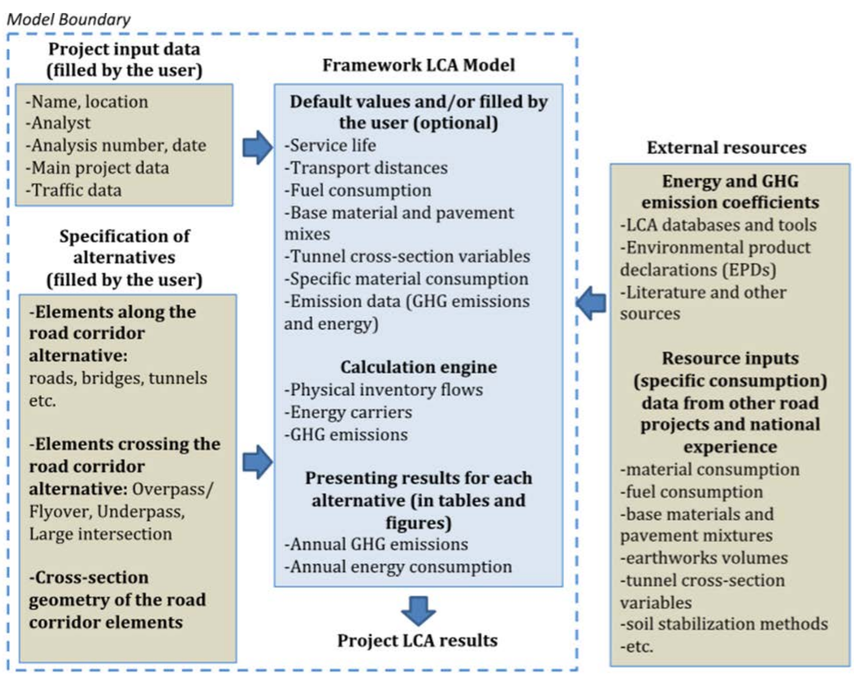

Figure 2: The LICCER model's framework (Brattebø et al., 2013a).

The model includes emissions from traffic, as an option for plotting AADT in the start year of the analysis time horizon is available. The analyst can also choose to set an average yearly growth in traffic.

AADT is both employed for calculating a pavement layer replacement frequency and emissions from traffic. A regional vehicle stock mix can also be set by the analyst, where the following vehicle types are included in the model:

- Trucks with trailer
- Trucks without trailer
- Electric vehicles
- Diesel passenger car
- Petrol passenger car

Fuel consumption for the above-mentioned vehicle types are by default determined by national averages (Brattebø et al., 2013a).

Finally, the LICCER model is in this study employed to calculate the life-cycle impact of each tunnel design as specified by the NPRA. The LICCER model is, however, not utilized for calculating traffic emissions. The model is, as of now, not fit to calculate emissions from traffic where a project can influence traffic volume on a variety of routes.

2.5. Literature review

This section presents an overview on how this study's literature review is conducted; the literature reviewed for use in the article and further provide an expanded view on contextually relevant sources not included in the article.

This study utilizes data collected from literary sources and databases. The literary sources and databases are used define the amount of materials utilized by each tunnel's life cycle stage and further to assign an emission factor to material inputs included in study life cycle inventories. Furthermore, the databases employed, such as the SINTEF Emission Module Based on ARTEMIS (SEMBA) and the LICCER model, are both in part constructed from literary sources and empirical research. The literature review is a mainstay of research, employed to provide a context for study research questions and to support and provide a framework for the arguments or assumptions that the study may be based on.

The overall goal of this study's literature review is:

- To gain an overview of LCA studies on tunnels and infrastructure
- Providing LCA inventory data
- Identifying methodology for calculating fuel consumption
- Identifying literary sources that can support scenario creation

Literature presented in this study is gathered from search engines such as *Google*, *Google Scholar, DiVA and BIBSYS Ask*. DiVA and BIBSYS Ask are search engines provided by the Norwegian University of Science and Technology's (NTNU) university library.

The literature review as presented below includes a number of sources not included in the article. The sources presented in the article has been chosen on the following basis:

- Geographical relevance: Are the LCA studies on tunnels and infrastructure comparable to Norwegian tunnel standards? Studies describing the mitigating effects of infrastructure in a Norwegian context are given priority.
- Source type and place of publication: Priority given to sources published in journals and to other third party quality controlled publications.
- Time of publication: Newer articles are prioritized.
- Level of detail. LCAs including traffic emissions are included for comparison.

It should further be noted that, during the course of the study, there has been a shift from researching LCA case studies on infrastructure and tunnels towards assessing emissions from transport. This is due to preliminary results gained in the early stages of the study, showing the overwhelming effect traffic emissions have on each tunnel alternative's yearly life-cycle impact. Additionally, there is seemingly no best-practice present when conducting LCA studies on tunnels. There exists a variation of analysis time horizons, tunnel service life times, as well as functional units utilized in each study research. This makes comparison between studies challenging.

This process report, however, presents a more comprehensive overview of the landscape within assessments of infrastructure and tunnels. The process report has no particular limitations within the amount of pages and total amount of words. Additional sources with geographical correlation to Scandinavian conditions is thus included. Moreover, the research within state of the art LCAs of infrastructure and tunnels have been important in order to uncover under-developed qualities within the field, such as assessments of transport emissions pre and post construction of infrastructural projects. Research within the field does also uncover mitigation possibilities within life-cycle phases that contribute to the majority of life-cycle infrastructure emissions.

2.5.1. LCA of infrastructure

(Hammervold, 2014) surveys a number of infrastructure case studies using LCA methodology in "Towards a greener infrastructure". She maintains that energy intensive materials such as concrete, rebar, steel asphalt are inducing the most impact, noted in GHG emissions. Secondly, Hammervold emphasizes the need for decisions on the reduction of environmental impacts in the early-phase of projects. Decisions that can reduce project environmental impacts are, among others, maintained to be the choice of materials. This is furthermore in accordance with project management literature and the impact and cost of early-phase decisions (Samset, 2008).

She does also maintain, through an elaborate literature review, that many of the functional units employed in the studies reviewed does not reflect the actual function of the road. The functional unit does not include for example average annual daily traffic (AADT) on a stretch of road or any other infrastructural element going from point A to B.

This is furthermore very much the case for the literature reviewed in this study. The majority of sources reviewed are lacking emissions from traffic completely, or include traffic emissions in a rather crude detail. Examples include the study by (Treloar et al., 2004).

(Treloar et al., 2004) proposes in "Hybrid Life-Cycle Inventory for Road Construction and Use" a hybrid LCA method that utilizes input-output data in order to fill gaps in inventory commonly left in LCA inventories. Their case study includes eight road types with a length of 5 KMs in a rural environment, as well as vehicle manufacturing, operation and maintenance. The study includes all life-cycle stages but end-of-life, and finds the emissions from road construction initially substantial, but eventually overshadowed by the use and maintenance of vehicles. Their traffic in operation inventory includes an assumed average vehicle energy use per km (GJ/100 km) and a vehicle park ratio of 90% PC and 10% HDV.

The traffic emissions life cycle inventory is, moreover, crude in detail, as it contains assumptions based on estimates by the authors as well as some literary sources on heavy duty vehicle fuel consumption dating from the late 1970s. The life-cycle inventories pertaining to road construction materials is however more detailed. Considering that the emissions and energy use are in the majority, this does although suggest that studies assessing emissions from traffic, using more up to date and reliable data, in combination with emissions from infrastructure are in order.

2.5.2. LCA of tunnels

(Huang et al., 2013) analyses the life cycle impacts of a standard Norwegian road tunnel in "Life Cycle Assessment of Norwegian Standard Road Tunnel," where they discover that the standard Norwegian tunnel is a 3 km long, 9.5 m wide rock excavated tunnel. The construction phase is maintained to be the largest contributor. The construction phase does however include the production of materials, which is the most dominant contributor to their included ReCiPe impact categories (Goedkoop et al., 2013). The authors further maintain that, over a service lifetime of 100 years, the tunnel has an impact of 13 ton CO_2-eq per m of tunnel.

(Hammervold, 2014) states in her previously mentioned doctoral thesis that the average life-cycle impact of Norwegian tunnel, expressed in CO_2-eqs per m, is 337 kg. This with an assumed tunnel lifetime of 100 years and an analysis time horizon (ATH) of 40 years. She further discovers that a tunnel with a similar design to (Huang et al., 2013)'s studied tunnel has an impact of 570 kg CO_2-eq per m.

The results beween the two authors are however not very dissimilar, with Hammervold's tunnel, assuming a 9.5 m wide, 2.4 km long tunnel with a 40 year ATH, having a net impact of 13 680 ton CO_2-eqs. If using the average impact values by (Huang et al., 2013), the net impact is calculated to be 12 480 ton CO_2-eq. The difference between the two studies is 1200 ton CO_2-eq, which can, among others, be attributed to geographical variations in material consumption or different emission factors.

(Miliutenko et al., 2012) presents an LCA case study on the Swedish tunnel Norra Länken in "Energy Use and Greenhouse Gas Emissions during the Life Cycle of a Road Tunnel – the Swedish Case Norra Länken." The Norra Länken tunnel consists of two shafts, where the total length of the shafts is 11 kilometers.

The analysis time horizon and the service lifetime of the tunnel is assumed to be 100 years. The study's system boundary includes construction, operation, and maintenance. The end-of-life phase is omitted from the study. The total CO_2-eq emissions, including operation and maintenance, amounts to 430 893 ton CO2-eq, which is estimated to be 24 186 ton CO2-eq per lane km. The total cumulated energy demand is found to be 29 372 TJ-equivalents. The emissions per lane km, compared to (Huang et al., 2013) and (Hammervold, 2014), translates to a net impact of 23 218 ton CO_2-eqs, assuming the same analysis time horizon and tunnel length as above.

The study's life cycle inventory included data from the tender's Bill of Quantities and expert assumptions by the Swedish Transport Administration. The CO_2-eqs of the type of electricity delivered to the tunnel in operation was 91.3 kg CO2-eq/mWh. Life-cycle emissions from the tunnel in operation are, in part, because of this greater than what (Huang et al., 2013) and (Hammervold, 2014) have found. Emissions from traffic or changes in traffic are not included in the study. However, Miliutenko does maintain that the emissions from the tunnel's construction phase, amounting to 155 000 ton CO_2-eqs, are approximately 6% of the Stockholm county's traffic emissions.

2.5.3. The ARTEMIS project

The ARTEMIS project is a European research project aimed at providing a harmonized methodology that can estimate pollutants from transport emissions at a national and international level. Forty research laboratories have been involved in designing applications of the project, such as emission inventories, which this study utilizes. Laboratory testing of a variety of vehicles enabled the compilation of emission inventories covering, among others, CO_2, PM10 and NO_x. Moreover, the testing of heavy duty vehicles resulted in 102 engine maps for vehicle vintages ranging from Euro 0 to Euro 3 engine technologies. This enabled the compilation of averaged emissions up to Euro 5 engine technology (André et al., 2009). From the test cycles of heavy duty vehicles, the model PHEM (passenger car and heavy-duty vehicle emission model) has been developed.

Furthermore, the research project has enabled a compilation of a light vehicle emission inventory. The inventory is compiled from about 3500 test runs on more than 150 light vehicles. This enabled the construction of several fuel consumption or emission models, such as a discrete model that accounts for traffic situations (dense, free-flowing etc.) and continuous models using driving behaviour through average speed, which this study utilizes (Joumard et al., 2007).

2.5.4. Light vehicle emission modelling within ARTEMIS

(Joumard et al., 2007) have compiled the ARTEMIS report "Emission factor modelling and database for light vehicles - Artemis deliverable 3," which describes the testing and validation routines performed in order to arrive at a set of emission and fuel consumption models. Of interest to this study is their traffic situations hot emissions model and the average speed hot emissions model.

The traffic situations model
The traffic situations model is a micro-scale model, used at a low spatial scale, i.e. a specific street. Traffic models, such as Aimsun, that can simulate micro-scale driving behavior (driving patterns) is compatible with the ARTEMIS traffic situations model. When employing the traffic situations model, the analyst defines a traffic situation pertaining to the street of interest, and the analyst decides if the street or road is in an urban or rural environment. The analyst can choose between four traffic situations: free-flow, heavy traffic, saturated and stop & go, where emissions are increasing from free-flow to stop & go. The model thus accounts for pollutant emissions' sensitivity to driving conditions and the kinematics of stop & go driving patterns.

The average speed emissions model(s)
The average speed emissions model calculates average hot emissions for average speeds ranging from 5 km/h to 135 km/h. Two average speed models are presented in their report, where this study utilizes the second model, which uses reference test pattern (RTP) data where emission data from their database is averaged against test patterns as compiled for their traffic situations model (Joumard et al., 2007). The model utilizes an emission function calculated by regression between reference test pattern emission factors, which are expressed by average speed. The emission factors calculated by the polynomial emission factors cover among others CO_2, hydrocarbons, NO_x for pre-Euro up to Euro 4 petrol and diesel vehicles. Reduction factors for future vehicles are also suggested in the report. The average speed model calculates CO_2/km directly using a carbon balance equation.

2.5.5. Heavy duty vehicle modelling within ARTEMIS

Heavy duty vehicle emission factors and fuel consumption is within the ARTEMIS project estimated by the PHEM model, which uses driving cycles to calculate the amount of energy required to move the vehicle, including transmission losses. A gearshift model calculates engine speed, and emissions are interpolated from a steady state emissions map given the vehicles calculated power and engine speed.

ARTEMIS has also provided a set of average speed functions that describe emissions or fuel consumption as a function of average speed, vehicle type, gradient and loading. The average speed functions are documented in (Boulter and Barlow, 2005). HDV are in addition separated into two categories: rigid and truck-trailer (Levin, 2012). The two categories can be seen in *figure 3*.

Figure 3: Articulated truck (to the left) and rigid truck (to the right) (Levin, 2012).

2.5.6. SEMBA

SEMBA is an open-source python module database containing an inventory of per km fuel consumption and emissions from heavy duty vehicles, passenger cars, light duty vehicles, rail and transport by sea. Hot emissions and fuel consumption data is built upon ARTEMIS parameters and functions pertaining to each vehicle category. The modules within SEMBA uses the ARTEMIS parameters and functions to calculate vehicle fuel consumption and emissions. SEMBA has been created as a part of Thomas Levin's (2012) doctoral thesis "Developing a New Emission Model for Freight Transport." In use, in order to calculate, for example, heavy duty vehicle fuel consumption; the user plots a vehicle ID, which pertains to vehicle category, euro class and weight, speed, gradient, load and emission component or fuel consumption.

In this study, SEMBA is used to calculate heavy duty vehicle fuel consumption as well as adopting coefficients for calculating passenger car fuel consumption, using the ARTEMIS average speed model's polynomial functions. (Levin, 2012) did further document that using the HDV average speed functions as built-in in SEMBA should yield plausible emission and energy consumption results for vehicles operating in Norwegian driving conditions. It has further been assumed for this study that this is also valid for passenger cars. In addition to being employed in Levin's doctoral thesis (2012), SEMBA has been utilized in the SINTEF research project "Green Freight Transport" (Norvik et al., 2011).

2.5.7. GHG mitigation effects of improving infrastructure

The report "Miljømessige konsekvenser av bedre veger" by (Knudsen and Bang, 2007) states that a GHG mitigating effect is expected from constructing new roads and otherwise improving infrastructure. Their report employed the traffic microsimulations model Aimsun, which includes data from the ARTEMIS project, on a number of prototypical road sections, containing a reference and an "improved" alternative. The reduction in GHG emissions is mainly attributed to a reduction in congestion and steadily flowing traffic. The report does however state that increasing the capacity of the road sections can lead to growth in car traffic.

A decrease in, among others, the share of cyclists, pedestrians and public transportation is also expected, although the report does not state the magnitude of these effects. The authors maintain that an increase in car traffic is most likely to occur in urban areas where congested traffic is most common, due to a larger reduction in travel time.

Another Norwegian report, "Gir bedre veger mindre klimagassutslipp?" by (Strand et al., 2009) in part contradicts Knudsen and Bang's (2007) report. (Strand et al., 2009) maintain that the growth in traffic volume and change in mode of traffic will outweigh the mitigating effect of steadier flowing traffic. The researches does also state that the mitigating effect of improving stretches of road are marginal, as the speed limit heighten to 80 km/h with an improvement in road standard. This is in an interval above optimal speed in terms of fuel consumption (Joumard et al., 2007). The two reports fueled a public debate at the time of publication, where one of the authors in (Knudsen and Bang, 2007) redacted Strand et al.'s findings. Bang stated that not using microsimulations on their prototypical routes will lead to underestimation of GHG-emissions, and that the effects of improving roads is more profound in urban areas where average speeds are lower (Tunmo, 2010).

(Bart and Boriboonsomsin, 2008) examined the short-term impacts from reducing congested traffic in their journal article "Real-world carbon dioxide impacts of traffic congestion," where the authors maintain that traffic emissions (resulting from congestion) can be reduced by three different strategies. Among the strategies are ramp metering, speed management techniques and variable speed limits. The report does, however, state that this effect is specific to local fleet mix and time spent in congested traffic. The researchers do also highlight a misalignment between steady state vs. real world activity (decelerations and accelerations included), where they maintain that CO_2-emissions/km were higher when considering real-world activity. Bart and Boriboonsomsin's discussion of real world activity vs. steady state did further prompt the inclusion of actual measured average speeds for routes in Trondheim where available, and further making these routes suitable for scenario analysis in this study.

(Wood et al., 1994) discusses the generation of traffic because of new or improved roads in "Trunk roads and generation of traffic." The authors discuss this phenomenon, referred to as induced traffic, where reductions in travel time due to improvements in infrastructure causes a higher traffic volume than expected. The authors associate induced traffic with a gradual build-up in traffic volume over time and changes in land-use development. The magnitude of induced traffic is however expected to vary, and can be difficult to quantify through traffic analyses.

It is further maintained in their report that the generation of induced traffic matters the most where certain routes are plagued by severe congestion. Improving the routes with the most congestion can lead to a higher surge in travelers, the authors maintain. It is further suggested that caution must prevail when planning improvements of roads to and in urban areas and strategic capacity-enhancing interurban programmes. The authors maintain that the economic values associated with a project can be over-estimated if induced traffic occurs to a higher degree.

The report resonates well with modern findings by (Strand et al., 2009) and (Knudsen and Bang, 2007), where improvements to infrastructure in urban areas is expected to provide modest to little mitigation due to increases in traffic volume.

(Wood et al., 1994) recommends that scheme appraisal must be undertaken within the context of environmental and economical appraisals at a strategic, area-wide level, which takes account for induced traffic through variable demand methods within traffic analysis.

(Klunder et al., 2013) presents an introduction to macro emission models and macroscopic traffic models in "Integrating a Macro Emission Model with a Macroscopic Traffic Model." The authors maintain that two types of emission models exist: microscopic and macroscopic emission models. Microscopic emission models are intended for use when assessing detailed vehicle behavior, such as acceleration, deceleration and driving patterns in certain situations. Macroscopic emission models typically employ averaged emission factors and macro (aggregated) traffic data. The authors do further list a number of interesting applications of macroscopic emission models, such as assessments helping legislation of air quality and CO_2 emission reductions. Moreover, in their study, the authors did further employ parameters such as average speeds and aggregated traffic data in order to construct an emissions model apt for traffic emissions in the Netherlands and the rest of Europe.

