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Quantifying energy demand and greenhouse gas emissions of road infrastructure projects: An LCA case study of the Oslo fjord crossing in Norway

Reyn O'Born[1]
Faculty of Engineering and Science, University of Agder, Norway.

Helge Brattebø[2], **Ole Magnus Kålas Iversen**
Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Norway.

Sofiia Miliutenko, José Potting
Division of Environmental Strategies Research, Royal Institute of Technology (KTH), Sweden

The road sector consumes large amounts of materials and energy and produces large quantities of greenhouse gas emissions, which can be reduced with correct information in the early planning stages of road project. An important aspect in the early planning stages is the choice between alternative road corridors that will determine the route distance and the subsequent need for different road infrastructure elements, such as bridges and tunnels. Together, these factors may heavily influence the life cycle environmental impacts of the road project. This paper presents a case study for two prospective road corridor alternatives for the Oslo fjord crossing in Norway and utilizes in a streamlined model based on life cycle assessment principles to quantify cumulative energy demand and greenhouse gas emissions for each route. This technique can be used to determine potential environmental impacts of road projects by overcoming several challenges in the early planning stages, such as the limited availability of detailed life cycle inventory data on the consumption of material and energy inputs, large uncertainty in the design and demand for road infrastructure elements, as well as in future traffic and future vehicle technologies. The results show the importance of assessing different life cycle activities, input materials, fuels and the critical components of such a system. For the Oslo fjord case, traffic during operation contributes about 94 % and 89 % of the annual CED and about 98 % and 92 % of the annual GHG emissions, for a tunnel and a bridge fjord crossing alternative respectively.

Keywords: *cumulative energy demand, greenhouse gas emissions, life cycle assessment (LCA), road infrastructure, road planning.*

1. Introduction

The global atmospheric concentration of CO_2 is now for the first time over 400 parts per million (Global Greenhouse Gas Reference Network, 2014). The increase in biogenic CO_2 and other greenhouse gases (GHGs) in the atmosphere leads to an increasingly volatile and unpredictable global climate. According to the Intergovernmental Panel on Climate Change (IPCC), the road transportation sector contributed approximately 5.0 Gt CO_2-eq in 2010 (IPCC, 2014) representing

[1] A: Jon Lilletunsvei 9, Grimstad, Norway T: +47 45128535 E: reyn.oborn@uia.no
[2] A: Sem Sælands vei 7, Trondheim, Norway T: +47 73594744 E: helge.brattebo@ntnu.no

some 16% of total global energy related greenhouse gas (GHG) emissions. The IPCC stated; "The continuing growth in passenger and freight activity could outweigh all mitigation measures unless transport emissions can be strongly decoupled from GDP growth" (IPCC, 2014, p 603). It is critical that the transportation sector reduces its total cumulative energy demand (CED) and GHG emissions, and the road transportation sector provides the largest opportunity for achieving this.

In 2007, the government of Norway set targets to reduce the overall climate impact of land- and air-based transportation by 4.4 million tons CO_2-eq by the year 2020; equivalent to a 38% reduction from 2012 emission levels (Norwegian Parliament, 2007). High priority was to be given to road infrastructure projects that reduce negative climate effects, but these targets have since been replaced with a tailpipe direct emissions target of 85 g CO_2-eq per km driven (Norwegian Parliament, 2012). Emissions from road infrastructure and fuel production, however, are deemed outside of the scope and not considered in the government targets.

In the most recent data from 2012, 88% of Norwegian domestic personal travel and 92% of domestic goods travel was done on roads (Statistics Norway, 2013a and 2013b). Goods transported on roads increased 32% between 2002 and 2012 to a total of 31 million ton kilometers (Statistics Norway, 2013b). In the same time period, personal transportation by roads increased by 12%, to nearly 66 million passenger kilometers (Statistics Norway, 2013a). The corresponding annual GHG emissions increase from traffic was 11.3% (compared to 2002) to a total reported emission of 10.1 million tons CO_2-equivalents in 2012 (Statistics Norway, 2013c). 4.4 million tons come from goods transport and 5.7 million tons from personal transport. Road transportation as a whole represents 19% of total GHG emissions in Norway.

The Norwegian national statistics database contains no information on emissions from road infrastructure. While this data has not been systematically collected or compiled, the Norwegian Public Roads Administration, or Statens vegvesen (SVV), today accounts for CED and life cycle GHG emissions from the road infrastructure of new road projects in the early planning stage by using a recently developed calculation tool known as EFFEKT (Straume, 2011), (Lundberg, et al., 2013). The EFFEKT tool uses a rough calculation method with corresponding large uncertainties in results. SVV has made emissions reduction and energy efficiency a priority and aims to increase the use of such types of analysis tools for more informed planning decisions (Transnova, 2013).