Lastly, the literature reviewed in this section reveals the many aspects of improving or constructing new infrastructure. Improving infrastructure in urban areas are maintained to have slightly unpredictable effects. This does, however, strengthen the assumption that there is a need for assessments combining direct effects resulting from constructing infrastructure with indirect effects stemming from such projects. Macro traffic emissions are further in order to reliably assess the direct effects of traffic volume control strategies such as road tolling and speed management techniques.

2.6. Data collection

Each tunnel alternative's life cycle inventory is compiled in the LICCER model during previous project work. The life cycle inventories pertaining to each tunnel alternative includes parameters from NPRA handbooks on road and tunnel construction (Vegdirektoratet, 2014b, Vegdirektoratet, 2014a, Vegdirektoratet, 2014d, Vegdirektoratet, 2014c). Each alternative's tunnel length is compiled from unpublished project documents received from the NPRA (Spilsberg and Harbo, 2011). The dimensioning of parameters such as lane width and the replacement of pavement wear-layer frequency are dimensioned in coherence with NPRA guidelines and project specific traffic analyses.

The CO_2 emissions associated with the operation and maintenance of the reference alternative's "synthetic route" are calculated in Excel, using LICCER emission factors. The life cycle emission inventory for operation and maintenance is compiled from NPRA handbooks and personal communication with expert NPRA personnel (Vegdirektoratet, 2014d, Vegdirektoratet, 2014a, Vegdirektoratet, 2014c). Transport distances to asphalt plants etc. is estimated by Google Maps.

Parameters applied to the traffic emissions inventory, such as route length, gradient and route average speed, are compiled from Google Maps, personal communication with expert NPRA personnel and the NPRA’s online GIS service “Vegkart” (Statens Vegvesen, 2015b).

Route specific traffic volume, expressed in annual average daily traffic (AADT), is gathered from NPRA traffic analysis documents. Traffic volume pertaining to this project is classified as sensitive by the NPRA, and will not be foreshown in this study.

Fuel consumption matrices pertaining to each included route are compiled in Excel. Heavy duty vehicle fuel consumption is extracted directly from SEMBA. Passenger car fuel consumption is calculated and compiled using parameters from the ARTEMIS project. Reduction factors for future engines’ fuel consumption is also from the ARTEMIS project. Emission factors for passenger car, heavy duty vehicle and electric vehicle emissions are collected from the LICCER model.

Regional data on passenger car and heavy vehicle stock is gathered from Statistics Norway and personal communication with Opplysningsrådet for Veitrafikken AS, which is an organization collecting regional and national statistics on vehicles (Statistisk Sentralbyrå 2014, Statistisk Sentralbyrå, 2014, Opplysningsrådet for Veitrafikken AS, 2015).

2.7. Traffic analysis

Traffic analysis is a method of predicting traffic, for example, between two parts of a city, using mathematical calculations based on a model of prognosis. Traffic analysis is, like all models, a simplification of reality. The model of prognosis is fed with a number of variables, such as demographic or socio-economic variables, area use, settlement structure and area road standard. A change in either of the variables can affect traffic volume on certain parts of a stretch of road or route, when undergoing assessment. The input variables for the regional Norwegian model are gathered from travel behavior research. The regional model is otherwise updated with data on areal use from municipal and county wide data on i.e. area use (Saga, 2013).

Traffic analysis and the use of scenarios is typically employed to answer questions related to changes in traffic. Changes in traffic can result from establishing new areas for settlement and the implementation of toll stations or otherwise increasing the cost of travel. Moreover, by using traffic analysis models, the analysts can estimate reductions in travel time or the increase in traffic from removing certain barriers, such as tolling stations. The overall purpose of traffic analysis is typically to provide a decision basis for decision makers, and further for cost/benefit analysis of improving infrastructure. Traffic analysis can, in addition, be employed to estimate earnings from tolling stations (Tørset et al., 2013).

Typical traffic analysis tools for modelling traffic can, for example, be the CUBE regional model for passenger traffic provided by Citilabs (CITILABS, 2014). Another popular model, employed by among others (Knudsen and Bang, 2007) is Aimsun.

Models used for traffic analysis are typically divided into regional models, referred to as DOM (subline territory models). Furthermore, the transport models are typically divided into three types of levels, namely macro, meso and micro. Macro-models, as utilized for predicting the traffic volume in this report, analyses and predicts the volume of demand and travel patterns taken given certain changes within the transport system they operate. Macro-models are typically used to analyze measures, such as improving infrastructure, at the regional level (ARRB Group Ltd, 2009).

2.8. The National Transport Plan and the NPRA decision process

The Byåsen tunnel is a costly project, exceeding 750 million NOK, which makes the project subject to stringent NPRA and governmental guidelines. For relevant context, this section provides a brief thematic overview of the Norwegian National Transport Plan and the NPRA decision process involved in larger infrastructure projects.

2.8.1. The National Transport Plan

The Norwegian National Transport plan is a strategic document outlining how the Norwegian Government intends to develop its infrastructure for transportation purposes. The timeframe for the most recent and current transport plan is 10 years, effective from 2014 to 2023. The National Transport Plan is revised every four years.

The aim of the National Transport plan is to plan effective use of resources, to strengthen the interaction between various modes of transport and to provide a super ordinate and technical basis on which to make decisions (The Norwegian Ministry of Transport and Communication, 2013).

The NPRA and other governmental transport agencies propose a joint proposition to the Norwegian government on the premise of an economical frame set by the Norwegian Ministry of Transport and Communications. This forms the basis for a plan of actions for the NPRA, where goals, strategies and an implementation plan is presented. This plan allocates the yearly budgets for each infrastructure project initiated by the NPRA. This further means that projects such as the Byåsen tunnel, can be postponed or cancelled during transport plan revisions, if the project is found unsustainable (Statens Vegvesen, 2013).

2.8.2. The NPRA Decision process

Every large infrastructure project exceeding a cost of 750 million NOK is subject to assessment, typically in the form of a cost-benefit analysis of a variety of proposed concepts. The benefits of a given project, such as reductions in travel time, are weighed against the costs of the project, as well as the environmental impact of the project in some assessments.

The NPRA is responsible for making a document that assesses each concept within a programme or project. The document addresses strategic and tactical goals set in the National Transport Plan. Greener Trondheim and the Byåsen tunnel are both included in documents that have undergone assessments by third-party institutions in the Norwegian quality control process.

The NPRA document assessing each concept is quality controlled in Quality Assurance 1 (QA1) by an external agent. This functions as a professional control of findings, such as the cost or benefit of each concept, within the preliminary project documents. After the first round of quality assurance, the Norwegian Government will then in turn make a decision on whether to give permission to proceed or scrap the project. Findings from a concept investigation report compiled by the third-party auditors, the quality assurance document and other hearing documents make up the basis for this decision.

If the decision to go ahead with the project is made, the project is typically incorporated in municipality zoning plans. This does also mark the beginnings of round two of the quality control process, Quality Assurance 2 (QA2). QA2 is the last step before construction can proceed. The aim of the whole process is to assess a variety of measures, known as concepts or design, and to choose the concept or design that can best solve the needs of the municipal or region (Statens Vegvesen, 2014).

3. Methodology

This section outlines the methodology employed throughout the study. The section consists of the following: LCA methodology and the traffic emissions model, aptly separated in their respective sub-sections.

3.1. LCA Methodology

This study is a life cycle analysis aimed at evaluating the environmental performance of a project in its early phase. It considers greenhouse gas (GHG) emissions expressed CO_2-equivalents/year resulting from the production of materials required for excavating each tunnel design, the construction phase and the operation and maintenance (O&M) phase.

The LICCER LCA model is utilized to calculate GHG-emissions from each life cycle phase. Tunnel design parameters are gathered and plotted based on findings in the NPRA's handbooks on Norwegian tunnel and road design (Vegdirektoratet, 2014b, Vegdirektoratet, 2014a, Vegdirektoratet, 2014c). Traffic emissions are calculated based on vehicle fuel consumption and the associated CO_2-emissions from the production of fuel and the combustion of hydrocarbons as included in the LICCER LCA tool's database (Brattebø et al., 2013a). Traffic emissions are calculated in a separate Matlab model.

Regional traffic data is supplied by the NPRA. A select amount of routes in Byåsen and western Trondheim, traveling to the Byåsen area are assumed affected by the construction of the tunnel. These routes have been included in order to calculate traffic volume in a 0-alternative and after the tunnel's construction.

In this study, a tunnel service lifetime of 100 years is assumed, based on findings in literature (Miliutenko et al., 2012, Huang et al., 2013, Hammervold, 2014) and personal communication with LCA expert analysts. By request from the NPRA, the analysis time horizon (ATH) is set to 20 years. This also includes the 0-alternative.

The system boundary for each tunnel design is tunnel length and a roundabout at the outlet. For the roundabout at the outlet, a life cycle inventory is compiled in a dedicated Excel model. The assessed roundabout is designed by the signatory, using NPRA handbooks on road and roundabout design (Vegdirektoratet, 2014d). Roundabout life-cycle emissions are calculated using LICCER emission factors.

Life cycle emissions from the operation and maintenance of a synthetic route designed for the 0-alternative are calculated in Excel. As there currently exists no tunnel in the area where the Byåsen tunnel is projected, a synthetic route length is calculated for comparison between the existing alternatives, and in case the tunnel is not built. The synthetic route's length dictates the amount of inputs required for operation and maintenance over the analysis time horizon.

The calculated synthetic route length is based on an allocation of the vkm travelled in the tunnel, relative to total vkm travelled in the 0-alternative. The length of the synthetic route included in this study is 1 km. Operation and maintenance life-cycle impacts are allocated to the project within the analysis time horizon for all alternatives included in the study.

Life cycle phases included in this study are:

- Production
- Construction
- Operation and maintenance

Whereof, the production phase is defined as the extraction and processing of raw materials needed to produce road and tunnel construction materials. The construction phase includes on-site operations, such as internal transportation of earthworks. The operation and maintenance phase includes, among others, the replacement of components and energy used for lighting within the 20-year analysis time horizon. The end-of-life phase is omitted from this study.

This phase is typically omitted from assessments considering elements with a long service lifetime (Hammervold, 2014, Miliutenko et al., 2012) as large infrastructural elements like tunnels are rarely demolished.

3.1.1. Goal and scope of the analysis

The purpose of the study is to evaluate the environmental impacts of excavating and operating a tunnel using an early phase LCA model (LICCER) and the following changes in traffic volume after its construction. The study further aims to evaluate the influence of tunnel design, shifting traffic from included routes in the study through a tunnel and the effect of tolled vs. non-tolled roads measured in GHG-emissions.

The functional unit is defined as "a road system with a simulated AADT that offers traffic between Sluppen and Byåsen over a time horizon of 20 years."

3.2. The traffic emissions model

The traffic emissions model employed in this study is a considerable improvement over the foregoing project work's study when it comes to calculating traffic emissions. This study's traffic emissions model inventory contains statistical data on regional vehicle stock and route specific fuel consumption data, as well as traffic volume data stemming from recent NPRA traffic assessments.

The traffic emissions model employed in this study is considered a macro emissions model, assessing traffic emissions on a regional level (Klunder et al., 2013). This means, however, that driving patterns, including sudden accelerations and decelerations are not accounted for in this study. This is typically something that is studied by employing a micro-scale emissions model. Furthermore, the scope of this study allows the emission model to calculate emissions based on route average incline an average speed. This can underestimate the calculated traffic emissions somewhat, given that real-world fuel consumption is typically higher than in models assuming steady-state fuel consumption. (Levin, 2012) solved this methodological problem elegantly in his doctoral thesis, by combining the SEMBA Python module with designated routes plotted in a GIS program. This allows the GIS program to calculate fuel consumption values continually using typography and local speed limits as deciding parameters. Constructing a GIS model is however somewhat out of scope within the temporal boundaries of this study, although relevant for further studies.

The strength of the model, however, is its inclusion of regional vehicle stock data and depth of detail, found lacking in other assessments of infrastructure. This makes the traffic emissions model relatively reliable, if appropriately adjusted to local parameters and vehicle stock.

The inclusion of statistical data does in addition allow for scenarios that explore the phasing of older vehicles and the introduction of vehicles with enhanced engine technologies.

The SEMBA and Artemis models, both employed in this study, contain an inventory of emission factors of pollutants such as NO_x, PM10 and hydrocarbons (HC). Within the scope of this study however, emphasis is placed on yearly CO_2-eq emissions from traffic. Yearly CO_2-eq emissions from traffic are arguably somewhat more relatable than yearly emissions of hydrocarbons. CO_2-emissions from traffic are furthermore usable for the evaluation of the project up against goals set in the Greener Trondheim programme.

The traffic emissions model contains the following parameters.

Table 1: Parameters applied to each route used for constructing a traffic emissions and inventory and subsequently calculating traffic emissions.

Route #	Length (km)	Curvature (% incline)	Avg. Speed (km/h)	Share of HDV (% of AADT)
1	7,40	0,25	58,46	10
2	6,50	1,44	45	9
3	5,20	1,91	45	9
4	5,50	1,91	45,00	7
5	6,60	1,69	50,00	7
6	5,20	0,02	50,00	10
7	7,30	0	40,00	11
Tunnel alt. 1	2,51	5,00	60,00	7
Tunnel alt. 2	2,30	5,00	60,00	7
Tunnel alt. 3	2,85	5,00	60,00	7

The average speeds of each route is assumed to be an average of each route's speed limits, where data on actual average speeds has not been available. Actual measured average speeds has been supplied by the NPRA for three of seven routes included in the 0-alternative (Statens Vegvesen, 2015a).

A number of routes, (routes 1-7 in *table 1*) in the western Trondheim area are found to be utilized by travellers in order to circumvent traffic jam and slow moving traffic in the Sluppen area. These routes are included in the study in order to assess changes in traffic resulting from the excavation and operation of the Byåsen tunnel. Each route included in the study is referenced against an unpublished project specific NPRA document, documenting assumptions and data utilized for their traffic assessment of the Byåsen tunnel and the area surrounding it. The routes included are assumed to be the most affected by the tunnel, as per the NPRA document. Traffic volume is a vital parameter not shown in the table above. Traffic volume is included, but traffic volume is in this project considered sensitive data, and will not be foreshown.

Each route included in the study consists of several links, where each link has a dedicated amount of traffic travelling upon it. The amount of links on one route or stretch of road can be several thousands in number, which is useful when conducting microsimulations of traffic.

The traffic analysis, as provided to the signatory, contains macroscopic level resolution that shows the average AADT of each link separated onto longer links.

The weighted average AADT of each of the longer links is for this study calculated and assigned to each route. This enables the calculation of route specific traffic volume, where the route average AADT is multiplied with route length. It has been assumed that this is a valid approach as per (Klunder et al., 2013) and personal communication with expert NPRA traffic analysts.

The model further contains the following vehicle specific parameters:

- Age (euro class)
- Engine volume (litres)
- Fuel type (petrol or diesel)
- Vehicle weight (total weight)
- Load (0-100%)

The share of electric vehicles (EV) in the regional vehicle stock is 2.38% and the split between fossil fueled vehicles is 46% diesel and 54% petrol for all routes (Opplysningsrådet for Veitrafikken AS, 2015). 3.5% biofuel is assumed to be mixed in both fuels (Statens Vegvesen, Unknown year).

3.2.1. Constructing the regional vehicle stock and setting emission factors

The traffic emissions model consists of several Matlab and Python scripts and Excel documents. Two Matlab scripts calculate traffic emissions from heavy duty vehicles and passenger vehicles. Seven scripts are constructed for scenario analysis. Fuel consumption matrices for passenger cars and heavy duty vehicles are compiled in two different Excel files, and imported into Matlab for calculation purposes. The regional car stock of heavy duty and passenger vehicles are represented by coefficient matrices compiled from recent regional statistics. Fuel consumption matrices corresponding to each individual route are combined with coefficient matrices pertaining to passenger car and heavy duty vehicles for the calculation of traffic emissions.

Each route assessed in this study has a both a dedicated fuel consumption matrix and a vkm (traffic volume) matrix. A total of 42 fuel consumption matrices has been compiled throughout the study. Each fuel consumption matrix is calculated by employing functions embedded in the Artemis RTP average speed model.

The Artemis RTP average speed model employs emission functions calculated by regression between reference test pattern emission factors, which are expressed by average speed. The emission factors calculated by the polynomial emission factors cover among others CO_2, HC, NO_x for pre-Euro up to Euro 4 petrol and diesel vehicles.

Their general formulae for calculation of emission factors for a second order polynomial function is:

$$\text{Emission factor}\left[\text{g / km}\right] = \text{a}0 + \text{a}1\text{V} + \text{aV}^2 \tag{1}$$

Where V = average speed and a_0, a_1 are coefficients (Joumard et al., 2007 p. 179). This formula is adopted for calculating passenger car hot emissions in this study.

The RPT average speed model calculates g CO_2/km directly using a carbon balance equation, making it necessary to convert from CO_2/km to l fuel/km for this study. The following formulae has been applied for both diesel and petrol as per (Joumard et al., 2007 p. 204) .

$$C_{CO_2/l,i} = \frac{m_{CO_2}}{v_{fuel}} = \frac{44.011}{12.011 + 1.008 * r_{H/C_i}} * \rho_{fuel,i} \tag{2}$$

Where r_{H/C_i} = the carbon/hydrogen ratio, which is 1.8 for petrol and 2 for diesel. $\rho_{fuel,i}$ is 0.766 kg/l for petrol and 0.8414 kg/l for diesel. The calculated mass (g CO_2/l) for each fuel is employed to calculate l fuel/km by dividing g CO_2/l over the carbon mass of each fuel.

In the earlier stages of this study, a second average speed model presented in the Artemis report by (Joumard et al., 2007) has been utilized. This model calculates fuel consumption directly, by the following general equation (Joumard et al., 2007 p. 51):

$$y = \frac{a + c * x + e * x^2}{1 + b * x + d * x^2} + \frac{f}{x} \tag{3}$$

Where y = fuel consumption (g/km), x = average speed (km/h) and a to f are coefficients. This model is easier to use rather than the reference test pattern (RTP) average speed model, as it is not dependent upon regression functions and calculating backwards from CO_2/km as in the RTP model. However, in use, this model calculates lower fuel consumption values than otherwise seen in literature. This effect is most prominent for vehicles with motor volume less than 1.4 l. This average speed model does also not cover pre-Euro vehicles. Because of this, the RTP average speed model is employed for calculating vehicle fuel consumption in this study. Moreover, the polynomial coefficients necessary for use in the RTP model are included in the SEMBA Python model. The functions from SEMBA are adopted and fitted to an Excel document, calculating passenger car fuel consumption. Adopting the polynomial coefficients from SEMBA to the dedicated traffic emissions model made the conversion between average speed models convenient.

The RTP model does not, however, cover diesel Euro 4 vehicles with a motor volume > 2 l. A 10% reduction factor from Euro 3 to Euro 4 vehicles, as proposed by (Joumard et al., 2007) is applied and assumed valid for these vehicles.

The general equation for calculating transport emissions, expressed as kg CO_2-eq/km, within this study is:

$$(\mathrm{VKM}, \mathrm{i}, \mathrm{j}, \mathrm{k} * \mathrm{FC}, \mathrm{i}, \mathrm{j} * \mathrm{EF}, \mathrm{i} * (1-0.035) + 0.035 * VKM, \mathrm{i}, \mathrm{j}, \mathrm{k} * \mathrm{FC}, \mathrm{i}, \mathrm{j} * \mathrm{EF}, \mathrm{biofuel} \quad (4)$$

Where FC,i,j is the fuel consumption matrix per fuel type (i) and route (j). Vkm,i,j is the route specific traffic volume matrix (i) fuel type (j) and alternative (k). EF,i is the fuel dependant emission factor. EF, biofuel is the biofuel emission factor.

3.2.2. The regional passenger car stock

The regional passenger car stock applied to this study consists of data from Statistics Norway and Opplysningsrådet for Veitrafikken AS (OFVAS) (Statistisk Sentralbyrå 2014, Opplysningsrådet for Veitrafikken AS, 2015). The statistics from Opplysningsrådet for Vegtrafikken is received from personal communication, and may not be available online for non-subscribers to their statistics series. The Artemis RTP average speed model requires vehicle age, engine volume and fuel type to calculate passenger car fuel consumption.

Yearly statistics on national and regional car stock from Statistics Norway is available, sorted in variables such as age, manufacturer, region and year. In this study, the statistics from Statistics Norway are provided as the amount of registered vehicles in the Trondheim municipality for the year of 2013. Statistics Norway does not provide statistics of the amount of registered vehicles by manufacturer models. To compensate for this, the year of 2013 is chosen. This is the most recent year where OFVAS has published statistics of the national car stock in Norway, sorted by manufacturer and model. Manufacturers listed in OFVAS statistics from year 2013 is employed to sort the statistics provided by Statistics Norway (Opplysningsrådet for Veitrafikken AS, 2013). This is the first step towards the compilation of a regional passenger car stock coefficient matrix.

Secondly, a sum of the included manufacturers registered vehicles in Trondheim is calculated. This sum is utilized to calculate the coefficient matrix employed for calculating passenger car emissions. The amount of registered vehicles, sorted by age, pertaining to each individual manufacturer is divided by the total amount of registered vehicles. This is the second step towards the regional passenger car stock coefficient matrix. The coefficient matrix now consists of the regional passenger car stock, sorted by manufacturer and age, looking like the example matrix provided in *table 2*.

Table 2: Example passenger car coefficient matrix sorted by manufacturer and age.

Passenger car coefficient matrix, sorted by manufacturer and age (Euro class)

	Euro 5 2013 - 2009	Euro 4 (2006 - 2008)	Euro 3 (2000-2005)	Euro 2 (1999-2000)	Euro 1 (1993 - 1998)	Euro 0	Sum
Volkswagen	0,04	0,04	0,04	0,03	0,03	0,01	0,19
Audi	0,01	0,02	0,02	0,02	0,01	0,00	0,08
BMW	0,01	0,02	0,01	0,01	0,01	0,00	0,07
Ford	0,02	0,02	0,02	0,01	0,01	0,01	0,09
Nissan	0,01	0,01	0,01	0,01	0,01	0,00	0,05
Opel	0,01	0,01	0,01	0,02	0,02	0,01	0,07
Peugeot	0,01	0,01	0,02	0,01	0,01	0,00	0,06
Toyota	0,03	0,04	0,04	0,03	0,03	0,01	0,18
Volvo	0,02	0,02	0,02	0,01	0,01	0,01	0,11
Mercedes-Benz	0,01	0,02	0,02	0,02	0,01	0,01	0,09
Sum	0,18	0,22	0,21	0,17	0,15	0,07	1,00

However, the Artemis RTP model requires vehicle motor volume for it to calculate fuel consumption. The amount of models issued by each brand is considerable, and there is no exact statistics available from among others Statistics Norway on this subject. The most recent statistics on popular passenger car models is from (Opplysningsrådet for Veitrafikken AS, 2013). This is furthermore the same source utilized to separate the data from Statistics Norway into the most popular manufacturers in the Trondheim municipality. It is further assumed that the models listed by OFVAS is representative for the Trondheim municipality, which enables the separation of manufacturers into popular models by each manufacturer.

Each model's vehicle volume is set as per technical specifications listed on manufacturer websites (Audi AG, 2013, Bayerische Motoren Werke Aktiengesellschaft, 2011, Ford Motor Company, Unknown year , Mercedes-Benz, 2015, Werner, 2013, Nissan, Unknown year, Opel, 2015, Peugeout, 2015, Toyota Motor Corporation, 2015, Volkswagen, 2015, Volvo Cars, 2014).

Each manufacturer is assigned a model, assumed prototypical for the manufacturer and a motor volume. The coefficient matrix is now classified by vehicle age and engine volume. The end-product, the regional coefficient car stock matrix is show in *table 3*.

Table 3: The regional passenger car vehicle stock coefficient matrix.

Passenger car coefficient matrix, sorted by engine volume and age (Euro class)

Engine size (l)	Prototypical PC	Euro 5 2013 - 2009	Euro 4 (2006 - 2008)	Euro 3 (2000-2005)	Euro 2 (1999-2000)	Euro 1 (1993 - 1998)	Euro 0	Sum
<1,4	Volkswagen Golf	0,04	0,04	0,04	0,03	0,03	0,01	0,19
1.4 - 2	Audi A4	0,01	0,02	0,02	0,02	0,01	0,00	0,08
	BMW 3-series sedan	0,01	0,02	0,01	0,01	0,01	0,00	0,07
	Ford Mondeo	0,02	0,02	0,02	0,01	0,01	0,01	0,09
	Nissan Qashqai	0,01	0,01	0,01	0,01	0,01	0,00	0,05
	Opel Astra	0,01	0,01	0,01	0,02	0,02	0,01	0,07
	Peugeot 308	0,01	0,01	0,02	0,01	0,01	0,00	0,06
	Toyota Corolla L	0,03	0,04	0,04	0,03	0,03	0,01	0,18
	Volvo V70	0,02	0,02	0,02	0,01	0,01	0,01	0,11
>2	Mercedes-Benz E-class sedan	0,01	0,02	0,02	0,02	0,01	0,01	0,09
	Sum	0,18	0,22	0,21	0,17	0,15	0,07	1,00

The ARTEMIS model lacks measurement data of engines with Euro 5 technology. To compensate for this, (Joumard et al., 2007) considers Euro 5 and Euro 4 emission standards to remain the same. It is therefore, in this study, applied Euro 4 engine technology to Euro 5 passenger cars.

3.2.3. The regional heavy vehicle stock

The regional heavy vehicle stock is represented by a coefficient matrix, constructed from statistical data. Through personal communication with OFVAS, regional statistical data on heavy vehicle stock for the year of 2015, separated by total weight and age is obtained (Opplysningsrådet for Veitrafikken AS, 2015). The Artemis heavy vehicle emissions model does not for instance require engine volume. This means that a coefficient matrix is calculated directly in Matlab, without any aggregation.

Secondly, heavy vehicle fuel consumption is calculated in the SEMBA Python module, using dedicated scripts for each vehicle weight class. An example Python string is shown below.

```
print HDV.CalculateHDV(42, 'FC', 58.46, 0.0, 100)[0]/1000
```

Where, CalculateHDV calls upon the integrated heavy duty vehicle fuel consumption model, constructed from the Artemis heavy duty vehicle emissions methodology. 42 refers to vehicle ID, which in this example is a 7.5-12 ton Euro 5 rigid truck. Generally, vehicle ID is chosen based on total vehicle weight, age and type of truck (rigid or articulated).
FC is fuel consumption. 58.46 refers to average vehicle speed, 0.0. is in this case the route gradient and 100 is vehicle load. [0]/1000 is added for the model to calculate fuel consumption in l/km.

Thirdly, fuel consumption pertaining to vehicle weight, age and route parameters are compiled into matrices in Excel. A fuel consumption matrix for heavy vehicles travelling on a route with an average speed of 50 km/h and an average gradient of 0% is shown beneath.

Table 4: Heavy duty vehicle fuel consumption a route with an average vehicle speed = 50 km/h and a 0% average gradient.

Heavy duty vehicle fuel consumption with avg. Speed = 50 km/h and gradient = 0%

Total weight	Euro 5	Euro 4	Euro 3	Euro 2	Euro 1	Euro 0
a <= 7,5 t	0,10	0,10	0,10	0,10	0,10	0,12
b > 7,5-12 t	0,15	0,14	0,15	0,15	0,17	0,10
c > 12-14 t	0,16	0,16	0,17	0,16	0,17	0,20
d > 14-20 t	0,19	0,19	0,20	0,20	0,20	0,26
e > 20-26 t	0,25	0,25	0,26	0,26	0,27	0,33
f > 26-28 t	0,26	0,26	0,28	0,27	0,28	0,36
g > 28-32 t	0,31	0,30	0,33	0,32	0,33	0,41
h > 32 t	0,31	0,31	0,33	0,33	0,33	0,42

3.2.3. The calculations process

The general calculations process for the traffic emissions model, including both the heavy duty vehicle and passenger car emissions model can be summarized in the following manner:

1. Compile the regional vehicle stock. Normalize the vehicle stock in order to create a coefficient matrix (C,i).
2. Import traffic volume (expressed in vehicle kilometers) from Excel.
3. Split traffic volume into volume travelled by petrol and diesel passenger cars. This is not necessary for heavy duty vehicles, as they are assumed to be run exclusively on diesel.
4. Calculate a route and alternative specific vkm matrix: $\mathrm{VKM}, i, j, k = C, i * vkm, i, j, k$ (5). This matrix is calculated using a loop, where each variable in the vkm matrix is multiplied with each route's specific traffic volume.
5. Import route specific fuel consumption matrices.
6. Apply equation (4) to calculate a route specific CO_2-emissions matrix.
7. Sum the route specific CO_2-emissions matrix.

3.2.4. Emission factors

Fuel consumption emission factors are gathered from the LICCER database. For electric vehicles, electricity consumption per km is collected from the LICCER database, where the energy consumption is expressed as MJ/km.

SEMBA and the Artemis RTP average speed model offer the calculation of emissions expressed as CO_2-equivalents directly. This study, however, assumes a 3.5% share of bio fuel in both petrol and diesel, making traffic emissions more easily calculated using LICCER emission factors. Additionally, this makes scenario analysis employing i.e. a higher percentage of biofuels less time consuming. The LICCER emission factors do furthermore take upstream emissions into consideration, of which the Artemis and SEMBA models do not (Brattebø et al., 2013a, Joumard et al., 2007).

The vehicle emission factors employed in this study are:

- Petrol: 2.75 kg/l
- Diesel: 3.19 kg/l
- Biofuel: 0.69 kg/l
- Electricity: 0.001 kg/l (Norwegian electricity mix) and 0.029 kg/l (Nordic electricity mix)

Biofuel is here (and in the LICCER model) expressed as a collective term for ethanol and bio-diesel mixed with petrol and diesel (Modahl et al., 2009). The Nordic electricity mix is applied for scenario testing, and is not applied to the baseline scenarios presented in this study (Schakenda and Nyland, 2008).

4. Case

This section presents the case at hand in this case study: the Byåsen tunnel. Current projected design parameters, along with assumed tunnel geometry is outlined throughout the section. The routes of traffic assumed affected by the tunnel are in addition further presented throughout. The section is separated into the following: The Byåsen tunnel and routes of traffic assumed affected by the tunnel.

4.1. The Byåsen tunnel

There are six tunnel designs included in the study, whereof three of the tunnel designs are single and the remaining three are double shafted tunnels. All tunnels have a 5% incline. The length of each tunnel is 2510 m for tunnel alt. 1, 2300 m for tunnel alt. 2 and 2850 m for tunnel alt. 3. The tunnel design parameters are summarized in *table 5*.

Table 5: A summary of tunnel design parameters.

Alternative	Incline	Road length (m)	Main tunnel length (m)	Adjacent tunnel length (m)
1	5%	2510	2380	
2	5%	2300	2170	
3	5%	2300	2250	600

The tunnel connects with the proposed new Sluppen Bridge. The outlet of the tunnel is, however, yet to be decided. In their project documents, The NPRA are considering the Munkvoll area in Byåsen as a possible outlet. Tunnel alternative 3 consists of a main tunnel splitting into two adjacent tunnels that exit at to different points at Byåsen. The inlet at Sluppen is one single tunnel.

The pathway of each tunnel alternative, as envisioned in an unpublished NPRA project document is illustrated in *figure 4*.

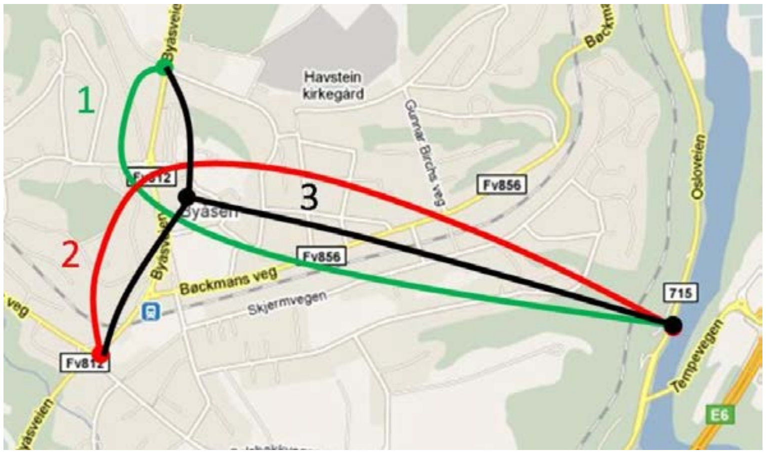

Figure 4: Each tunnel alternative's pathway illustrated (Spilsberg and Harbo, 2011)

This study's life cycle inventory, and further the LICCER model inventory pertaining to this study, consists of, among others, material amounts calculated from traffic analyses and personal communication with NPRA personnel.

The AADT expressed in NPRA traffic analyses for the Byåsen tunnel designates a tunnel class E tunnel for the double-shafted alternatives. This corresponds to a T9.5 tunnel profile in each shaft, illustrated in *figure 5* (Vegdirektoratet, 2014b).

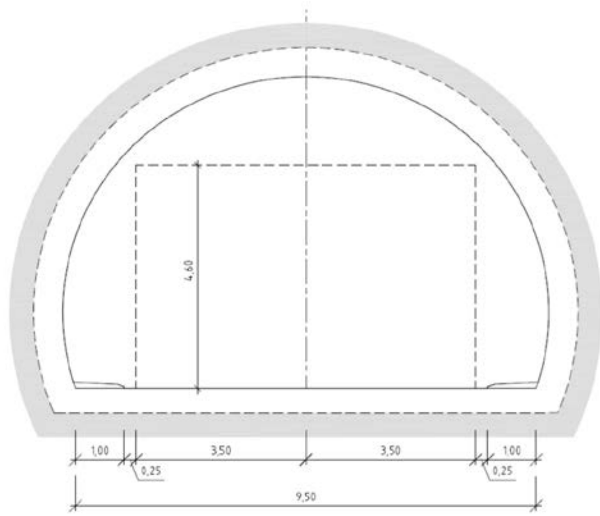

Figure 5: A T9.5 tunnel profile. Tunnel dimensions are expressed in meters.

Tunnel design factors such as tunnel lining and sub base materials are not yet decided. It is assumed that the tunnel lining will be lined with cast-on-site concrete.

The sub-base materials are assumed to be 100% aggregate. Sub-base and base-layer thickness is dimensioned to fit an assumed finely purged tunnel bed. Driving line width, hard shoulder width and other road and tunnel design relevant parameters are aligned with each tunnel alternative's tunnel profile. All roads in the open are assumed to have dimensions as the NPRA's H1 profile (Vegdirektoratet, 2014a).

The single-shafted tunnel design corresponds to tunnel class D. It is considered likely that the tunnel will be designed with three lanes, which corresponded to tunnel profile T14 (Vegdirektoratet, 2014b).Tunnel profile T14 is illustrated in *figure 6*.

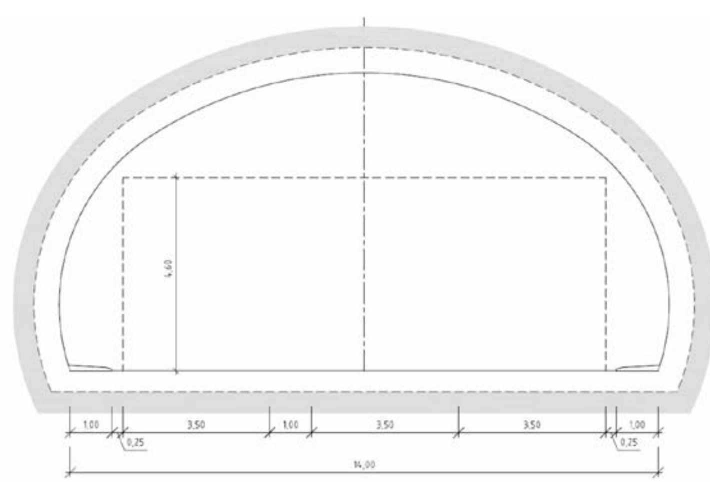

Figure 6: Tunnel profile T14. Tunnel dimensions are expressed in meters.

Each tunnel does in addition contain a roundabout at the outlet. The roundabout included in this study's life cycle inventory is a generic roundabout, dimensioned as outlined in NPRA handbooks on roundabout design (Vegdirektoratet, 2014d). It is further assumed that heavy vehicles will use the roundabout, which designates a wider lane width.

4.2. Routes of traffic assumed affected by the tunnel

It is assumed that both the new Sluppen Bridge and the Byåsen tunnel will affect certain routes of traffic currently used to circumvent the commonly congested Sluppen Bridge. To assess the assumption that the Byåsen tunnel can reduce traffic volume on known route choices employed to circumvent the bridge, seven routes are included in the traffic emissions model. Each route included in the study is referenced against an unpublished project specific NPRA document, documenting assumptions and data utilized for their traffic assessment of the Byåsen tunnel and the area surrounding it. The routes included are assumed to be the most affected by the tunnel, as per the NPRA document.

Each route travels to a designated address in Byåsen: Byåsveien 194. This address is located midway between the selection of projected tunnel entrances. Of the routes included, each individual route has an individual designated starting point. Each starting point is intended to function as a representative of commonplace locations travellers to the Byåsen area are travelling from.

The included routes are the following:

Route	Route #	Km
From Tonstadkrysset through Granåsen	1	7,4
From Brattøra through Byåsvegen	2	6,5
From Ila through Bøckmanns veg	3	5,2
From Ila through Osloveien and Stavne	4	5,5
From Omkjøringsvegen through Sluppen	5	6,6
From Tonstadkrysset - Bjørndalen	6	5,2
From Midtbyen through Bøckmanns veg	7	7,3

No growth in traffic is assumed throughout the analysis time horizon, as per Greener Trondheim's project goals. Growth in traffic is envisioned to be handled by an increase in the share of cyclists and the use of public transportation (Trondheim Bystyre, 2008).

5. Results and findings

This section provides an overview over the yearly GHG emissions resulting from the Byåsen tunnel's life cycle stages and traffic in operation for all alternatives included in this study. The section does further address the research questions posed in the introduction. The total environmental impacts of the included alternatives are presented in section *5.1. Baseline results and findings* as a baseline for the presentation of results from scenarios, which is presented in section *5.2. Scenario results and findings*.

Data on a non-tolled 0-alternative is not available, and is not presented in this study. Route specific traffic volume is furthermore considered sensitive data and is not presented. This section presents a larger amount of results and findings than the article, which is more selective in its presentation of results and findings. The figures and findings not presented in the article have generally been excluded due to a greater relevance of the included findings. Figures presenting, among others, tunnel life-cycle emissions have been excluded in the article in order to give leeway to a more in-depth assessment of traffic emissions

Lastly, the section is divided into the following parts: baseline results and findings & scenario results and findings.

5.1. Baseline results and findings

Table 6: Summary of GHG-emissions/year over the ATH (20 years) for all tolled tunnel alternatives.