The choice of a road corridor location may heavily influence the overall CED and GHG emissions of a given road project. In order to minimize impacts, environmentally responsible decisions have to be taken in the early planning stage, i.e. at a time when there is limited access to detailed life cycle inventory data on the consumption of material and energy inputs, and when there are large uncertainties in design and material choices of road infrastructure elements (Kluts & Miliutenko, 2012). Future traffic and vehicle technologies are also not known in detail in the early planning stage, which further complicates analysis. Hence, it is difficult to perform a conventional life cycle assessment (LCA), forcing national road administrations to seek the use of simplified LCA methods and tools. The aim would be to aid road planners in making more informed decisions where environmental considerations can be included early in the road planning process (Norris, 2001), (De Benedetto & Klemes, 2009). LCA can also be used to calculate the CED and GHG emissions of multiple road alternatives to incorporate the results as part of an environmental impact assessment (EIA).

Advocates for the implementation of life-cycle assessment in transport systems have come from a diverse number of countries around the world. For road transport systems, some of the earliest and most influential work comes from Stripple (1995), who compiled life cycle inventory data for Swedish road components and road systems. This work was later improved by Stripple (2001) for full life cycle impact assessment. Stripple (2001) has for more than 10 years been the benchmark for Scandinavian LCA road infrastructure studies because it includes life cycle infrastructure information and one of the few studies that also considers impacts from traffic. Assessment on tunnels and bridges, which are critical typologies in the Scandinavian road system (and even more so in the Norwegian national road system), are however notably absent in the above cited studies. Stripple chose to analyze road sections with a functional unit of 1 km road length, which forms the basis of other prominent LCA road studies.

Treloar et al. (2004) is also notable for including traffic information in the analysis of a rural Australian road system. This study defined multiple fixed road typologies and compared them to one another by utilizing a hybrid LCA over a 40 year period and normalizing to per meter road length. The constructions of LCA tables were supplemented by substituting input-output information when LCA information was not available. The result is a more comprehensive analysis (in the absence of full LCA data) that was used to calculate embodied energy in materials and cumulative energy use over the lifetime of the road typologies for a functional unit of 1 km built road. GHG emissions were not explicitly calculated but estimated in terms of CO_2-eq per GJ. Interestingly, Treloar also included vehicle production as part of the analysis, which was estimated to as much as 28% of all GHG emissions in the total life cycle of a road project.

More recently Barandica et al. (2013) analyzed four Spanish roads using the CO_2NSTRUCT LCA tool. Four roads were compared to one another with a functional unit of 1 km built road with differing road dimension (i.e. lane width). The purpose of the study was to offer a basic range of GHG emissions and energy use in Spanish road constructions. The CO_2NSTRUCT tool contains a detailed list of material and construction machinery inputs, making the tool more applicable in the later stages of road planning and construction. Traffic emissions were not included in this study, but land use changes due to construction were.

Huang et al (2013) used the LCA tool CHANGER to analyze the total carbon footprint of three separate highway projects in India, the United Arab Emirates and the United Kingdom. Life cycle inventory information from the eight roads included in these three highway projects were compiled and inputted into the CHANGER software. The results were organized according to a functional unit of 1 km per built road with CO_2-eq emissions the main impact measured. The study did not calculate emissions due to traffic, but one of the main findings was that roads with greater traffic levels increased the overall infrastructure emissions, due to increased maintenance and build requirements.

Other recent LCA studies have focused on individual road elements or processes. Weiland and Muench (2010), Cass and Mukherjee (2011), Chowdury et al (2008), Yu and Lu (2012), and Birgisdóttir (2005) have focused primarily on road pavement layers and surface material selection. Birgisdóttir (2005) is notable for including material recycling while Cass and Mukherjee (2011) included the impact of manufacturing machinery used in construction. Intelligent Energy Europe (2010) has the most comprehensive study on surface design, which also integrates traffic but does not include upstream emissions and energy use from material production (ECRPD, 2010). Hammervold et al. (2013) studied road bridges in Norway, while Du and Karoumi (2013) studied railway bridges in Sweden, providing results which can also be applied to road bridge construction. Other useful studies include Ahn et al. (2010), which looked at tunnel construction, and Capony et al (2013), which looks at earthworks in road construction. A recent comprehensive study by Hammervold (2014) examined two Norwegian highway projects, and compared all together 52 separate road element cases (9 open road sections, 10 tunnels and 33 bridges) on the basis of 1 m2 of effective surface road area, using bill-of-quantity inventory data from tender and construction accounting documents.

Common to all these reported LCA-studies is that they are not offering a system-wide analysis of CED and GHG emissions in the early stages of planning. It is important to have this information available as early as possible, as the CED and GHG emissions from infrastructure, maintenance and traffic from are locked-in once the route selection is made. This study will show, by use of a developed model, how life cycle CED and GHG emissions can be determined in the early planning stages of road construction and how this information can best influence the decision making process for road planners.

2. Methodology

This study demonstrates the use of a simplified LCA method for use in early planning of road projects, developed during the LICCER project initiated by "ERA-NET ROAD II", for estimation of CED and GHG emissions for comparing alternative road corridors. The case study examined in this paper is the proposal for an expanded Oslo fjord crossing in Norway, where one alternative is primarily the construction of a new long underwater tunnel parallel to the existing underwater Oslo fjord tunnel (opened in year 2000) and the other alternative involves two new long bridges that will replace the existing underwater tunnel.

2.1 Life cycle assessment

Life Cycle Assessment (LCA) is a comprehensive methodology for evaluating the total environmental impact of a product or process over its lifetime, commonly known as "cradle to grave". The LCA framework described by ISO 14044:2006, "Environmental management – Life cycle assessment – Requirements and guidelines" outlines four phases of a life cycle assessment as shown in Figure 1 below (ISO, 2006).

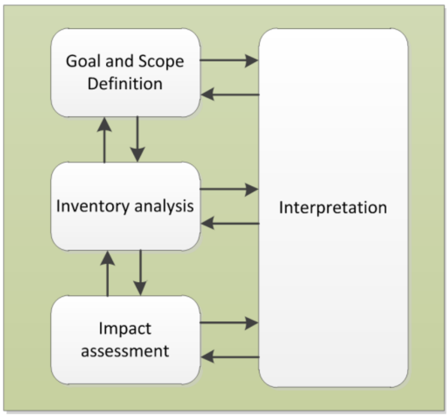


Figure 1. LCA framework adapted from ISO 14044

The goal and scope definition phase lays the foundation for an LCA study and determines the level of detail in which a process will be analyzed. The goal definition is the stated purpose of the LCA and the scope determines the depth in which the LCA will explore a process or chain of processes. The scope definition process sets the assumptions and choices made as part of the LCA with regards to data quality, data availability and the complexity of a system with respect to the defined goal. Defining the scope includes defining the system boundary, which determines limits to the system and chooses which unit processes, inputs, and outputs are to be included in the LCA. Defining a functional unit as part of the scope offers a basis of a neutral comparison among multiple processes or multiple scenarios of the same process.

The life cycle inventory (LCI) analysis is a compilation of all input and output data that relates to each unit process in an LCA. The compilation of this data includes any modifying calculations (i.e. allocation) required on the data. The treatment of missing data, such as replacement data or modifying calculations, should be transparent and documented. The data selected in inventory analysis is dependent on the goal and the scope of the study and should be representative of the system being studied.

The life cycle impact assessment (LCIA) converts inventory data to potential environmental impacts. The main elements in an impact assessment are: the selection of impact categories, indicators and characterization models; the classification of LCI results into impact categories; and the calculation of category indicator results, also known as characterization.

The final step in an LCA study is the interpretation of the impact assessment results and first requires an identification of the major impacts within a system process. The interpretation process is a continuing process of the LCA and may lead to adjustments in the model. The interpretation should also reflect upon the quality of the data, the system boundaries and methodologies employed. A sensitivity analysis, where elements of the model are adjusted and calculations re-done, can be employed as part of the interpretation process.

2.2 Model

Among several LCA tools that are used in the road sector, very few are designed to analyze environmental impacts at early stages of planning new road projects. The LICCER model, developed under the ERA-NET ROAD II program, is a comprehensive LCA-based model developed for use in the early planning stages of road construction. The model structure is summarized in Figure 2 below.

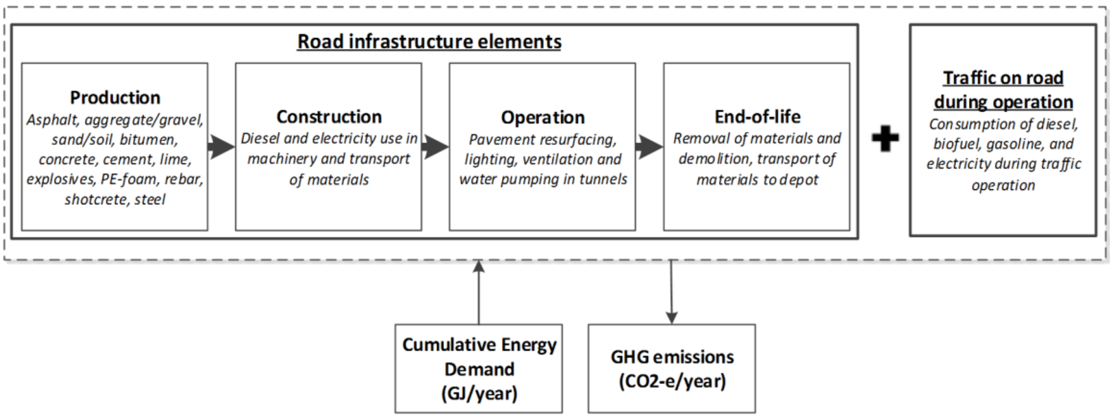


Figure 2. LICCER model structure, adapted from (Brattebø, et al., 2013)