			Double-shafted tunnel			Single-shafted tunnel		
		Alt. 0	Alt. 1	Alt. 2	Alt. 3	Alt. 1	Alt. 2	Alt. 3
Infrastructure	ton CO2-eq/year	169,2	5 217,5	4 732,5	5 509,3	3 432,4	3 106,4	4 063,6
Traffic	ton CO2-eq/year	80 347,0	71 230,5	70 632,0	72 341,9	71 230,5	70 632,0	72 341,9
Net total	ton CO2-eq/year	80 516,1	76 447,9	75 364,4	77 851,2	74 662,9	73 738,4	76 405,5
Net total (Δ from alt. 0)	Δ CO2-eq/year		-4 068,2	-5 151,7	-2 665,0	-5 853,2	-6 777,8	-4 110,7

The above presented table shows that both the tolled double-shafted and single-shafted tunnel alternatives provide some mitigation of yearly GHG-emissions compared to the reference alternative (Alt. 0). Tunnel alternative 2, both designs included, provides the largest savings in CO_2-eq/year, due to its shorter length (2.3 KMs). Of the two design alternatives, the single-shafted tunnel alternative 2 has the largest negative Δ over the reference alternative by a margin of 1626 ton CO_2-eq/year. The 0-alternative has the smallest amount of CO2-eq/year resulting from infrastructure, as its inventory only contains operation and maintenance for its "synthetic route", which is 1 km in length.

Infrastructure is in this study expressed as a collective term that includes production, construction, operation & maintenance. The following figure presents each tunnel's life-cycle emissions.

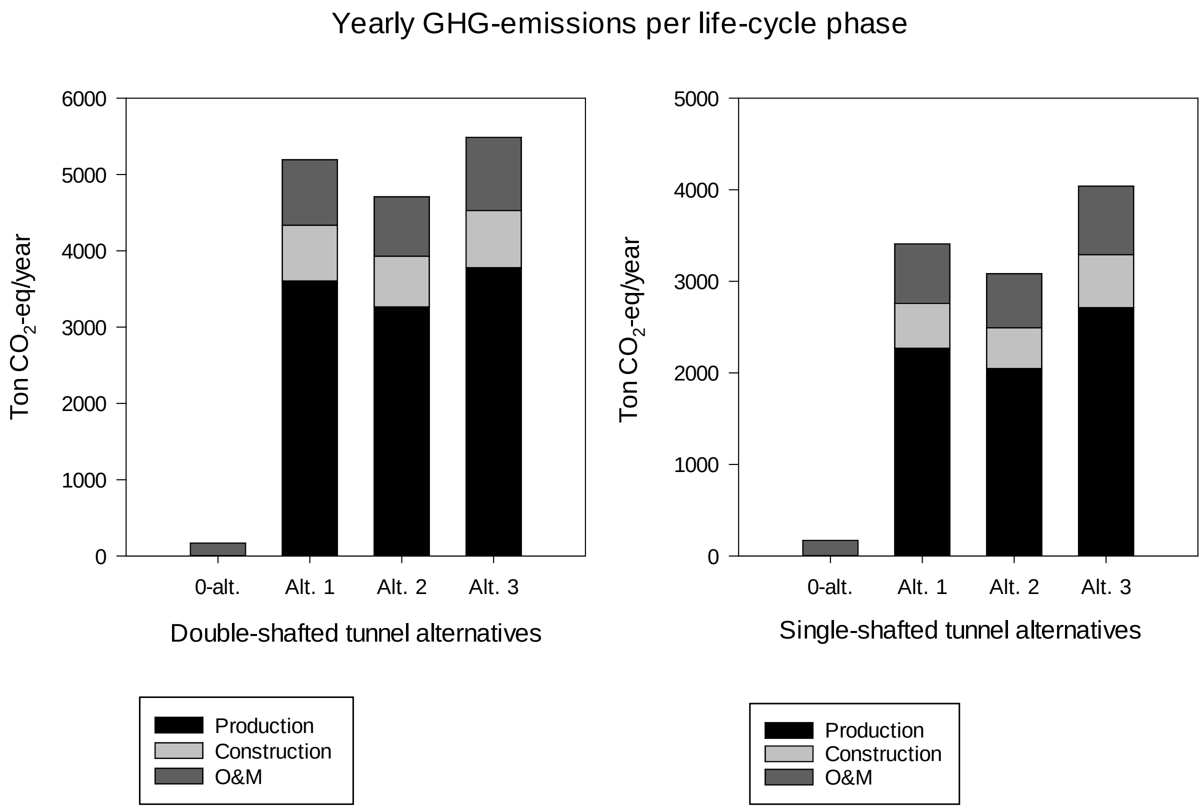

Figure 7: The yearly GHG-emissions per life-cycle phase for all alternatives included in this study.

The production phase dominates yearly GHG-emissions, with about 70% of total yearly GHG-emissions from infrastructure. This is further in line with findings by (Hammervold, 2014, Huang et al., 2013) and Miliutenko et al. (2012). Production and maintenance hold the remaining 30%, which are distributed as 16% operation and maintenance and 14% production, between the two phases.

In her case study of a Swedish road tunnel, (Miliutenko et al., 2012) finds that the operation phase is the largest contributor to total CO_2-eq emissions over a 100 year time period. Although not tested in this study, it is likely that this study's operation and maintenance could have larger share of total yearly GHG-emission if assuming another electricity mix. The tunnel is assumed to operate on a 0.02 kg/kWh Norwegian electricity mix. Electricity mixes are known to fluctuate, and it is therefore likely that emissions from the operation phase are somewhat under-estimated.

The 0-alternative offers negligible yearly GHG-emissions from infrastructure. This is largely due to it being represented as a synthetic route, 1 km in length. A longer analysis time horizon should ,however, allocate a larger share of emissions from its O&M phase as guard-rails are typically replaced every 30 years (Simonsen, 2010). Generally, a longer analysis time horizon entails greater yearly GHG-emissions, as a larger share of the life-cycle emissions from each infrastructural element is allocated to the project. Operation and maintenance routines such as pavement layer resurfacing do also occur more times. Moreover, steel, the material that guard rails are commonly made of, hold a relatively large share of production emissions, presented in *figure 8*.

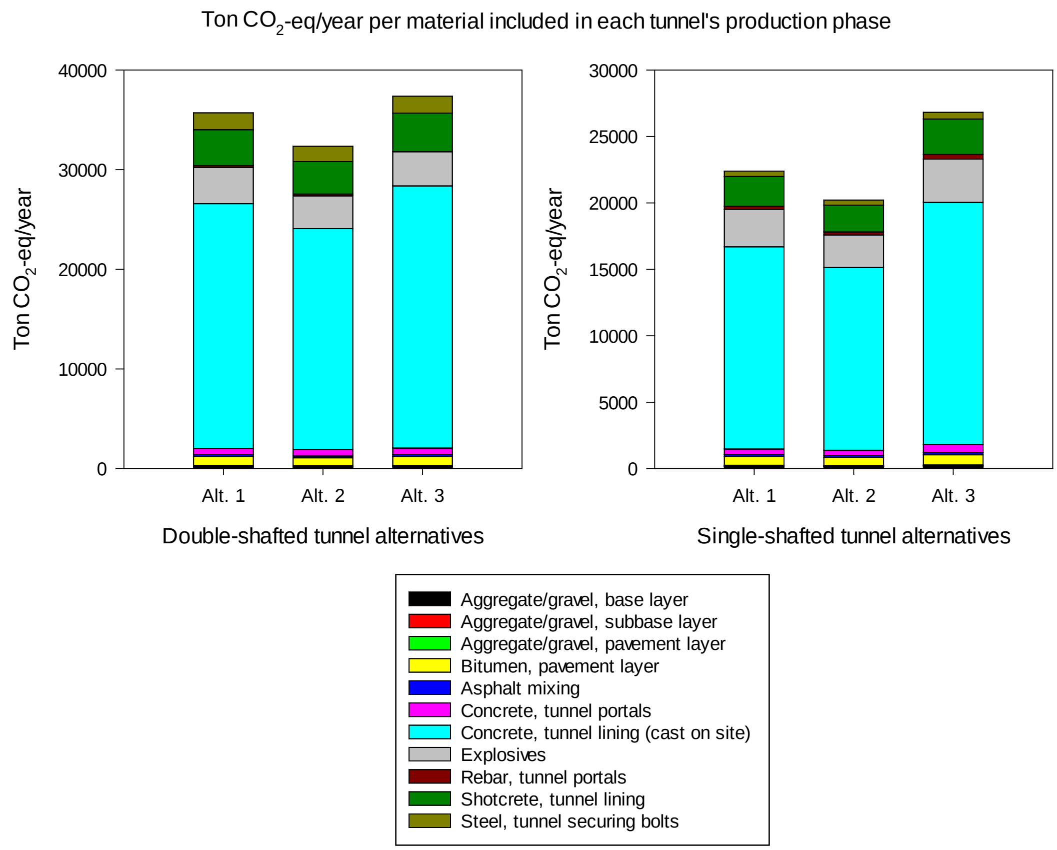

Figure 8: Yearly GHG-emissions per material included in each tunnel's production phase.

Concrete, explosives and steel hold the majority of each tunnel's yearly production phase emissions. This is in line with the aforementioned literature by (Hammervold, 2014, Huang et al., 2013) and Miliutenko et al. (2012). The large share of CO_2-eq emissions from concrete in the production phase does however mean that there are mitigation opportunities in, among others; the choice of tunnel lining and in some cases the concrete recipe. Choosing, for instance, concrete elements over cast-on-site tunnel lining in the LICCER model show, for the double-shafted tunnel alternatives, GHG-reductions in the magnitude of -1968 – 2322 ton CO_2-eq/year. This does furthermore highlight the importance of early-phase decisions on design and materials used, as well as LCAs assessing available design choices.

However, comparing yearly GHG-emissions from infrastructure, the yearly emissions are small in comparison to emissions from traffic, which are considerable in magnitude. The emissions from infrastructure amount to about 6% of the net total emissions/year. The net total emissions from a situation with tunnel will, depending on tunnel alternative, amount to a net saving of 3.3-8.4% in net yearly GHG-emissions, compared to the 0-alternative. The reductions in emissions per year is mainly due to a large amount of vehicles routed through the tunnel. This replaces traffic from other longer routes previously used by travellers to avoid congested traffic in the Sluppen area. Traffic volume is in turn reduced, given the shortcut the tunnel provides for vehicles travelling to the Byåsen area.

Table 7: Summary of yearly greenhouse emissions/year without tolling stations. The 0-alternative is not included due to lacking data.

		Double-shafted tunnel			Single-shafted tunnel		
		Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 1**	**Alt. 2**	**Alt. 3**
Infrastructure	ton CO2-eq/year	5 217,5	4 732,5	5 509,3	3 432,4	3 106,4	4 063,6
Traffic	ton CO2-eq/year	79 059,4	78 347,2	80 382,1	79 059,4	78 347,2	80 382,1
Net total	ton CO2-eq/year	84 276,9	83 079,6	85 891,4	82 491,8	81 453,6	84 445,7
Net total (Δ from tolled tunnel alts)	Δ CO2-eq/year	7 828,9	7 715,2	8 040,2	7 828,9	7 715,2	8 040,2

Removing tolling stations increases net GHG-emissions by 7715-8040 ton GHG-emissions per year when compared to a situation with tolled tunnel alternatives. Furthermore, the removal of tolling stations amounts to a 10% increase in yearly traffic emissions from the tolled tunnel alternatives. The delta is calculated as the increase from each tunnel alternative, as non-tolled tunnel alternative minus tolled tunnel alternative. Each tunnel alternative edges onto the 0-alternative's yearly GHG-emissions, with alt. 3 surpassing it with 5375 ton GHG-emissions/year. It should however be noted that comparing such a situation directly is not necessarily a fair comparison, as a non-tolled 0-alternative has not been provided. It is likely, however, that a non-tolled 0-alternative would surpass each tunnel alternative given the reduction in traffic volume the tunnel provides. The increase in emissions per year is due to a relatively large increase in AADT on nearly all involved routes, and for the proposed tunnel in particular.

Due to the increase in traffic volume on the majority of the routes, this has led to a number of scenarios that aim to investigate the effects of reduced average speeds throughout the day due to an assumed more severe congestion along some of the included routes. A breakdown of yearly traffic emissions is presented below.

Table 8: Yearly GHG-emissions from traffic for all tunnel alternatives

	With toll				Without toll			
	0-alternative	Tunnel alt. 1	Tunnel alt. 2	Tunnel alt. 3	Tunnel alt. 1	Tunnel alt. 2	Tunnel alt. 3	
PC, petrol	28 780,0	25 610,1	25 407,5	25 986,4	28 617,2	28 376,1	29 065,0	ton CO2-eq/year
PC, diesel	25 701,1	22 643,2	22 466,1	22 972,2	25 164,9	24 954,1	25 556,4	ton CO2-eq/year
EV	6,3	5,5	5,4	5,5	6,1	6,0	6,1	ton CO2-eq/year
HDV	25 859,6	22 971,7	22 753,0	23 377,8	25 271,2	25 010,9	25 754,5	ton CO2-eq/year

Emissions from passenger cars are the largest, ranging from 47 874 – 54 621 ton CO_2-eq/year. Petrol passenger cars emit the most CO_2-eqs of all light vehicles included. Emissions from electric vehicles are negligible, with a share of around 0.0078% of total traffic emissions depending on tunnel alternative. A relatively large amount of GHG-emissions stem from HDVs, which have a share of 7-11% of AADT depending on route alternative. This is generally due to their low drivetrain-efficiency and a large share of older vehicles (Euro 3 and older) in use for HDVs with a total weight of 12-14 t and lower.

As presented in the above table however, an increase in electric vehicles, increased engine efficiency or an inflow of newer cars as well an overall reduction in traffic volume should provide some traffic emissions mitigation promise. More on this below.

5.2. Scenario results and findings

This section provides results and findings from scenarios crafted from findings in the baseline results and the literature reviewed. All scenarios present the effects on total GHG-emissions from traffic only. Eleven scenarios have been tested, where assumptions on congestion and shifts in vehicle park composition is applied. Literature suggests that reducing congestion, thus increasing average speeds should produce some mitigation (Knudsen and Bang, 2007, Bart and Boriboonsomsin, 2008). This prompts the inclusion of scenarios testing increased average speeds, with assumptions applied where reasonable. Through earlier project work it is discovered that reducing fuel consumption and increasing the amount of electric vehicles has considerable effects. Scenarios that tests these effects is provided. Congestion, leading to reduced average speeds, in the Byåsen tunnel is also tested, where the effects are presented in *table 9*.

Table 9: This table shows the effect of reducing the average speeds in the Byåsen and its effect (increase) on total yearly emissions from traffic. The original average speed in the tunnel is assumed 60 km/h.

	avg. Speed	Δ tunnel alt. 1	Δ Tunnel alt. 2	Δ Tunnel alt. 3	
w/toll	50 km/h	26,36	24,16	30,46	ton CO2-eq/year
without toll		31,37	28,75	36,25	ton CO2-eq/year
w/toll	45 km/h	132,11	121,05	152,63	ton CO2-eq/year
without toll		157,22	144,06	181,64	ton CO2-eq/year
w/toll	40 km/h	263,21	234,79	315,98	ton CO2-eq/year
without toll		404,21	370,39	467,02	ton CO2-eq/year

The traffic analysis for the Byåsen tunnel (without toll) reveals that the tunnel will experience a traffic volume over capacity, which prompts this scenario.

The effects of congestion is difficult to predict, and a 5 km/h increment from 50 km/h is chosen to represent the effects of different average speeds. The results from this scenario show that the effects of lower average speeds are more profound as the average speeds decline, which is in agreement with the findings by (Bart and Boriboonsomsin, 2008). The potential for mitigation of traffic emissions is however not as profound as in their study. Nevertheless, the Byåsen tunnel is located close to dense residential areas, which in a situation with severely congested traffic could mean elevated local emissions stemming from traffic in the tunnel. Elevated local emissions from traffic in the tunnel is likely to be detrimental to the health of residents situated close to the tunnel ventilation outlet. This is however something that should be quantitatively elaborated upon in a further study.

Furthermore, it can be seen that the emissions are in total only 24-30 ton CO_2/year higher for the tolled v50 scenario, which suggests that assuming the tunnels speed limit to be its average speed should only provide a marginal underestimation of yearly emissions. The effects of increasing average speeds on select routes using tunnel alt. 2 as baseline is also tested, along with the effects of changing the composition of the regional car park, presented in *table 10*.

Table 10: Summary of scenarios using tunnel alt. 2 w/toll as baseline. The mitigating effect of each scenario is split into vehicle type and fuel.

	Δ Tunnel alt. 2 with toll				
Scenario	PC, petrol	PC, diesel	EV	HDV	
r7 v 45 km/h	-109,8	-80,6	0,0	-120,8	ton CO2-eq/year
r5 v 55 km/h, r7 v 45 km/h	-294,4	-202,2	0,0	-305,6	ton CO2-eq/year
EV_4.8%	-588,1	-523,1	5,5	0,0	ton CO2-eq/year
vkm_shift	-537,8	-124,8	0,0	-1135,0	ton CO2-eq/year
vkm_shift2	-2013,8	-1573,5	0,0	-1135,0	ton CO2-eq/year

The ***r7 v45 km/h*** scenario tests the effect of increasing the average speed in route 7 by 5 km/h, from 40 to 45 km/h. Scenario ***r5 v 55 km/h***, ***r7 v45 km/h*** studies the effect of increasing the average speed on route 5 and route 7 with 5 km/h. ***EV_4.8%*** increases the share of electric vehicles in the regional car park, from 2.38% to 4.8%. The ***vkm_shift*** scenarios studies the effects of shifting the amount of vkms by each euro class, simulating a phasing of newer vehicles into regional vehicle stock, 20 years into the future.

Vkm_shift has one cycle of phasing, where 90% of Euro 0 vehicles (passenger cars & heavy duty vehicles) are replaced with new vehicles, which are assumed to be today's Euro 5 vehicles with a 10% reduction in fuel consumption. The average age of the regional passenger cars is roughly 11 years, which makes this a viable assumption (Statistisk Sentralbyrå, 2014). The 10% reduction in fuel consumption is based off assumed reduction factors used in the ARTEMIS project for future engine technologies (Joumard et al., 2007).

Vkm_shift2 includes two phasings, where 95% of Euro 0 and Euro 1 vehicles are replaced by Euro 5 vehicles with a 10% reduction in fuel consumption and a Euro X vehicle. The Euro X is an assumed vehicle standard with a 10% improvement in FC over the improved Euro 5 vehicle in ***vkm_shift***. HDVs are, in the ***vkm_shift2*** scenario, assumed to have the same improvements in fuel consumption as in ***vkm_shift***

The net total and relative effect of each scenario presented in the table above is visualized in *figure 9*.