The LICCER model takes user-inputted road parameters and characteristics and compiles life cycle inventories among multiple road alternatives or road components for the basis of comparison in the early planning stages of road construction. The model uses the compiled life cycle inventories to calculate lifetime material consumption, cumulative energy demand (CED), and life cycle greenhouse gas (GHG) emissions for the production, construction, operation and end-of-life stage of road infrastructure as well as from traffic during the operation stage.

The calculations follow LCA principles and are carried out by use of built-in formulas and sets of background data. The background data is compiled from industry and academic sources as well as national statistics tables from Norway and Sweden. The background data can be modified according to project specific material and fuel consumption parameters, transport distances and emission values if desired, as it can often be difficult to attain large amounts of data at the early planning stage. Traffic mode and quantity inputs and the service life of road infrastructure and maintenance frequency of pavement surface materials in the project can also be modified.

The impact assessment results are presented with information on annual CED (in GJ of primary energy per year) and annual GHG-emissions (in ton CO_2-equivalents per year) from each life cycle stage of infrastructure and from traffic during operation, and by contributing materials and traffic type. The calculations are carried out in terms of the following functional unit: *road infrastructure with a defined level of traffic for given road corridor locations between two end points during one year operation.*

The goal of an analysis using a LICCER model is to provide decision makers with climate and energy demand impact information to influence the decision-making process. The LICCER model is innovative in that simple volumetric parameters, such as road layer depths, lane widths, and route length, can be used to automatically calculate robust LCA information based on standard road design principles and a built-in database. The model is also unique that it can calculate traffic emissions and energy demand based on national traffic data as part of the defined functional unit for up to three variants and one existing road. The use of infrastructure and traffic calculations in the early planning process allows for a complete understanding of the road project(s) being analyzed. The model offers flexibility to the user in that any parameter can be overridden with data that is specific to the project being analyzed. This flexibility means that the LICCER model is both basic enough to be used in the early planning stages when detailed information is unavailable yet flexible enough to be used in all stages of road construction and operation.

The model contains road typologies not included in other models, such as underwater tunnels, multiple bridge types, roads below groundwater levels, and aqua-ducts. Detailed definitions of each road typology used in the LICCER model can be found in Brattebø et al. (2013) and more information about the Oslo fjord crossing can be found in the LICCER case study report by O'Born et al. (2013).

2.3 *Case study description*

The goal of this case study is to determine the annual CED and GHG emissions of two alternatives for the Oslo fjord crossing. The Oslo fjord tunnel crosses from National Road 23 near Drøbak, connecting Hurum and Frogn in southeastern Norway. It is a strategic entry point for those travelling between the eastern and western sides of the fjord south of the city of Oslo. The current public debate over proposals for a new crossing of the Oslo fjord date back to the mid-1960s and have been covered well in the media (Bentzrød, 2013), (Nikolaisen, 2014). The existing crossing option is the Oslo fjord tunnel which opened in year 2000 after Parliament Proposition 87 (1995-96) declared it a necessity to meet the need for immediate traffic demands with a possibility of later expansion dependent upon future traffic growth (Statens Vegvesen, 2012a).

The current tunnel has a daily traffic of 7000 vehicles per day with an expected increase in the future and is already at capacity and often closed due to accidents, maintenance or other unforeseen circumstances. Phase two of the Oslo fjord tunnel project is currently under construction, but this will still not be enough to meet future increasing traffic and safety demands, and as a result SVV is considering a proposal to build an additional bridge or tunnel crossing (Statens Vegvesen, 2014a & 2014b).

The two possible route alternatives for crossing the Oslo fjord crossing are presented in Figure 3, where Alternative 1 involves an extension of the existing tunnel while Alternative 2 involves two new large bridges. In our analysis, both routes begin at point A at the intersection of County Road11 (Fylkesveg 11) and National Road 23 (Riksveg 23) and end at point C at the intersection of the European Road 6 (E6) at Vassum. The route for Alternative 1 travels through point D, E, and B and includes an expansion and widening of existing roads and the construction of a new underwater tunnel parallel to the existing Oslo fjord tunnel.