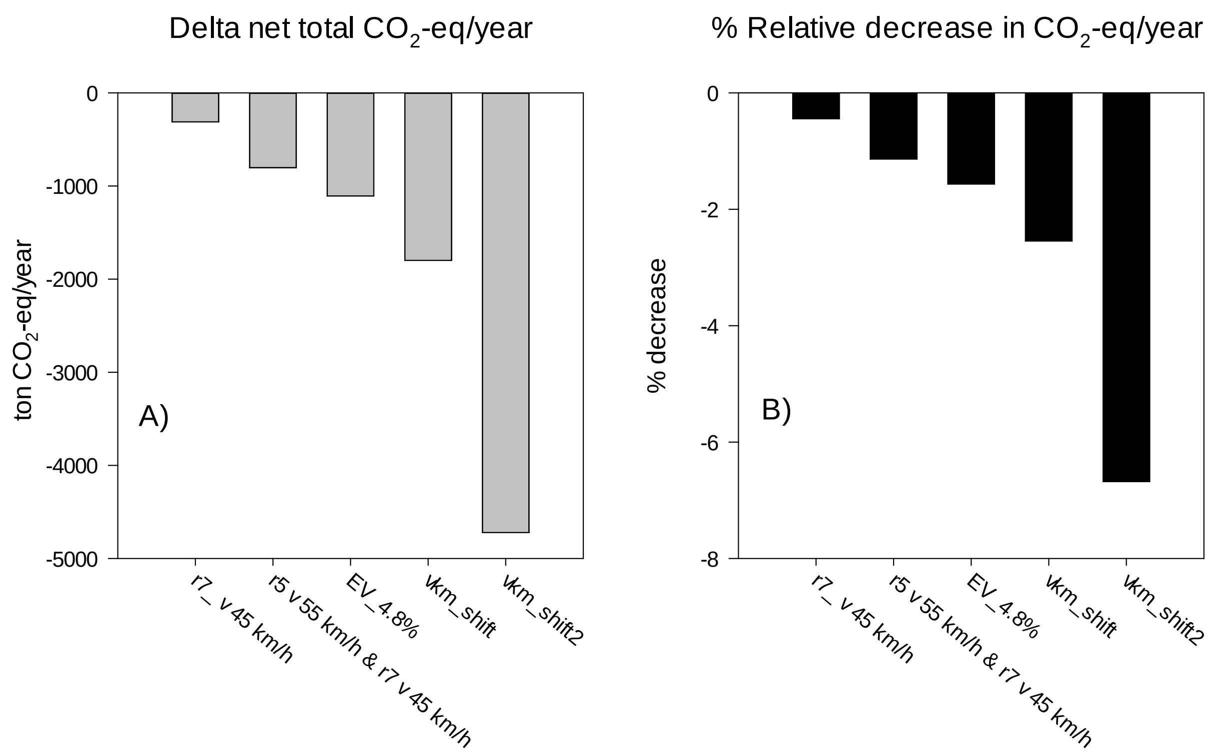

Figure 9: The absolute (a) and relative (b) net decrease of each scenario tested.

Firstly, the effect of increasing average speeds on one route is marginal. Although, if two routes are assumed relieved of congestion issues, the effects are more profound. The effect is quite prominent on heavy duty vehicles, with a reduction of 305.6 ton CO_2-eq/year.

Secondly, it is interesting to note that the effect of increasing average speeds slightly outweigh the effect of doubling the share of electric vehicles. The increase in EV shares would imply a nearly direct deduction of traffic emissions given the EVs emissions of 0.89 g CO_2-eq/km assuming a Norwegian electricity mix. The ***EV_4.8%*** scenario does however represent a large mitigation effect considering that this scenario has only one change in variables.

Thirdly, the largest reductions in CO_2-eqs/year is found in the ***vkm_shift*** scenarios. The effect of reducing fuel consumption through replacing older vehicles and implementing assumed new engine technology is quite prominent and far outweigh the scenarios with an assumed higher average speed. This confirms that improvements to engine technology is relatively important in order to reduce vehicle fleet emissions, and further that the yearly emissions from traffic in the year of the tunnel's construction might be slightly lower than what is calculated in this study.

This study employs vehicle stock data with current engine technology; whereas the tunnel will be built in a time where newer technologies are available. It is furthermore likely that the vehicle stock composition might be slightly different in the year of its construction, which may alter yearly emissions from traffic somewhat. Lastly, the effect of each scenario tested is close to marginal.

However, when combining certain scenarios with the mitigating potential of tunnel alternative 2, the effects are more profound. Moreover, scenario ***vkm2*** and tunnel alternative 2 combined amount to a reduction of about 13-15%, depending on design, in yearly GHG-emissions, which should be effective in reaching future Greener Trondheim mitigation targets.

6. Discussion

The results discussed above show that the yearly emissions from traffic in the western Trondheim area are considerable. The yearly emissions caused by constructing the Byåsen tunnel are quite small in comparison to emissions resulting from actual use of the tunnel via traffic in operation. This further suggests that an analysis of the infrastructural element subject to life cycle analysis should include actual use of the element. Preferably as an analysis of traffic and the eventual changes in traffic from constructing it. This is from the results of this study perceived as instrumental in a concept choice or any decision making process. Moreover, this section will provide a wider discussion of the study's most important findings as well as a separate sub-section discussing this study's strengths and weaknesses.

1. The Byåsen tunnel's greenhouse gas mitigation potential

Firstly, the Byåsen tunnel will succeed in providing some mitigation of yearly emissions in the range of 2665-6778 ton CO_2-eq, by providing a shortcut to Byåsen from the greater Trondheim area and by reducing traffic volume on several longer routes used for travelling to the Byåsen area. This should contribute to Greener Trondheim's goals pertaining to reductions in traffic emissions. This can, among others, be further interpolated into benefits such as overall less traffic noise and lesser amounts of local pollution from traffic.

However, purely considering the tunnel's life-cycle emissions (including traffic emissions) and high construction costs, the tunnel's socio-economical cost/benefit ratio does not seem so sustainable. The mitigating effect of the tunnel is quite modest at a 3.3-8.4% reduction in net yearly GHG-emissions. Although, if considering indirect effects assumed stemming from the tunnel, such as moving traffic out of the city-centre, improved air quality and reduced travel time, the socio-economic benefits revolving around such a project are more complex than what can be covered in this study. This suggests, however, that an in-depth assessment covering, among others, emissions such as PM10 and NO_x, is in order to widen the scope of analysis as performed in this study.

Secondly, among the tunnel alternative designs suggested, there is no clear "winner." Tunnel alt. 2 emits the least per year for both designs, being the shortest in length. The single-shafted tunnel design has the least emissions per year of all tunnel alternatives included due to its lesser amount of materials used due its shorter length and design.

Although, a single-shafted tunnel design is considered less adaptable to changing traffic demands. A double-shafted tunnel design is, for instance, capable of utilizing one lane in each shaft for public transportation. Escaping from a double-shafted tunnel is in addition considered safer, given an excavated escape route between the two shafts. The mitigation the double-shafted tunnel alternatives provide is on the other side close to marginal. There is, however, a significant reduction to be found when assuming a concrete element tunnel lining. The choice of materials is, from this finding, effective in reducing tunnel life-cycle emissions and is something that needs to be considered when having chosen the most apt tunnel alternative.

Thirdly, the tunnel is successive in reducing inner city yearly greenhouse gas emissions. Less traffic routed through the inner city can further be interpolated to less PM10, NOx and other air-quality reducing emissions from vehicles. Interpolated further, this can, among others, lead to health-benefits and improved traffic security for inner-city residents, which are all socio-economic benefits amounting from the project. Trade-offs however, are the release of local emissions stemming from vehicle traffic in the tunnel. The tunnel and its ventilation outlet is projected to be located near residential areas in Byåsen, which may be affected by the release of emissions and road dust. The magnitude of this effect is however not calculated in this study, but the effect can, again, be studied in an in-depth further study of various emissions stemming from the construction of the tunnel.

2. *Regional traffic emissions*

Passenger cars are found to have the largest share of net total traffic emissions per year, with emissions from heavy duty vehicles coming in at second. Petrol cars, being in the majority share of passenger cars, emit the most CO_2-eqs per year. Heavy duty vehicles, assumed to be run on diesel with 3.5% biofuel mixed in, emit a considerable amount of CO_2 relative to their share of AADT. Electric vehicles on the other hand emit a negligible amount of CO_2 with emissions in the range of 5.4-6.3 ton per year, which is 0.011% of total PC emissions and roughly 0.008% of total yearly emissions from traffic.

This is although with electricity assumed to be delivered by the Norwegian electrical grid, consisting mainly of hydropower renewables. If assuming a NORDEL energy mix, yearly EV CO_2-emissions rise to 715-836 ton depending on alternative (Schakenda and Nyland, 2008). This is a considerable leap from emissions around 6 ton per year, but still a small portion of total emissions of traffic, at 1.05% and 1.55 % of passenger car emissions. It should further be noted that for both passenger cars and heavy duty vehicles, the emissions are appropriated for "hot" conditions. The Scandinavian climate does not dictate that engines are operating in optimal hot temperatures throughout the year, and cold start emissions are likely to occur. This may underestimate emissions during seasons such as winter or late fall.

3. *Critical factors for minimizing life-cycle impacts*

It is maintained that, within the regional passenger car stock, the age and engine size of vehicles are important drivers. From scenario testing, the replacement of a majority of older vehicles is the most effective at decreasing yearly traffic emissions of the scenarios presented. Increasing the amount of electric vehicles is also an effective means of reducing emissions.

The share of electric vehicles used in the scenarios presented above might be small, but it the share represents a doubling of the current amount of EVs in the regional PC stock. A further increase could be investigated, but as of 2017 the current legislation on electric vehicles that include incentives such as an exemption from VAT, free parking etc. is in jeopardy. Including a scenario with i.e. an EV share of 10% would seem too uncertain given the short analysis time horizon. (Samferdselsdepartementet, 2014).

This finding, along with the moderate increase in yearly CO_2 emissions employing a Nordic electricity mix, does however support that incentives contributing to a growth in electric vehicle ownership is an important factor for reducing yearly regional transport emissions. Given the rise in Norwegian electric vehicle ownership, unparalleled to any other European country, largely due to the aforementioned incentives, it would seem of importance to continue EV incentives beyond 2017 (Vidal, 2014).

Secondly, the scenarios that simulate a higher average speed and thus clearing effect on congestion show a marginal effect on emissions. These results should be somewhat approached with caution, as this study does not perform microsimulations on the routes included, meaning that driving through different gradients, major accelerations and decelerations is not thoroughly analysed. The effects of an increase in average speeds can be underestimated, however to an unknown degree, and only general conclusions should be drawn from this scenario.

The effects of congestion in the Byåsen tunnel are minimal to moderate as average speed lowers in the tunnel. This is in agreement with Bart and Boriboonsomsin's (2008) findings, although the effect of dissolving congestion is more profound in their report. Congestion can however arise several places along the routes included in the study because of congestion in the Byåsen tunnel, and the effects may indeed be larger than presented in this study. Both these findings, the increase in route average speeds and decline in route average speeds in the Byåsen tunnel, however, suggest that road tolling is a cost-effective measure way of reducing traffic emissions. Road tolling might further stabilize or increase route average speeds by reducing traffic volume. Considering road tolling rather than improving infrastructure is an important factor that should be considered when faced with traffic volumes exceeding road capacity. Furthermore, it should be noted that only the ***vkm_shift2*** scenario comes close to the significant effect road tolling has on reducing emissions. The combined effect of a phasing of newer vehicles, an influx of electric vehicles and the continuation of tolling can however prove to reduce traffic emissions further.

Tolling is, furthermore, considered instrumental in controlling both traffic volume, GHG-emissions and local air pollution. Out of the scenarios tested, reducing traffic volume via tolling and further renewing the regional car stock are the most critical factors. However, it should also be mentioned that implementing measures that severely limit passenger traffic within the city centre along with tolling should suppress traffic emissions even further. Limiting traffic volume on road arteries to and from the city centre should improve traffic safety, which can further encourage alternative transportation measures, such as cycling, and decreasing public transportation transit times. These measures are however not tested quantitatively within this study, although the effect is likely and further qualitatively covered in studies such as (Strand et al., 2009).

Lastly, this study's analysis time horizon is admittedly quite short for such a large project, which still has 5-10 years at the minimum before completion. An analysis time horizon of 40 years is perhaps more apt as this is closer to the project's assumed lifetime, and in line with current practice for infrastructural projects (Longva and Tverstøl, 2014). A longer time horizon implies higher yearly emissions from infrastructure. Higher yearly emissions from infrastructure reduce the benefits from this project, namely the net mitigation of yearly GHG-emissions, compared to the 0-alternative, quite significantly.

If assuming an ATH of 40 years, which means a doubling of yearly emissions from infrastructure, yearly net mitigation is expected be reduced to -970 – 4222 ton CO_2-eq/year. Of the double-shafted tunnel alternatives, only tunnel alternative 2 provides some mitigation. All of the single-shafted tunnel designs do however provide some mitigation. This limits the choice of designs from six to four, with a single-shafted tunnel design assumed to be the most beneficial in contributing to reducing yearly GHG-emissions from infrastructure and traffic. Additionally, the analysis time horizon must be considered a critical factor, as it can increase yearly GHG-emissions in a magnitude comparable to the most effective scenario for reducing traffic emissions (***vkm_shift2)***.

Furthermore, increasing the analysis time horizon to 60 years decreases the benefits of the project even further. Of the six available alternatives, it is only alternative 1 and 2 of the single-shafted tunnel alternatives that can provide a small margin of mitigation. The general trend of increasing the analysis time horizon is a decreasing margin of potential yearly net GHG-mitigation, as a larger share of life-cycle infrastructure emissions are allocated to the project. However, increasing the analysis time horizon does increase the uncertainty of the results, and furthermore the uncertainty of scenarios that look further than 20 years into the future.

The shrinking mitigation potential, when applying a 40 or 60-year analysis time horizon, does further question the benefits of the Byåsen tunnel project, opposed to, for instance, allocating money towards improved public transportation and intra-city cycling pathways. Furthermore, an increasing amount of electric vehicles, or even hydrogen vehicles, can in 40-60 years' time decrease yearly emissions from traffic even further. The combined effect of doubling the amount of electric vehicles and the influx of newer vehicles do provide mitigation of emissions in the same range as the tunnel provides. These findings speak for the 0-alternative, as mitigation of traffic emissions is in fact possible to a similar degree as the tunnel provides.

However, considering that the project is successful in reducing inner city traffic, by routing traffic through the tunnel, the project can contribute to socio-economical benefits like improved air quality, reduced traffic noise, traffic safety and otherwise improved living conditions, which may contribute to inner city densification.

4. *The effects of road tolling*

Tolling is in this study proven instrumental for not only mitigating traffic emissions, but also further helping Greener Trondheim obtain its goals. The 2018 target, where year 2008 traffic emissions are targeted to be reduced by 20% will be expired by the time of the tunnel's construction. It is considered likely that Greener Trondheim will not be able to reach future targets of reduced traffic emissions by only constructing the Byåsen tunnel.

Road tolling is instrumental for lowering traffic volume, and other side effects from reduced travel costs, such as increased travel-time through slow-moving traffic and congestion. The provided traffic data with no tolling stations present do also show a slight increase in traffic in the road artery travelling through Trondheim's city centre. This is at odds with Greener Trondheim's project goals, such as reducing traffic noise and measures intended to route traffic away from the inner city road arteries.

The significant effect tolling has on suppressing traffic volume could perhaps to be attributed to latent induced demand and price elasticity – with a quite significant increase in traffic volume when the price of each travel is relaxed (Odeck and Bråthen, 2008). This is largely in agreement with this study, as the traffic volume increases in nearly each route without tolling. The lack of a non-tolled 0-alternative makes comparison between non-tolled tunnel alternatives non-relevant, but it can be seen that a non-tolled tunnel will closely rival this study's tolled reference alternative.

Thirdly, the increase in traffic through the city centre (without toll) is an interesting point for further study. A study that can analyse the effect the tunnel has on reducing e.g. PM10, PM2.5 and NO_x emissions in the city centre is most welcome, and the study will further assess whether there are any problem-shifting effects induced by the project. The methodology developed for this study is able to contribute to the assessment of strategies for reducing traffic emissions and improving air quality. Traffic analyses and life cycle assessment, in combination, should contribute to future emission targets and strategies, highlighting the importance of various measures. This is especially relevant in light of IPCC calls for mitigation strategies within the traffic sector of a region or nation.

If available, scenarios that present the outcome of implementing traffic control measures, such as tolling, should be implemented in assessments of early-phase projects. Politics, on a local level, are susceptible to decisions based on whim and voter majority. Removing tolling stations along with improving infrastructure as means for reducing travel time and costs have for years been a rallying cause for certain political parties. However, as this study shows, reducing travelling costs and travel time does trigger induced demand, limiting the intended effect of the project and progress towards achieving municipal goals within Greener Trondheim.

Moreover, a sustainability impact analysis (SIA) could further be implemented with this study's results in order to gain a wider picture on the tunnel's effect on traffic and means of travel. A life cycle assessment alone is not wide enough in its gaze to uncover effects from constructing infrastructure outside of GHG-emissions. The LCA could however be a part of a SIA, which could further uncover direct and indirect societal and economic benefits of the project.

Lastly, traffic volume is after all a critical factor when it comes to reducing traffic emissions. Questions should be raised on whether constructing urban infrastructure designed for vehicle travel is a sound strategy looking 10-20 years into the future. The effects of increasing the price of travel, as seen in when removing tolling stations, are quite significant. Along with the diminishing mitigation of yearly GHG-emissions, when increasing the analysis time horizon, it can therefore be argued that the answer to reducing yearly traffic emissions might after all lie within the price of travel, and further the attractiveness of traveling by car versus by bike or public transportation. More research is, however, in order to unravel possible positive and negative effects of the Byåsen tunnel project.

6.1. Strengths and weaknesses

The life cycle assessment of the Byåsen tunnel is performed using the early-phase model LICCER, enabling direct comparison between other assessments using the same model. This can be considered a strength of this study, as comparison between studies of infrastructure is typically considered challenging due to different system boundaries, service life times and analysis time horizons. Comparison between past assessments of infrastructure will remain challenging, however.

The LICCER model inventory, as well as the life cycle inventory compiled for this study, consists of empirical NPRA data on material consumption and material consumption dimensioned in line with NPRA methodology on road and tunnel construction. With the abundance of empirical data within the LICCER model, this strengthens its robustness. However, the project is still in its early-phase, and no project-specific material consumption data has been made available during the workings of the study. This increases the level of uncertainty in both the calculated material consumption and net yearly emissions from infrastructure. Emissions from production is, for instance, found to fluctuate around 2000 ton CO_2-eq/year by choosing a different tunnel lining. The LICCER model, however, is nevertheless an early-phase model tool designed for comparison between project designs and concepts.

Project uncertainty is typically at its peak in the early-phase, and the LICCER model can contribute to selecting the most favourable design before an in-depth analysis of the tunnel design can commence. The ease of using the LICCER model makes updating yearly emissions from infrastructure, for use in further studies, easy to correct.

Data included in the traffic emissions model is founded in methodology from a large research project, with numerous testing cycles of engines from a variety of manufacturers. Although the ARTEMIS model is based on a large number of tests (empirical data), some assumptions are applied throughout their project. Relevant to the context of this discussion is in particular their assumptions on unchanged engine technologies between Euro 5 and Euro 4 vehicles as well as improvements to future engine technologies. It has not throughout this study been conducted a literature study that investigates these assumptions.

(Joumard et al., 2007) have however based their assumptions on literature data and emission trends. It is further assumed that their literature data and expert knowledge cements the reliability of their assumption for use in this study.

Moreover, the regional passenger car stock matrix requires some aggregation and assumptions on popular vehicle model and manufacturers within the region. This is a slight weakness of this study, as manual sorting of manufacturers, although referenced against statistical data, can give leeway for systematic errors or an uneven distribution of engine volumes within the region. In this study, the passenger car manufactures and models represent the distribution of engine volume, which in turn dictates fuel consumption – found to be an important driver of traffic emissions within the system. Future use of the methodology described in this study, employed to calculate passenger car emissions, should, if available, include statistical data of regional engine volume statistics for optimal reliability.

Steady-state fuel consumption over the entirety of the routes included is not ideal in terms of comparability with real-word activity. (Bart and Boriboonsomsin, 2008) finds real-world activity traffic emissions, expressed as g CO_2/mile, to be about 100 g CO_2/mile higher than steady state emissions travelling at the same speed. This indicates that the calculated traffic emissions are somewhat underestimated, although this can in some ways be considered a methodological flaw or unavoidable when employing a macro emissions model. A micro emissions model can represent driving patterns more precisely, albeit typically requiring a traffic model, such as Aimsun. Cold start emissions are in addition not accounted for, which may underestimate the yearly emissions from traffic to some degree, which can be considered a slight methodological weakness.