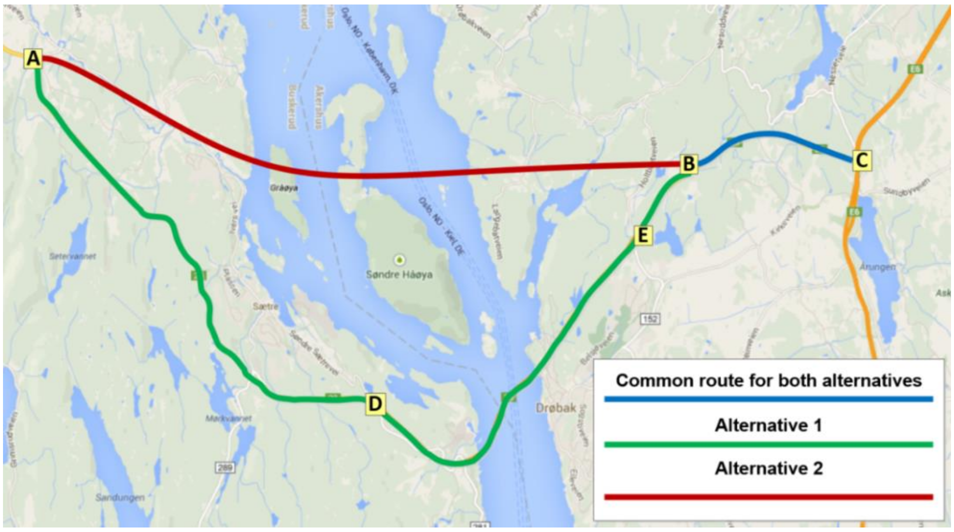


Figure 3. Oslo fjord crossing alternatives (adapted from Statens Vegvesen, 2014a)

The total distance of new constructions in Alternative 1 is 13,282 metres with a total one-way driving distance (including already built road) of 24,440 metres. Alternative 2 travels directly through point B and involves construction of three new bridges and new roads between A and B. The total distance of new constructions in Alternative 2 is 17,892 meters with a total one-way driving distance of 18,010 meters. The respective road geometries for each road typology are summarized in Table 1 and Table 2.

Table 1. Summary of road lengths for each Oslo fjord crossing alternative

Construction	Typology	Alt 1	Alt 2
Existing infrastructure (m)	Road	11140	1300
	Tunnel	5598	1988
	Underwater tunnel	7306	0
	Concrete bridge	262	262
New infrastructure (m)	Underwater tunnel	7400	0
	Tunnel	1870	1870
	Concrete bridge	262	2822
	Steel bridge	0	1500
	Extended road	3750	1300
	New road	0	10400
Total length of new infrastructure (m)		13282	17892
Total one way driving length (m)		24400	18010

Table 2. Summary of road widths for each Oslo fjord crossing alternative

Width of road elements (m)	Alt.1	Alt.2
Existing road (2 lane)	10	10
Extended/New road (2 lane)	12	n.a.
Extended/New road (4 lane)	12	20
Small concrete bridge	8	8
Wide concrete bridge	n.a.	19
Steel bridge	n.a.	19
Tunnels	9.5	9.5
Underwater tunnels	10.5	n.a.

The goal of this case study is to determine the annual CED and GHG emissions of the two alternatives for the Oslo fjord crossing. The case study uses the LICCER model to determine these

impacts for each road corridor according to the functional unit. The functional unit is meeting the requirement of Annual Average Daily Traffic (AADT) crossing the Oslo fjord, since the road width is designed to meet the design traffic. The life cycle stages included in the study are production (of materials and fuels), construction, operation (traffic and maintenance), and end-of-life according to the frameworks of the LICCER model and ISO14044.
The chosen time horizon for the analysis is 40 years. The service life of open road infrastructure is assumed to be 40 years, while the structures of bridges and tunnels are expected to have a service life of 60 years. The top layer of pavement is assumed to be replaced every 7 years, according to the national road requirements. The AADT is assessed at 7000 vehicles daily in year 0 with an assumed 1.5% annual growth in traffic, which corresponds to 12,698 vehicles in year 40.

The current vehicle type mix (in 2013) include passenger cars using petrol (40.7% of national total transport), diesel (36.1%), electricity (0.2%) and trucks using diesel with separate trailers (4.4%) and without separate trailers (18.6%). 69% of the total diesel fuel consumed is used in trucks while passenger vehicles use the remaining 31%. National vehicle mix and fuel consumption averages for each of these vehicle types are assumed to remain constant over time and contain a mix of 3.5% biofuel. The speed limit along the stretch is assumed to be 70 km/hour (Statens vegvesen, 1997).