The major strength of the methodology applied for calculating traffic emissions within this study however, is the possibilities the model provides for scenario analysis. This allows testing the phasing of older vehicles and the influx of vehicles with a variety of engine technologies and volumes. Moreover, the model does provide results that are more reliable rather than, for instance, fuel consumption parameters found in various literature and averaged over an entire vehicle stock. Comparison between assessments of infrastructure can although be found difficult, as a relatively large amount of routes is assumed affected by the excavation of the tunnel.

Some studies might find that emissions from traffic are less than what is portrayed in this study due to, among others, different system boundaries and vehicle stock composition. However, the model's simplicity should further strengthen the reliability of the results presented in this study.

Input data for both the LICCER model, and in part, the traffic model is outlined throughout, making it possible to replicate the methodology and results for other users. Traffic volume data is withheld however, which may make creating exact replication of the results found within this study challenging.

The emission factors employed throughout this study might not be 100% correct. Emission factors are generally estimates, and emissions related to, among others, the processing of materials are typically industry averages or represent foreign technologies that may not reflect domestic technology. Biofuel, for instance, is typically represented as carbon-neutral; the carbon emitted to air when burned is offset by plant absorption during growing.

Within the LICCER module, biofuel us assigned a emission factor of 0.690 kg CO_2-eq/l, based on a study done on ethanol production within the Norwegian company Borregaard (Modahl et al., 2009). The emission factors of biofuel, petrol and diesel may indeed vary over different courses of the year, and thus the results will not be a 100% correct. However, the factors are applied equally to each alternative assessed in this study, and it is the overall emissions and the emission trends when i.e. removing tolling that are the highlights of this study.

Whether or not the routes included can represent the changes in traffic from constructing the tunnel is another assumption worth discussing. Within life cycle assessment literature, there is no definite answer to how changes in traffic and traffic emissions in general should be allocated to the element undergoing assessment. The routes of traffic assumed affected by the tunnel however, are included based on project documents and traffic analyses verifying the tunnel’s influence on traffic volume in the area. This enables the highlighting of regional traffic emissions, and further the changes in traffic emissions from improving infrastructure. It is from these findings possible to maintain that assessments employing traffic analyses and LCA methodology should be considered a mainstay in future infrastructure life-cycle assessments.

7. Conclusions

Using regional car stock and traffic analysis data, along with the early phase LCA tool LICCER, this study assesses the impacts from the life cycle phases of a proposed tunnel in Trondheim, Norway, with six alternative designs and the changes in emissions from traffic resulting from its completion. The study's traffic inventory employs fuel consumption data from the ARTEMIS project and the Python open source database SEMBA. Results from the study highlight the importance of including traffic emissions and changes in traffic following the proposition of new infrastructural projects in LCA. Of the findings presented in the study, the following are highlighted:

- The project's environmental impacts are between 73.738 – 77.851 thousand ton CO_2-eq/year, depending on tunnel design, and 80.516 thousand ton CO_2-eq/year for the reference scenario, with no tunnel constructed. This shows a potential reduction of 2665-6778 ton CO_2-eq/year from a reference alternative, which should help towards Greener Trondheim obtaining their politically approved goals. However, assuming an analysis time horizon of 40 years, this limits net mitigation of yearly GHG-emissions to -970 – 4222 ton CO_2-eq/year and further limits the choice of tunnel designs that prove mitigation from six to four. The mitigating potential of the tunnel is, furthermore, seen to decrease along with an increasing analysis time horizon.
- This study does in addition explore the impact of removing tolling stations currently found in the greater Trondheim area. Simulating a removal of tolling stations increased traffic volume on nearly every route included. Yearly net GHG-emissions are shown to increase by 7715-8040 ton CO_2-eqs, and a 10% increase in traffic emissions from tolled tunnel alternatives is expected.
  The road tolling stations are further maintained to be instrumental towards achieving Greener Trondheim goals such as reduced inner city traffic and air quality.
- Several scenarios are tested in the study, with assumptions on phasing of older vehicles and engine technology as well as scenarios that test the effect of decreasing and increasing average speed on select routes. Along with road tolling, the phasing of older vehicles and improving engine technology is the most effective. Assumed severe congestion in the Byåsen tunnel alone could increase total yearly GHG-emissions from traffic with at least 24 ton CO_2-eqs. A continued influx of electric vehicles is beneficial in reducing yearly traffic emissions. Doubling the amount of electric vehicles stimulates an 1105-ton decrease in GHG-emissions/year.
- Lastly, it is maintained that none of the scenarios could match the mitigating effect currently present in the region of analysis, namely "Bomringen" – the road tolling stations.

8. Recommendations for future work

Based on the findings in this study, it is recommended to present future research more closely related to Greener Trondheim's project goals. The following studies, relevant to the context of Greener Trondheim are recommended:

- A study assessing changes in local air emissions (NO_x, PM10, PM2.5 etc.) in Trondheim's city centre from traffic, following the construction of an infrastructural project.
- A study assessing changes in street-level traffic emissions, using traffic micro-simulation, following the construction of an infrastructural project. The study will assess changes in traffic emissions after simulating dissolving congestion and the change in driving (acceleration) patterns.
- A study assessing strategies towards a 20% reduction of year 2008 traffic emissions towards 2018. The study can, among others, include traffic mitigation strategies and improvements in traffic safety and infrastructure.
- Developing a model, based on a combination of SEMBA and GIS, to assess changes in traffic emissions after constructing new infrastructure or i.e. closing select routes of traffic.
- A SIA assessing indirect and direct effects of constructing the tunnel. The framework of the SIA study could further be streamlined to perform assessments of other projects within Greener Trondheim.

On a more general level, outside of Trondheim and Greener Trondheim, recommended to emphasize future studies or improvements to the following:

- The SEMBA database, and in particular the passenger car module, should be updated to function in the same manner as the heavy duty vehicle emissions module. This is however something that can be done on a user basis, as SEMBA is an open-source model.
- Developing a dynamic material flow analysis model that can simulate the inflow of vehicles with improved engine technologies. The model can be integrated with SEMBA or a user-constructed model, utilizing ARTEMIS or any other fuel consumption model.

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«Fremskritt, hva er det? At vi kan kjøre fortere på veiene? Nei, fremskritt det er legemets nødvendige hvile og sjelens nødvendige ro. Fremskritt er menneskets trivsel.»

- Knut Hamsun, Festina lente.

Part II: The article

Life Cycle Assessment of the Byåsen tunnel in Trondheim, Norway – assessing emissions from traffic and infrastructure

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Abstract

Context:
The Byåsen tunnel is a tunnel proposed by the Norwegian Public Roads Administration (NPRA), and an infrastructural element in an environmental programme (Greener Trondheim) initiated by the Trondheim municipality, Norway. Among the main goals is an overall decrease in CO_2 emissions from traffic.
Objective:
This study assesses the environmental impacts (expressed in greenhouse gases) induced by the construction of the tunnel and emissions from traffic in operation. Additionally, the study gauges its coherence with goals set in the Trondheim municipality's environmental programme.
Method:
The study utilizes LCA methodology, including regional traffic data and parameters pertaining routes travelled by vehicles included in the study.
Results:
The project's environmental impacts are between 73.738 – 77.851 thousand ton CO_2-eq/year, depending on tunnel design (length), and 80.516 thousand ton CO_2-eq/year for the reference scenario, with no tunnel constructed. Net GHG-emissions related to the excavation and operation of a tunnel in excess of 2 km proves to be between 3106- 5509 ton CO_2-eq/year depending on design, which is about 6% of yearly emissions from traffic. A simulation of traffic volume (after excavating the Byåsen tunnel) without tolling reveals an increase of 7715-8040 ton CO_2-eqs/year. This is a 10% increase in traffic emissions from tolled tunnel alternatives.
Conclusion:
The results found in this study shows that the construction of the Byåsen tunnel leads to a net decrease of 2665-6778 ton CO_2-eq/year. That is a net decrease of 3.3-8.4% over the reference alternative. This study does also show the importance of including traffic in operation when assessing infrastructure as well as the significant effect tolling stations has on traffic volume and yearly GHG-emissions.

1. Introduction

Transport emissions was in the year 2010 responsible for 23% of the world’s energy-related greenhouse gas (GHG) emissions, amounting to 6.7 Gt CO_2. In 2010, the final energy consumption used for transport worldwide reached 28%, where around 40% was utilized in urban areas (R. et al., 2014). The Intergovernmental Panel on Climate Change (IPCC) maintains that “[w]ithout aggressive and sustained mitigation policies being implemented, transport emissions could increase at a faster rate than emissions from any other energy end-use sector and reach around 12 Gt CO_2eq/year by 2050” (R. et al., 2014 p. 603). Such a potential increase supports the relevance of measures for mitigating transport emissions, both on a national and local level.

Greener Trondheim is an intra-municipal infrastructural transport plan proposed and adopted by the Trondheim municipality. It aims at mitigation of traffic emissions through 10 politically approved goals (Trondheim Bystyre, 2008). In the context of this study, the following goals are found to be most relevant:

- Reducing travel by passenger car and a 20% cut in CO_2-emissions from traffic in 2008 to 2018
- Reducing NO_x and particulate matter emissions.
- Reducing traffic noise.

Measures adopted for reducing traffic emissions employed are, among others, increasing the length of cycle pathways, increasing the frequency of travels by public transport and infrastructural projects aimed at reducing congestion and reducing travel length by car.

Furthermore, the municipal authorities wish to relieve traffic congestion and reduce traffic emissions through constructing a main road network that can route traffic away from low capacity road arteries found in the city centre and roads surrounding it. As a part of this project, the Trondheim municipal and the Norwegian Public Roads Administration (NPRA) are currently working on a zoning plan that incorporates a tunnel towards Byåsen in the western Trondheim area. The NPRA estimates the cost of the Byåsen tunnel to be between 0.8 – 1.4 billion NOK depending on design (Statens Vegvesen, 2012).

The tunnel connects with the proposed new Sluppen Bridge, of which the older version has been a cause of congested traffic for decades due to its low capacity. Congestion has been especially prominent during rush hour times, causing travellers to choose a variety of routes to circumvent the traffic jammed bridge. To the authors’ knowledge, the environmental impact of the tunnel has not so far been assessed.

Traffic analyses has, however, been performed by expert NPRA personnel for the following scenarios:

- No tunnel constructed (reference scenario)
- Tunnel constructed, with tolling stations present
- Tunnel constructed, no tolling stations present

To explore the environmental impacts of the tunnel, this study will employ LCA methodology to assess yearly CO_2-emissions before and after construction of the tunnel. The LCA inventory includes NPRA provided traffic data for the above-mentioned scenarios and NPRA handbooks on road and tunnel construction. This permits for, in the opinion of the authors, a more reliable LCA than is common within the literature.

Moreover, standard LCA methodology utilized for assessing GHG-emissions from early-phase projects commonly employ average values for fuel consumption. Other studies, such as (Treloar et al., 2004) include average energy use or fuel consumption assumed valid for an entire region's vehicle stock. A lesser amount of LCA of infrastructure include the actual use of the infrastructural projects assessed, mostly focusing on the environmental impact from constructing and operating a project over a given time.

Improving infrastructure typically leads to an increase in traffic emissions through induced demand or decreasing it by shortening the length travelled. This study will show the importance of including traffic emissions from constructing new infrastructure. Additionally, it will show how LCA methodology can assess the environmental impact of infrastructural projects within Greener Trondheim, when combining early-phase LCA tools with detailed traffic data, regional vehicle stock data, local gradients and vehicle speeds. More precisely, the study aims to address the following questions:

1. Using LCA methodology, what are the net life cycle environmental impacts (expressed in GHG emissions/year) of the Byåsen tunnel?
2. Compared to a reference scenario with no tunnel, how will the Byåsen tunnel affect yearly GHG-emissions from traffic?
3. What effect will removing local road tolling stations have on yearly GHG-emissions from traffic?
4. What are critical factors for minimizing life cycle environmental impacts?

2. Method

This study is a streamlined LCA aimed at evaluating the environmental performance of a project in its early phase. It considers greenhouse gas (GHG) emissions in CO_2-equivalents resulting from the production of materials required for excavating each tunnel design, the construction phase and the operation and maintenance (O&M) phase. The Life Cycle Considerations of EIA of Road Infrastructure (LICCER) model has been used to calculate GHG-emissions from each life cycle phase (Brattebø et al., 2013b). Tunnel design parameters are gathered from the NPRA's handbooks on tunnel and road design in Norway (Vegdirektoratet, 2014b, Vegdirektoratet, 2014a, Vegdirektoratet, 2014c). Traffic emissions are calculated based on fuel consumption and the associated CO_2-emissions from the production of fuel and the combustions of hydrocarbons as included in the LICCER LCA tool's database (Brattebø et al., 2013a). Regional traffic data is supplied by the NPRA. A select amount of routes in the Byåsen and western Trondheim, traveling to the Byåsen area are assumed affected by the construction of the tunnel. These routes have been included in order to calculate traffic volume in a 0-alternative and after the tunnel's construction.

2.1. Goal and scope of the study

The purpose of the study is to evaluate the environmental impacts of excavating and operating a tunnel using an early phase model (LICCER) and the following changes in traffic volume after its construction. It further aims to evaluate the influence of tunnel design, shifting traffic from included routes in the study through a tunnel and the effect of tolled vs. non-tolled roads measured in GHG-emissions. The system boundary for each tunnel design is tunnel length and a roundabout at the outlet. Each tunnel is assumed to have a lifetime of 100 years, whereas the analysis time horizon of the study is set to 20 years.

There are six tunnel designs included in the study, whereof half of the tunnel designs are single/double shafted tunnels. All tunnels have a 5% incline. The length of each tunnel is 2510 m for tunnel alt. 1, 2300 m for tunnel alt. 2 and 2850 m for tunnel alt. 3. The 0-alternative contains a "synthetic route," given no tunnel currently present. The route contains an inventory for O&M compiled from NPRA handbooks and personal communication with expert NPRA personnel (Vegdirektoratet, 2014d, Vegdirektoratet, 2014c).

Fuel consumption matrices included in the traffic emissions model is constructed from fuel consumption data in the SINTEF Emission Module Based on ARTEMIS (SEMBA) for heavy duty vehicles (HDV) (Levin, 2012). Fuel consumption (FC) and CO_2 emissions per km is gathered and corrected for gradient, using calculation methodology and coefficients from the ARTEMIS project (Joumard et al., 2007). The average gradient and speed limits for each route is from Vegkart, an NPRA developed online map service (Statens Vegvesen, 2015b). Regional vehicle stock data is collected from Statistics Norway and Opplysningsrådet for Veitrafikken AS (Statistisk Sentralbyrå 2014, Opplysningsrådet for Veitrafikken AS, 2015).

Average speeds for each route is assumed to be an average of each route's speed limits, where data on actual average speeds has not been available.

Actual measured average speeds is supplied by the NPRA for three of seven routes included in the 0-alternative (Statens Vegvesen, 2015a). The macro traffic emissions model used in this study calculates fuel consumption by vehicle age (EURO-class), average speed, fuel type and gradient. For HDVs, fuel consumption is also calculated from total vehicle weight, vehicle category and load (0-100% load). This study's HDV inventory only contains the vehicle category rigid truck. Below is a summary of route specific parameters included in the traffic inventory.

Table 11: Parameters applied to each route used for constructing a traffic emissions and inventory and subsequently calculating traffic emissions.

Route #	Length (km)	Curvature (% incline)	Avg. Speed (km/h)	Share of HDV (% of AADT)
1	7,40	0,25	58,46	10
2	6,50	1,44	45	9
3	5,20	1,91	45	9
4	5,50	1,91	45,00	7
5	6,60	1,69	50,00	7
6	5,20	0,02	50,00	10
7	7,30	0	40,00	11
Tunnel alt. 1	2,51	5,00	60,00	7
Tunnel alt. 2	2,30	5,00	60,00	7
Tunnel alt. 3	2,85	5,00	60,00	7

The share of electric vehicles (EV) is 2.38% and the split between fossil fueled vehicles is 46% diesel and 54% petrol for all routes (Opplysningsrådet for Veitrafikken AS, 2015). 3.5% biofuel is assumed to be mixed in both fuels (Statens Vegvesen, Unknown year).

2.2 Functional unit

The functional unit is defined as "a road system with a simulated AADT that offers traffic between Sluppen and Byåsen over a time horizon of 20 years."

3. Theory

This section will provide this study' theoretical framework and a number of LCA case studies found relevant to the context of this study.

3.1. LCA of infrastructure

(Hammervold, 2014) surveys a number of infrastructure case studies using LCA methodology in "Towards a greener infrastructure". She discovers energy intensive materials such as concrete, rebar, steel asphalt etc. inducing the most impact noted in GHG emissions. Hammervold emphasizes the need for decisions on the reduction of environmental impacts in the early-phase of projects.

(Treloar et al., 2004) proposes in "Hybrid Life-Cycle Inventory for Road Construction and Use" a hybrid LCA method that utilizes input-output data in order to fill gaps commonly left in LCA inventories. Their case study includes eight road types with a length of 5 KMs in a rural environment, as well as vehicle manufacturing, operation and maintenance. The study includes all life-cycle stages but end-of-life, and finds the emissions from road construction initially substantial, but eventually overshadowed by the use and maintenance of vehicles. Their traffic in operation inventory includes an assumed average vehicle energy use per km (GJ/100 km) and a vehicle park ratio of 90% PC and 10% HDV.

3.2. LCA of tunnels

(Huang et al., 2013) analyses the life cycle impacts of a standard Norwegian road tunnel in "Life Cycle Assessment of Norwegian Standard Road Tunnel," where they find that the standard Norwegian tunnel is a 3 km long, 9.5 m wide rock excavated tunnel. The construction phase is found to be the largest contributor, where the production of materials is the most dominant contributor to their included impact categories. They further state that over its lifetime of 100 years, the tunnel has an impact of 13 ton CO_2-eq per m of tunnel.

(Hammervold, 2014) maintains in her previously mentioned doctoral thesis that the average life-cycle impact from tunnel construction and operation in CO2-eqs per m is 337 kg, with a tunnel lifetime of 100 years and an analysis time horizon of 40 years. She further discovers that a tunnel with a similar design to (Huang et al., 2013)'s studied tunnel had an impact 570 kg CO2-eq per m.

3.3. LICCER

The LICCER model contains empirical data gathered from the NPRA's EFFEKT model, which is an Excel model utilized for calculating CO_2-emissons and energy use from infrastructure projects in Norway (Straume, 2011). LICCER is an early-phase tool used to analyse GHG-emissions and cumulative energy consumption for a given road project during all life-cycle stages, and aims to support decision making when faced with several design alternatives or concepts. The model can include segments such as a new road in the open, bridges, aqueducts, tunnels and it supports analysis time horizon (ATH) and superstructure service lifetimes. The model includes a simplified calculations routine that can examine traffic emissions during a project's use phase utilizing fleet average FC. It supports comparison between three design alternatives and a reference alternative (Brattebø et al., 2013b). The model is tested against Norwegian (O'Born et al., 2013) and Swedish (Liljenström et al., 2013) conditions.