2.4 Data collection

The LICCER model has a default life cycle inventory information package included in the software as background data to the analysis. In most instances, the default data sets contained in the model were sufficient for the case study, but some additional data that describe the system in more detail were required. Data from the Norwegian Public Roads Administration (SVV) was used as a replacement for generic national data when available (O'Born et al., 2013). Alternative 1 uses tunnel specifications collected from the existing Oslo fjord tunnel bill of quantities (Statens vegvesen, 1997) and from publicly available information on the construction of the new Oslo fjord tunnel (Statens vegvesen, 2012a).

While there have been previous successful attempts at life cycle modelling of bridge construction projects (Hammervold et al. 2013), (Du and Karoumi, 2013), the difficulty is that no large bridge design is standardized, and generic data for use in LCA in early stage planning are therefore hard to find. Alternative 2 therefore uses material inputs from two other recently built Norwegian large bridges: the predominantly concrete Tresfjord Bridge (Statens vegvesen, 2013) and the predominantly steel Hardanger Bridge (Statens vegvesen, 2012b).

Background data used in the model calculations can be found in Appendix to this article. Of particular relevance is that all calculations are carried out assuming the use of the Norwegian electricity mix, which includes typical net import/export. The Norwegian electricity mix is a much less carbon-intensive electricity mix than what is normally the case in other countries, but it is expected to be the preferred assumption for electricity use in Norway. This assumption influences the results in such a way that the Norwegian case study is only applicable to Norway and not necessarily other countries.

3. Results

3.1 Life cycle inventory results

Table 3 shows the complete life cycle inventory results for Alternatives 1 and 2. This is based on calculations for construction and operational energy consumption, material production and material transport to site, and fuels used in traffic across the four life-cycle stages.

Table 3. Life cycle inventories of Oslo fjord crossing alternatives 1 and 2

Phase	Resource input	(Units)	Alt 1	Alt 2
Production	Asphalt membrane	ton/year	1	34
	Aggregate/gravel, base layer	ton/year	1 189	675
	Aggregate/gravel, subbase layer	ton/year	371	2 619
	Aggregate/gravel, pavement layer	ton/year	480	1 150
	Bitumen, pavement layer	ton/year	31	73
	Concrete, concrete bridges	ton/year	78	3 969
	Concrete, steel bridges	ton/year	-	878
	Concrete, tunnel portals	ton/year	68	39
	Concrete, tunnel lining (cast on site)	ton/year	3 541	150
	Explosives	ton/year	25	-
	Rebar, bridges	ton/year	-	528
	Rebar, tunnel portals	ton/year	5	3
	Shotcrete, tunnel lining	ton/year	582	85
	Steel, guardrails	ton/year	1	4
	Steel, tunnel securing bolts	ton/year	7	1
	Steel, steel bridges	ton/year	-	532
Construction	Total transport of all materials, construction phase	tkm/year	943 401	1 458 484
	Total diesel fuel used in construction machinery	m3/year	4	2
	Total electricity used in construction machinery	kWh/year	55 500	20 425
Operation	Aggregate/Gravel, pavement resurfacing	ton/year	5 026	5 646
	Bitumen, pavement resurfacing	ton/year	321	360
	Transport, pavement resurfacing materials	tkm/year	160 366	180 194
	Electricity, lighting roads and bridges	kWh/year	313 824	441 627
	Electricity, lighting tunnel	kWh/year	542 327	72 167
	Electricity, ventilation tunnel	kWh/year	4 373 849	20 425
	Electricity, water pumping u.w.tunnel	kWh/year	265 200	-
End -of- life	Total transport of all material, end-of-life phase	tkm/year	9 136	13 873
	Total diesel use, end-of-life phase	m3/year	8	24
Traffic	Total Diesel, traffic use phase	m3/year	12 028	6 520
	Total Biofuel, traffic use phase	m3/year	598	324
	Total Gasoline, traffic use phase	m3/year	4 469	2 423

Production stage calculations for the above table are done according to construction standards set by the Norwegian Public Roads Administration for different road typologies and elements (Statens vegvesen, 2012c). Best-practice engineering principles are the basis for these construction standards and encompass the structural requirements for road design. The use of road construction standards for calculating life cycle inventories provides an advantage in the early planning stages when specific material requirements are unknown. The disadvantage with this method is that the results are less precise in comparison to a compiled life cycle inventory of a finished project. However, no alternative method is considered better for use at the early phase of planning for the Oslo fjord crossing case.