3.4. The ARTEMIS project

The ARTEMIS project is a European research project aiming at providing a harmonized methodology that can estimate pollutants from transport emissions at a national and international level. Forty research laboratories have been involved in designing applications of the project, such as emission inventories, which this study utilizes. The emission inventories for, among others, CO_2 have been compiled by testing 102 engine maps for Euro 0 to Euro 3 for HDV, which enables a compilation of averaged emissions up to Euro 5 engine technology (André et al., 2009). The passenger car and heavy-duty vehicle emission model (PHEM) is developed from test cycles within the project. A light vehicle emission inventory is compiled from about 3500 test runs on more than 150 vehicles. This has enabled the construction of several models, such as a discrete model that accounts for traffic situations (dense, free-flowing etc.) and continuous models using driving behaviour through average speed, which this study utilizes (Joumard et al., 2007).

3.4.1. Light vehicle emission modelling within ARTEMIS

(Joumard et al., 2007) compiled the ARTEMIS report "Emission factor modelling and database for light vehicles - Artemis deliverable 3," which describes the testing and validation routines performed in order to arrive at a set of emissions models. Of interest to this study is in particular their average speed hot emissions model.

The average speed emissions model calculates average hot emissions from speeds in the range of 5 km/h to 135 km/h. Two average speed models are presented in their report. This study utilizes the second model, which employs reference test pattern data.

Emission data from their database is here averaged against test patterns compiled for their traffic situations model (Joumard et al., 2007). The model employs an emission function calculated by regression between reference test pattern (RTP) emission factors, which are expressed by average speed. The emission factors calculated by the polynomial emission factors cover, among others, CO_2, HC, NO_x for pre-Euro up to Euro 4 petrol and diesel vehicles. Reduction factors for future vehicles are also suggested in the report. Their general formulae for calculation of emission factors for a second order polynomial function is:

$$\text{Emission factor}\left[\text{g / km}\right] = \text{a}0 + \text{a}1\text{V} + \text{aV}^2$$

Where V = average speed and a_0, a_1 are coefficients (Joumard et al., 2007 p. 179). This formula is further adopted for calculating PC hot emissions in this study. This model calculates g CO_2/km directly using a carbon balance equation, making it necessary to convert from g CO_2/km to l fuel/km for this study. The following formulae has been applied for both diesel and petrol as per (Joumard et al., 2007 p. 204)

$$C_{CO_2/l,i} = \frac{m_{CO_2}}{v_{fuel}} = \frac{44.011}{12.011 + 1.008 * r_{H/C_i}} * \rho_{fuel,i}$$

Where r_{H/C_i} = the carbon/hydrogen ratio, which is 1.8 for petrol and 2 for diesel. $\rho_{fuel,i}$ is 0.766 kg/l for petrol and 0.8414 kg/l for diesel. The calculated g CO_2/l for each fuel type is employed to calculate FC/l by dividing g CO_2/l over the carbon mass of each fuel.

3.4.2. Heavy duty vehicle modelling within ARTEMIS

Heavy duty vehicle emission factors and fuel consumption is within the ARTEMIS project estimated by the PHEM model, which uses driving cycles to calculate the amount of energy required to move the vehicle, including transmission losses. A gearshift model calculates engine speed, and emissions are interpolated from a steady state emissions map given the vehicles calculated power and engine speed.

ARTEMIS does also provide a set of average speed functions that describe emissions or fuel consumption as a function of average speed, vehicle type, gradient and loading. The average speed functions are documented in (Boulter and Barlow, 2005). Heavy duty vehicles are in addition separated into two categories: rigid and truck-trailer (Levin, 2012).

3.5. SEMBA

SEMBA is an open-source Python module database containing an inventory of fuel consumption and emission functions for HDV, PC, light duty vehicle, rail and sea transport. Hot emissions and fuel consumption data is built upon ARTEMIS parameters and functions pertaining to each vehicle category. The modules within SEMBA employ the ARTEMIS parameters and functions to calculate emissions such as CO_2 and NO_x. SEMBA is created as a part of Thomas (Levin, 2012) doctoral thesis "Developing a New Emission Model for Freight Transport." In order to calculate, for example, HDV fuel consumption, the user plots a vehicle ID, which pertains to vehicle category, euro class and weight, speed, gradient, load and emission component or fuel consumption. In this study, SEMBA is used to calculate HDV fuel consumption as well as adopting coefficients for calculating fuel consumption for passenger cars using the ARTEMIS average speed model's polynomial functions. (Levin, 2012) did further document that using the HDV average speed functions as built-in in SEMBA should yield plausible emission and energy consumption results for vehicles operating in Norwegian driving conditions. It is further assumed in this study that this is also valid for passenger cars.

3.6. GHG mitigation effects of improving infrastructure

The report "Miljømessige konsekvenser av bedre veger" by (Knudsen and Bang, 2007) maintains that a GHG mitigating effect is expected from constructing new roads and otherwise improving infrastructure. The authors employ the traffic microsimulations model Aimsun in their report to calculate traffic emissions. Aimsun includes data from the ARTEMIS project on a number of prototypical road sections, containing a reference and an "improved" alternative. Their report finds that reduction in GHG emissions is mainly attributed to a reduction in congestion and steadily flowing traffic.

The report does, however, state that increasing the capacity of the road sections can lead to growth in car traffic, and a decrease in i.e. public transportation. The report does although not state the magnitude of these effects. An increase in car traffic is maintained to most likely occur in urban areas where congested traffic is most common, due to a larger reduction in travel time.

Another Norwegian report, "Gir bedre veger mindre klimagassutslipp?" by (Strand et al., 2009) in part contradicts Knudsen and Bang's (2007) report. (Strand et al., 2009) maintain that the growth in traffic volume and change in mode of traffic will outweigh the mitigating effect of steadier flowing traffic. The researches do also state that the mitigating effect of improving stretches of road are marginal, as the speed limit heighten to 80 km/h with an improvement in road standard. This is in an interval above optimal speed in terms of fuel consumption (Joumard et al., 2007).

(Bart and Boriboonsomsin, 2008) examines the short-term impacts from reducing congested traffic in their journal article "Real-world carbon dioxide impacts of traffic congestion," where the authors present that traffic emissions (resulting from congestion) can be reduced by three different strategies. Among the strategies are ramp metering, speed management techniques and variable speed limits.

The report does however; state that this effect is specific to local fleet mix and time spent in congested traffic. The researchers do also highlight a misalignment between steady state vs. real world activity (decelerations and accelerations included), where they maintain that CO_2-emissions/km were higher when considering real-world activity. Their discussion of real world activity vs. steady state prompted the inclusion of actual measured average speeds for routes in Trondheim where this was available, and further making these routes suitable for scenario analysis in this study.

4. Results and findings

This section provides an overview over the GHG emissions resulting from the Byåsen tunnel's life cycle stages and traffic in operation for all alternatives included in this study. The section does further address the research questions posed in the introduction. Detailed results are presented according to their magnitude of impact. The total environmental impacts of the included alternatives are presented below as a baseline for the presentation of results from scenarios, which is presented further below. Data on a non-tolled 0-alternative is not available and is not presented in this study.

4.1. Baseline results and findings

Table 12: Summary of accumulated GHG-emissions over the ATH (20 years) for all tolled tunnel alternatives.

			Double-shafted tunnel			**Single-shafted tunnel**		
		Alt. 0	**Alt. 1**	**Alt. 2**	**Alt. 3**	**Alt. 1**	**Alt. 2**	**Alt. 3**
Infrastructure	ton CO2-eq/year	169,2	5 217,5	4 732,5	5 509,3	3 432,4	3 106,4	4 063,6
Traffic	ton CO2-eq/year	80 347,0	71 230,5	70 632,0	72 341,9	71 230,5	70 632,0	72 341,9
Net total	ton CO2-eq/year	80 516,1	76 447,9	75 364,4	77 851,2	74 662,9	73 738,4	76 405,5
Net total (Δ from alt. 0)	Δ CO2-eq/year		-4 068,2	-5 151,7	-2 665,0	-5 853,2	-6 777,8	-4 110,7

The above presented table shows that both the tolled double-shafted and single-shafted tunnel alternatives provide some mitigation of GHG-emissions over the analysis time horizon, compared to the reference alternative (Alt. 0). Tunnel alternative 2 provides the largest mitigation of CO_2-eqs/year, due to its shorter length (2.3 KMs).

Of the two design alternatives, the single-shafted tunnel alternative 2 has the largest negative Δ over the reference alternative by a small margin of 1626 ton CO_2-eq/year. The 0-alternative has the least CO2-eq/year resulting from infrastructure, as its inventory only contains operation and maintenance for its "synthetic route", which is 1 km in length. Moreover, comparing the yearly GHG-emissions from infrastructure, the emissions are quite small in comparison to emissions from traffic, which are considerable in magnitude. The emissions from infrastructure amount to about 6% of the net total emissions/year.

Infrastructure is here expressed as a collective term that includes production, construction, operation & maintenance. The net total from a situation with tunnel will, depending on tunnel alternative, amount to a net saving of 3.3-8.4% from the 0-alternative. The reductions in emissions per year is mainly due to a large amount of AADT routed through the tunnel, which again replaces traffic from other longer routes previously used by vehicle users to avoid congested traffic in the Sluppen area. Traffic volume is reduced, given the shortcut the tunnel provides for vehicles travelling to the Byåsen area.

Table 13: Summary of yearly greenhouse emissions/year without tolling stations. The 0-alternative is not included due to lacking data.

		Double-shafted tunnel			**Single-shafted tunnel**		
		Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 1**	**Alt. 2**	**Alt. 3**
Infrastructure	ton CO2-eq/year	5 217,5	4 732,5	5 509,3	3 432,4	3 106,4	4 063,6
Traffic	ton CO2-eq/year	79 059,4	78 347,2	80 382,1	79 059,4	78 347,2	80 382,1
Net total	ton CO2-eq/year	84 276,9	83 079,6	85 891,4	82 491,8	81 453,6	84 445,7
Net total (Δ from tolled tunnel alts)	Δ CO2-eq/year	7 828,9	7 715,2	8 040,2	7 828,9	7 715,2	8 040,2

Removing tolling stations increases GHG-emissions by 7715 - 8040 ton GHG-emissions per year when compared to a situation with tolled tunnel alternatives. This amounts to a 10% increase in yearly traffic emissions over the tolled tunnel alternatives.

The delta is calculated as the increase from each tunnel alternative; non-tolled tunnel alternative minus tolled tunnel alternative. Each tunnel alternative edges onto the GHG-emissions per year as seen in the 0-alternative, with alt. 3 surpassing it with 5375 ton GHG-emissions/year. It should however be noted that comparing such a situation directly is not necessarily a fair comparison, as a non-tolled 0-alternative has not been provided.

The increase in emissions per year is due to a relatively large increase in AADT on nearly all involved routes, and for the proposed tunnel in particular. Due to the increase in traffic volume on the majority of the routes, this has led to a number of scenarios that aim to investigate the effects of reduced average speeds throughout the day due to an assumed more severe congestion along some of the included routes. A breakdown of yearly traffic emissions is presented in *table 14*.

Table 14: Yearly GHG-emissions from traffic for all tunnel alternatives.

	With toll				Without toll			
	0-alternative	Tunnel alt. 1	Tunnel alt. 2	Tunnel alt. 3	Tunnel alt. 1	Tunnel alt. 2	Tunnel alt. 3	
PC, petrol	28 780,0	25 610,1	25 407,5	25 986,4	28 617,2	28 376,1	29 065,0	ton CO2-eq/year
PC, diesel	25 701,1	22 643,2	22 466,1	22 972,2	25 164,9	24 954,1	25 556,4	ton CO2-eq/year
EV	6,3	5,5	5,4	5,5	6,1	6,0	6,1	ton CO2-eq/year
HDV	25 859,6	22 971,7	22 753,0	23 377,8	25 271,2	25 010,9	25 754,5	ton CO2-eq/year

Emissions from passenger cars are the largest, ranging from 47 874 – 54 621 ton CO_2-eq/year. Petrol passenger cars emit the most CO_2-eqs of all light vehicles included. Emissions from electric vehicles are negligible, with a share of around 0.0078% of total traffic emissions depending on tunnel alternative.

A relatively large amount of GHG-emissions stem from HDVs, which have a share of 7-11% of AADT depending on route alternative. This is generally due to their low drivetrain-efficiency and a large share of older vehicles (Euro 3 and older) in use for HDVs with a total weight of 12-14 t and lower.

4.2. Scenario results and findings

This section will provide results and findings from scenarios created from findings in the baseline results presented above and literature reviewing. All scenarios present the effects on yearly GHG-emissions from traffic only. Eleven scenarios have been tested, where assumptions on congestion and shifts in vehicle park composition is applied. Literature suggests that reducing congestion, thus increasing average speeds should produce some mitigation (Knudsen and Bang, 2007, Bart and Boriboonsomsin, 2008). This prompts the inclusion of scenarios testing increased average speeds, with assumptions applied where reasonable. Through earlier project work, it is discovered that reducing fuel consumption and increasing the amount of EVs has considerable effects. Scenarios that tests these effects is provided. Congestion in the Byåsen tunnel is also tested, where the effects are presented below.

Table 15: This table shows the effect of reducing the average speeds in the Byåsen and its effect on total yearly emissions from traffic. The original average speed in the tunnel is assumed to be 60 km/h.

	avg. Speed	Δ tunnel alt. 1	Δ Tunnel alt. 2	Δ Tunnel alt. 3	
w/toll	50 km/h	26,36	24,16	30,46	ton CO2-eq/year
without toll		31,37	28,75	36,25	ton CO2-eq/year
w/toll	45 km/h	132,11	121,05	152,63	ton CO2-eq/year
without toll		157,22	144,06	181,64	ton CO2-eq/year
w/toll	40 km/h	263,21	234,79	315,98	ton CO2-eq/year
without toll		404,21	370,39	467,02	ton CO2-eq/year

The traffic analysis for the Byåsen tunnel (without toll) link reveals that the tunnel will experience a traffic volume over capacity, which prompts this scenario.

The effects of congestion is difficult to predict, and a 5 km/h increment from 50 km/h is chosen to represent the effects of different average speeds. The results from this scenario show that the effects of lower average speeds are more profound as the average speeds decline. It can be seen that the emissions are in total only 24.2-30.5 ton CO_2/year higher for the v50 scenario, which suggests that assuming the tunnels speed limit to be its average speed should only provide a marginal underestimation of yearly emissions. The effects of increasing average speeds on select routes using tunnel alt. 2 as baseline is also tested, along with the effects of changing the composition of the regional car park, presented below.

Table 16: Summary of scenarios using tunnel alt. 2 w/toll as baseline. The mitigating effect of each scenario is split into vehicle type and fuel.

	Δ Tunnel alt. 2 with toll				
Scenario	PC, petrol	PC, diesel	EV	HDV	
r7 v 45 km/h	-109,8	-80,6	0,0	-120,8	ton CO2-eq/year
r5 v 55 km/h, r7 v 45 km/h	-294,4	-202,2	0,0	-305,6	ton CO2-eq/year
EV_4.8%	-588,1	-523,1	5,5	0,0	ton CO2-eq/year
vkm_shift	-537,8	-124,8	0,0	-1135,0	ton CO2-eq/year
vkm_shift2	-2013,8	-1573,5	0,0	-1135,0	ton CO2-eq/year

The ***r7 v45 km/h*** scenario tests the effect of increasing the average speed in route 7 by 5 km/h, from 40 to 45 km/h. Scenario ***r5 v 55 km/h***, ***r7 v45 km/h*** studies the effect of increasing the average speed on route 5 and route 7 with 5 km/h. ***EV_4.8%*** increases the share of electric vehicles in the regional car park, from 2.38% to 4.8%. The ***vkm_shift*** scenarios studies the effects of shifting the amount of vkms by each euro class, simulating a phasing of newer vehicles into the car park, 20 years into the future. ***Vkm_shift*** has one cycle of phasing, where 90% of Euro 0 vehicles (PC & HDV) are replaced with new vehicles, which are assumed to be present Euro 5 vehicles with a 10% reduction in fuel consumption. The average age of the regional passenger cars is roughly 11 years, which makes this a viable assumption (Statistisk Sentralbyrå, 2014). The 10% reduction in FC is based off assumed reduction factors used in the ARTEMIS project for future engine technologies (Joumard et al., 2007).

Vkm_shift2 includes two phasings, where 95% of Euro 0 and Euro 1 vehicles are replaced by Euro 5 vehicles with a 10% reduction in fuel consumption and a Euro X vehicle, which is vehicle with a 10% improvement in FC over the improved Euro 5 vehicle. HDVs are assumed to have the same improvement in FC as in ***vkm_shift.*** The net total and relative effect of each scenario presented in the table above is visualized in *figure 10*.

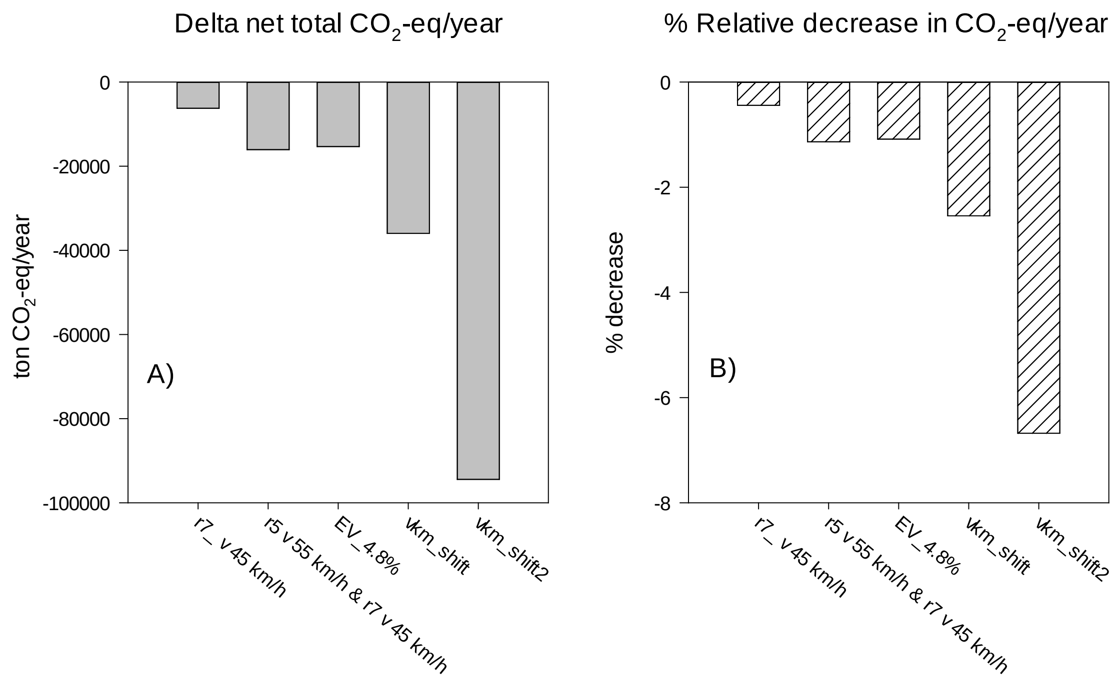

Figure 10: Summary of the net total effect (A) and the relative effect (B) of each scenario from the baseline tunnel alt.2 w/toll scenario.

The effect of increasing average speeds on one route is marginal. Although, if two routes are assumed relieved of congestion, the effects are more profound. The effect is prominent on heavy duty vehicles, with a reduction of 305.6 ton CO_2-eq.

It is interesting to note that the effect of increasing average speeds slightly outweigh the effect of doubling the share of EVs, as the increase in EV share would imply a nearly direct deduction of traffic emissions given the EVs emissions of 0.89 g CO_2/km assuming a Norwegian electricity mix. The EV scenario does however represent a large mitigation effect considering that this scenario has only one change in variables. The largest reductions in CO_2-eqs/year is found in the ***vkm_shift*** scenarios.