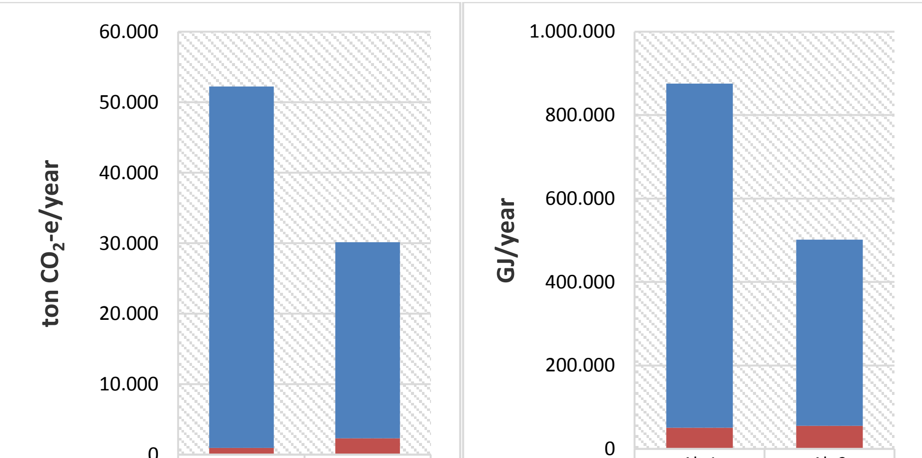
Concrete is the dominant input material in terms of weight in the production stage in both Alternative 1 and 2 is concrete. The tunnels in Alternative 1 are expected to be lined with cast concrete at a 50 cm depth along the walls, while most of the concrete in Alternative 2 is used in bridges. Shotcrete is used at a depth of 8 cm along the wall as a base for the cast concrete in tunnels used in both alternatives. Alternative 2 uses a total of 5120 tons/year concrete and shotcrete combined, while Alternative 1 uses 4269 tons/year.

The construction stage comprises of transportation of materials from production to site, fuel used in earthworks and construction machinery and electricity used in construction processes. Each material included in the analysis has separate transport distances. Steel and rebar have the largest assumed transport distances (500 km) followed by cement and explosives (300 km). Steel transport comprises 37% of all transport in Alternative 2 and only 1% for Alternative 1. Concrete materials only have an assumed transport distance of 150 km from production facility to construction site, but the total transport attributed to concrete is high due to the large overall mass of materials used. Concrete and cement materials represent 82% of all transport for Alternative 1 and 55% for Alternative 2. Machinery used in earthworks is the main contribution towards diesel fuel use in the construction phase. Alternative 1 has 242% more diesel fuel used in earthworks than Alternative 2 due to the large amount of earthworks involved in tunnel construction.

Material and energy use in infrastructure during the operations stage is from road surface maintenance and road lighting, as well as from water pumping and ventilation for tunnels. In total, Alternative 1 uses nearly 10 times the operations stage energy of Alternative 2, of which 84% of all energy demand comes from tunnel ventilation, as it is a very energy intensive process. If tunnel ventilation is excluded, Alternative 1 uses only 67% more energy than Alternative 2. The operations stage technically includes traffic, but in our study this is separated from the analysis of infrastructure in order to better document what are the impacts from road infrastructure versus those from the traffic itself.

3.2 *Life cycle impact results*

This study includes the potential impacts to climate change (in tons of CO_2-equivalents per year) and cumulative energy demand (in gigajoules of primary energy demand per year), as climate change and energy demand are the two impact categories currently focused by the Norwegian Public Roads Administration.



	Alt 1	Alt 2
Traffic	51.250	27.793
Infrastructure	966	2.320

	Alt 1	Alt 2
Traffic	823.991	446.747
Infrastructure	51.028	55.007

Figure 4. Annual greenhouse gas (GHG) emissions and cumulative energy demand (CED) from road infrastructure and traffic for Alt.1 and Alt.2

Figure 4 reports the overall life cycle impacts for each alternative in terms of contributions to greenhouse gas emissions (on the left side of the figure) and cumulative energy demand (on the right side of the figure), both from road infrastructure and from traffic on the road during operation adjusted to one year's usage of the road. It is meaningful to describe the annual calculated impacts in order to satisfy the constraints of the functional unit, since the service life of different road infrastructure elements (open roads, bridges, tunnels, and pavement layers) is not the same. Comparing on an annual basis is for this reason preferable to total service life or a given analysis time horizon.

The total GHG emissions for Alternative 1 and 2 are 52,216 and 30,113 tons CO_2-equivalents per year when including traffic and infrastructure together. Alternative 1 has 73% higher GHG emissions than Alternative 2, despite the fact that Alternative 2 has more than 2.4 times higher infrastructure-related emissions than Alternative 1, mostly due to higher emissions from the production stage. The material production stage dominates GHG emissions in Alternative 1 and 2, followed in order by operation emissions, construction emissions and end-of-life emissions. For Alternative 1 about 81% of production emissions are from concrete and shotcrete components, while for Alternative 2 steel and rebar represent 69% of total production emissions. Table 4 summarizes this information.