The effect of reducing fuel consumption through replacing older vehicles and implementing assumed new engine technology is quite prominent and far outweigh the scenarios with an assumed higher average speed. Lastly, the effect of each scenario tested is seen to be marginal. However, when combining certain scenarios with the mitigating potential of tunnel alternative 2, the effects are more profound. Scenario ***vkm2*** and tunnel alternative 2 combined amount to a reduction of about 14% in yearly GHG-emissions, which should be effective in reaching future Greener Trondheim mitigation targets.

5. Discussion

The results discussed above show that the yearly emissions from traffic in the western Trondheim area are considerable. The yearly emissions caused by constructing the Byåsen tunnel are small in comparison to emissions resulting from actual use of the tunnel via traffic in operation. This further suggests that an analysis of the infrastructural element subject to life cycle analysis should include actual use of the element. Preferably as an analysis of traffic and the eventual changes in traffic from constructing it. This is from the results of this study perceived as instrumental in a concept choice or any decision making process. Moreover, this section will provide a wider discussion of the study's most important findings.

1. The Byåsen tunnel's greenhouse gas mitigation potential

Firstly, the Byåsen tunnel will succeed in providing some mitigation of yearly emissions in the range of 2665-6778 ton CO_2-eqs, by providing a shortcut to Byåsen from the greater Trondheim area. This should contribute to Greener Trondheim's goals pertaining to reductions in traffic emissions. This can, among others, be further interpolated into overall less traffic noise. However, purely considering the tunnel's life-cycle emissions and high construction costs, the tunnel's socio-economical cost/benefit ratio does not seem sustainable. Although, it is likely that the tunnel can induce indirect benefits stemming from the tunnel, such as moving traffic out of the city-centre, improving air quality and reducing travelling time. This further suggest that more research is needed on the subject, as this study is not wide enough in its scope to unravel indirect effects stemming from the project.

Secondly, among the tunnel alternative designs suggested, there is no clear "winner." Tunnel alt. 2 emits the least per year for both designs, being the shortest in length. The single-shafted tunnel design induces the least emissions per year of all tunnel alternatives included due to its lesser amount of materials used. Thirdly, the tunnel is successive in reducing inner city yearly greenhouse gas emissions. Less traffic routed through the inner city can further be interpolated to less PM10, NOx and other air-quality reducing emissions from vehicles. Interpolated further, this can among others lead to health-benefits and improved traffic security for inner-city residents, all socio-economic benefits amounting from the project. Trade-offs may however occur as increased local emissions for residents living near the tunnel ventilation outlet.

2. Regional traffic emissions

Passenger cars are found to have the largest share of total CO_2 emissions per year, with emissions from heavy duty vehicles coming in at second. Petrol cars, being in the majority share of passenger cars, emit the most CO_2-eqs per year. Heavy duty vehicles, assumed to be run on diesel with 3.5% biofuel mixed in, emit a considerable amount of CO_2 relative to their share of AADT. Electric vehicles on the other hand emit a negligible amount of CO_2 with emissions in the range of 5.4-6.3 ton per year, which is 0.011% of total PC emissions and roughly 0.008% of total yearly emissions from traffic. This is although with electricity assumed to be delivered by the Norwegian electric grid, consisting mainly of hydropower renewables.

If assuming a NORDEL energy mix, yearly EV CO_2-emissions rise to 715-836 ton depending on alternative (Schakenda and Nyland, 2008). This is a considerable leap from emissions around 6 ton per year, but still a small portion of total emissions of traffic, at 1.05% and 1.55 % of passenger car emissions. It should further be noted that for both passenger cars and heavy duty vehicles, the emissions are appropriated for "hot" conditions. The Scandinavian climate does not dictate that engines are operating in optimal hot temperatures throughout the year, and cold start emissions are likely to occur. This may underestimate emissions during seasons such as winter or late fall.

3. *Critical factors for minimizing life-cycle impacts*

It is maintained that within the passenger car regional stock, the age and engine size of vehicles are important drivers. From scenario testing, the replacement of a majority of older vehicles is the most effective at decreasing yearly GHG-emissions of the scenarios presented. Increasing the amount of electric vehicles is also an effective means of reducing emissions. The share of electric vehicles used in the scenarios presented above might be a small share, but it is in fact a doubling of the current amount of electric vehicles in the regional passenger car stock. A further increase could have been investigated, but as of 2017 the current legislation on electric vehicles that include incentives such as no VAT, free parking etc. is in jeopardy. Including a scenario with i.e. an EV share of 10% would seem too uncertain given the short analysis time horizon. (Samferdselsdepartementet, 2014). This finding however, along with the moderate increase in yearly CO_2 emissions employing a Nordic electricity mix, does however support that incentives contributing to a growth in EV ownership is an important factor for reducing yearly regional transport emissions.

Secondly, the scenarios that simulate a higher average speed and thus clearing effect on congestion show a quite marginal effect on emissions. These results should however be somewhat approached with caution as this study does not perform microsimulations on the routes included, meaning that driving through different gradients, major accelerations and decelerations is not thoroughly analysed. The effects of such an increase could thus be somewhat underestimated, and only general conclusions should be drawn from this scenario.

The effects of congestion in the Byåsen tunnel are minimal to moderate as average speed lowers in the tunnel. This is in agreement with Bart and Boriboonsomsin's (2008) findings, although the effect of dissolving congestion is more profound in their report. Congestion can however arise several places along the routes included in the study because of congestion in the Byåsen tunnel, and the effects may indeed be larger than presented in this study. Both these findings however, suggest that road tolling is a more cost-effective measure way of reducing traffic emissions, and possibly stabilizing or increasing route average speeds. Considering road tolling rather than improving infrastructure is as such an important factor that should be considered when faced with traffic volumes exceeding road capacity.

Tolling is considered instrumental in controlling both traffic volume, GHG-emissions and local air pollution. Out of the scenarios tested, reducing traffic volume through tolling and further renewing the regional car stock are the most critical factors.

However, it should also be mentioned that implementing measures that severely limit passenger traffic within the city centre along with tolling should suppress traffic emissions even further. Limiting traffic volume on road arteries to and from the city centre should improve traffic safety, which can further encourage alternative transportation measures, such as cycling, and decreasing public transportation transit times. These measures are however not tested quantitatively within this study.

Lastly, this study's analysis time horizon is admittedly quite short for such a large project, which still has 5-10 years at the minimum before completion. A time horizon of 40 years is perhaps more apt as this is closer to the project's assumed lifetime, and in line with current practice for infrastructural projects (Longva and Tverstøl, 2014). Moreover, a longer time horizon implies higher yearly emissions from infrastructure. Assuming an analysis time horizon of 40 years reduces the mitigation potential of the project, as the yearly emissions from infrastructure is doubled. Secondly, this limits the choice of design alternatives that prove mitigation from six to four.

The analysis time horizon must be considered a critical factor within this study, as it increases yearly emissions in a magnitude comparable to the ***vkm_shift2*** scenario, as well as reducing the potential benefits measured in net GHG-emissions/year. Increasing the analysis time horizon does furthermore prove the diminishing mitigation potential of the project even further. This further decreases the net mitigating potential of the project, which can be translated a weakened sustainability in both cost and environmental terms. However, the inner-city benefits stemming from the project being, among others, improved air quality and traffic security should nonetheless prevail. An improvement to these variables can, however, further be interpolated to an increase in densification as a potential benefit from the project. Again, further research on possible indirect benefits from the project are needed to uncover benefits outside the scope of this study.

4. *The effects of road tolling*

Tolling is in this study proven instrumental for not only mitigating traffic emissions, but also further helping Greener Trondheim obtain its goals. The 2018 target, where year 2008 traffic emissions are targeted to be reduced by 20% will be expired by the time of the tunnel's construction. It is considered likely that Greener Trondheim will not be able to reach future targets of reduced traffic emissions by only constructing the Byåsen tunnel. Road tolling is instrumental for lowering traffic volume, and other side effects from reduced travel costs such as increased travel-time through slow-moving traffic and congestion. The provided traffic data with no tolling stations assumed do also show a slight increase in traffic in the road artery travelling through Trondheim's city centre, which is at odds with Greener Trondheim' project goals, such as reducing traffic noise and measures intended to route traffic away from the inner city road arteries.

The significant effect tolling has on suppressing traffic volume could perhaps be attributed to latent induced demand and price elasticity – with a quite significant increase in traffic volume when the price of each travel is relaxed (Odeck and Bråthen, 2008).

This is largely in agreement with this study, as the traffic volume increases in nearly each route without tolling. The lack of a non-tolled 0-alternative makes comparison between non-tolled tunnel alternatives non-relevant, but it can be seen that a non-tolled tunnel will closely rival this study's tolled reference alternative.

Thirdly, the increase in traffic through the city centre (without toll) is an interesting point for further study. Supporting studies that analyse project effects on reducing e.g. PM10, PM2.5 and NO_x emissions in the city centre should supplement studies used for decision making or case studies. A sustainability impact analysis (SIA) could further be implemented with case studies in order to widen the scope of each project's effect on traffic and means of travel.

Supporting studies such as these can examine any trade-off effects or problem shifting induced by projects in planning. Moreover, the methodology as developed for this study is able to contribute to assessments of strategies for reducing traffic emissions and improving air quality. Traffic analyses and life cycle assessment should contribute to future emission targets, and highlight the importance of measures.

Lastly, traffic volume is after all a critical factor when it comes to reducing traffic emissions. Questions should be raised on whether constructing urban infrastructure designed for vehicle travel is a sound strategy looking 10-20 years into the future. The effects of increasing the price of travel, as seen in when removing tolling stations, are quite significant. Along with the diminishing mitigation of yearly GHG-emissions, when increasing the analysis time horizon, it can therefore be argued that the answer to reducing yearly traffic emissions might after all lie within the price of travel, and further the attractiveness of traveling by car versus by bike or public transportation.

6. Conclusions

Using regional car stock and traffic analysis data, along with the early phase LCA model LICCER, this study assesses the impacts from the life cycle phases of a proposed tunnel in Trondheim, Norway, with six alternative designs and the changes in emissions from traffic resulting from its completion. The study's traffic inventory employs fuel consumption data from the ARTEMIS project and the Python open source database SEMBA. Results from the study highlight the importance of including traffic emissions and changes in traffic following the proposition of new infrastructural projects in LCA. Of the findings presented in the study, the following are highlighted:

- The project's environmental impacts are between 73.738 – 77.851 thousand ton CO_2-eq/year, depending on tunnel design, and 80.516 thousand ton CO_2-eq/year for the reference scenario, with no tunnel constructed. This shows a net potential reduction of 2665-6778 ton CO_2-eq/year from a reference alternative, which should help towards Greener Trondheim obtaining their politically approved goals. However, assuming an analysis time horizon of 40 years, this limits net mitigation of yearly GHG-emissions and further limits the choice of tunnel designs that prove mitigation from six to four. The projects mitigation potential is generally decreasing with an increasing analysis time horizon.

- This study does in addition explore the impact of removing tolling stations currently found in the greater Trondheim area. Simulating a removal of tolling stations increased traffic volume on nearly every route included. Yearly net GHG-emissions are shown to increase by 7715-8040 ton CO_2-eqs, and a 10% increase in traffic emissions from tolled tunnel alternatives is expected. The road tolling stations are further maintained to be instrumental towards achieving Greener Trondheim goals such as reduced inner city traffic and air quality.

- Several scenarios are tested in the study, with assumptions on phasing of older vehicles and engine technology as well as scenarios that test the effect of decreasing and increasing average speed on select routes. Along with road tolling, the phasing of older vehicles and improving engine technology is the most effective. Assumed severe congestion in the Byåsen tunnel alone could increase total yearly GHG-emissions from traffic with at least 24 ton CO_2-eqs. Doubling the amount of electric vehicles is discovered to be quite effective, stimulating an 1105-ton decrease in GHG-emissions/year.

- It is however maintained that none of the scenarios could match the mitigating effect currently present in the region of analysis, namely "Bomringen" – the road tolling stations.

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Appendix

Table A 1: Fuel consumption coefficients for driving in a gradient in an urban environment (Joumard et al., 2007) .

Diesel

Gradient	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
0 %	1,00	1,00	1,00	1,00	1,00
1 %	1,12	1,12	1,12	1,10	1,10
2 %	1,24	1,24	1,25	1,20	1,20
4 %	1,54	1,53	1,54	1,44	1,44
5 %	1,72	1,72	1,72	1,58	1,58
6 %	1,91	1,90	1,91	1,72	1,72

Table A 2: Fuel consumption coefficients for driving in a gradient in an urban environment (Joumard et al., 2007) .

Petrol

Gradient	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4
0 %	1,00	1,00	1,00	1,00	1,00
1 %	1,06	1,06	1,10	1,10	1,09
2 %	1,13	1,13	1,19	1,19	1,18
4 %	1,29	1,29	1,44	1,44	1,40
5 %	1,38	1,38	1,58	1,58	1,53
6 %	1,46	1,46	1,72	1,72	1,66

Table A 3: Heavy duty vehicle coefficient matrix (Opplysningsrådet for veitrafikken AS, 2015) .

Total weight	Euro 5	Euro 4	Euro 3	Euro 2	Euro 1	Euro 0
a <= 7,5 t	0,07	0,03	0,11	0,02	0,07	0,08
b > 7,5-12 t	0,02	0,00	0,00	0,00	0,01	0,02
c > 12-14 t	0,00	0,00	0,00	0,00	0,00	0,01
d > 14-20 t	0,03	0,02	0,03	0,01	0,01	0,03
e > 20-26 t	0,02	0,00	0,01	0,00	0,01	0,01
f > 26-28 t	0,15	0,04	0,04	0,01	0,01	0,00
g > 28-32 t	0,03	0,01	0,01	0,00	0,00	0,00
h > 32 t	0,05	0,02	0,02	0,00	0,00	0,00

Table A 4: Sample fuel consumption matrix for passenger cars traveling at an average speed of 50 km/h in 0% gradient.

Engine size (l)	Prototypical PC	Euro 5	Euro 4	Euro 3	Euro 2	Euro 1	Euro 0	
<1,4	Volkswagen Golf	0,058	0,058	0,061	0,059	0,054	0,054	l/km
1.4 - 2	Audi A4	0,064	0,064	0,068	0,068	0,071	0,071	l/km
	BMW 3-series sedan	0,064	0,064	0,068	0,068	0,071	0,071	l/km
	Ford Mondeo	0,064	0,064	0,068	0,068	0,071	0,071	l/km
	Nissan Qashqai	0,064	0,064	0,068	0,068	0,071	0,071	l/km
	Opel Astra	0,064	0,064	0,068	0,068	0,071	0,071	l/km
	Peugeot 308	0,064	0,064	0,068	0,068	0,071	0,071	l/km
	Toyota Corolla L	0,064	0,064	0,068	0,068	0,071	0,071	l/km
	Volvo V70	0,064	0,064	0,068	0,068	0,071	0,071	l/km
>2	Mercedes-Benz E-class sedan	0,092	0,092	0,078	0,069	0,068	0,068	l/km

Table A 5: Sample fuel consumption matrix for heavy duty vehicles travelling at an average speed of 50 km/h in 0% gradient.

Total weight	Euro 5	Euro 4	Euro 3	Euro 2	Euro 1	Euro 0
a <= 7,5 t	0,10	0,10	0,10	0,10	0,10	0,12
b > 7,5-12 t	0,15	0,14	0,15	0,15	0,17	0,10
c > 12-14 t	0,16	0,16	0,17	0,16	0,17	0,20
d > 14-20 t	0,19	0,19	0,20	0,20	0,20	0,26
e > 20-26 t	0,25	0,25	0,26	0,26	0,27	0,33
f > 26-28 t	0,26	0,26	0,28	0,27	0,28	0,36
g > 28-32 t	0,31	0,30	0,33	0,32	0,33	0,41
h > 32 t	0,31	0,31	0,33	0,33	0,33	0,42

Table A 6:Calculated emissions per km for electric vehicles.

kg CO2/km EV NORDEL	0,059	(Schakenda & Nyland, 2008)
kg CO2/km EV NO EL	0,001	(Brattebø et al., 2013a)

Table A 7: Maintenance parameters applied to calculating life-cycle emissions from operating & maintaining the 0-alternative's synthetic route.

Maintenance parameters			Source
Depth, resurfacing layer	0,05	m	EFFEKT
Percentage road lighting	1	share	Assumption
Electricity use	26,5	kWh/year/m	EFFEKT
Bitumen, asphalt mix	0,06	%	(Skjerve-Nielssen and Lyng, 2011)
Aggregate, asphalt mix	0,94	%	(Skjerve-Nielssen and Lyng, 2011)
Number of reasphaltations over the analysis period, road	2,86	#	Analysis time horizon
Number of reasphaltations over the analysis period, cycling/pedestrian lanes	0,5	#	Lifetime = 20 years. NPRA, personal communication
Milling work	6,37E-04	m^3 diesel /ton existing pavement layer	(Miliutenko et al., 2013)
Share of pavement layer being milled	0,75	%	(Statens Vegvesen, 2005)
Asphalt pavement layer life time, stone skeleton asphalt	7	years	(Vegdirektoratet, 2014d)
Guard rail life time	30	years	(Simonsen, 2010)
Number of replacements of guard rails	0	#	(Simonsen, 2010)
Road class	H1		(Vegdirektoratet, 2014d)
Synthetic route road length	1	km	Calculated
Pavement layer height	0,08	m	(Vegdirektoratet, 2014d)
Service lifetime road	40	years	Assumed
Transport distance asphalt	14	km	Veidekke Sjøla - Byåsveien 194. (Veidekke, Unknown year).
Analysis time horizon	20	years	
Meters pedestrian and cycling pathways in all route alternatives	28040	m	Veikart.
Meters pedestrian and cycling pathways in the synthetic route	770	m	Calculated from share of pavement and cycling pahtway.
Share pavement and cycling pathway	77%		Calculated from total route length and meters of pedestrian/cycling pathways.

Table A 8: Parameters applied for calculating roundabout life-cycle emissions.

Parameter			Source
Outer diameter	50	m	(Vegdirektoratet, 2014a)
Lanes	2	#	(Vegdirektoratet, 2014a)
Roundabout island diameter	35	m	(Vegdirektoratet, 2014a)
Length of road lane, outer diameter	157,08	m	Calculated
Length of road lane, inner diameter	109,96	m	Calculated
Transport distance asphalt	14	km	Veidekke Sjøla - Byåsveien 194. (Veidekke, unknown year).
Transport distance aggregate/sand	20	km	LICCER
Pavement layer thickness	0,08	m	(Vegdirektoratet 2014r)
Service life time, road:	40	years	LICCER
Depth, resurfacing layer	0,05	m	EFFEKT
Percentage road lighting	1	share	Assumption
Electricity use	26,5	kWh/year/m	EFFEKT
Bitumen, asphalt mix	0,06	%	(Skjerve-Nielssen and Lyng, 2011)
Aggregate, asphalt mix	0,94	%	(Skjerve-Nielssen and Lyng, 2011)
Number of reasphaltations over the analysis period, road	2,86	#	Over the analysis time horizon
Number of reasphaltations over the analysis period, cycling/pedestrian lanes	0,5	#	Lifetime = 20 years. NPRA, personal communication
Milling work	6,37E-04	m^3 diesel /ton existing pavement layer	(Miliutenko et al., 2013)
Share of pavement layer being milled	0,75	%	(Statens Vegvesen, 2005)
Asphalt pavement layer life time, stone skeleton asphalt	7	years	(Vegdirektoratet, 2014d)