Table 4. Life cycle stage greenhouse gas (GHG) emission contributions

Life cycle GHG emissions from infrastructure phase and traffic	(unit)	Alt 1	Alt 2
Production	ton CO_2-e/year	518	1 825
Construction	ton CO_2-e/year	136	183
Operation	ton CO_2-e/year	286	235
End-of-Life	ton CO_2-e/year	25	77
Infrastructure (total)	*ton CO_2-e/year*	*966*	*2 320*
Light vehicles gasoline	ton CO_2-e/year	12 289	6 663
Light vehicles diesel	ton CO_2-e/year	11 934	6 474
Light vehicles electricity	ton CO_2-e/year	391	212
Heavy vehicles diesel	ton CO_2-e/year	26 635	14 444
Traffic (total)	*ton CO_2-e/year*	*51 250*	*27 793*
Net total	**ton CO_2-e/year**	**52 216**	**30 113**

The infrastructure emissions for both alternatives are, however, by far dominated by the direct traffic-related emissions. Traffic on the road represents 98% of the total emissions for Alternative 1 and 92% of the total emissions for Alternative 2. Hence, traffic during the use of the road is the dominant factor in GHG emissions for both alternatives, and outweighs all infrastructure-related emissions. This is despite the use of material- and energy-intensive structures such as tunnels and bridges.

Total cumulative energy demand (CED) for Alternative 1 and 2 is 875,019 gigajoules per year and 501,754 gigajoules per year, respectively, when including traffic and infrastructure. The dominating life cycle stage is operation for Alternative 1 and both operation and production for Alternative 2. Some 43% of CED in operation in Alternative 1 comes from pavement resurfacing, while 53% comes from tunnel operation, primarily tunnel ventilation. Alternative 2 has marginally greater production energy demand than operation demand, with 79% due to steel in superstructures and 90% of operations energy demand from pavement resurfacing.

Table 5. Life cycle stage cumulative energy demand (CED) contributions

Life cycle energy demand from infrastructure phase and traffic	(unit)	Alt 1	Alt 2
Production	GJ/year	4 086	26 923
Construction	GJ/year	2 272	2 685
Operation	GJ/year	44 289	24 245
End-of-Life	GJ/year	381	1 153
Infrastructure (total)	*GJ/year*	*51 028*	*55 007*
Light vehicles gasoline	GJ/year	191 220	103 586
Light vehicles diesel	GJ/year	179 019	96 975
Light vehicles electricity	GJ/year	50 289	27 224
Heavy vehicles diesel	GJ/year	403 463	218 962
Traffic total	*GJ/year*	*823 991*	*446 747*
Net total	**GJ/year**	**875 019**	**501 754**

Infrastructure as a whole represents about 6% of total CED for Alternative 1 and 11% of total CED for Alternative 2. Hence, traffic is by far the dominant source of total annual cumulative energy demand for each alternative.

While traffic dominates the CED and GHG emissions of the two road corridor alternatives in the Oslo fjord case study, understanding contributions due to infrastructure is important and of general interest. For instance, these might be of much larger relative importance in another project, where alternative routes have large differences in their consumption of construction materials due to different amounts of tunnels and bridges, but only small differences in travelling distance and traffic during operation. Figure 5 and Figure 6 presents the LCA results from a contribution analysis for each life-cycle stage for the quantities of tunnels, bridges and roads involved in Alternative 1 and 2 for the Oslo fjord case study.

Figure 5 and 6 offer a visual representation of the relative importance of infrastructural components by life cycle stages and road element types for Alternative 1. Figure 5 shows the total annual GHG emissions for infrastructure while Figure 6 shows the total annual CED. The blue shaded innermost ring gives the life cycle stage, the green middle circle gives road type (bridge, tunnel or road), and the outer circle gives the contribution of each material or input activity. The rings are aligned so that each phase is disaggregated by road type, and each road type is further disaggregated by materials within that road type and life cycle stage. Hence, the figure should be read from the inner circle towards the outer circle while the bar graph show the total of all processes and materials as given in the outer circle.

In Alternative 1, more than half (518 tons) of the annual GHG emissions come from the production phase. Tunnels make up most of the production emissions, with (503 tons of the 518 tons) with concrete production (420 tons) being the single most dominant material. Replacement of pavement layer materials in tunnels (101 tons) and roads (66 tons) during the operation phase, production and use of explosives for tunnel construction (60 tons and 47 tons), emissions from operational energy use (ventilation) in tunnels (79 tons) as well as transport of tunnel materials (84 tons) are also large contributors to total annual GHG emissions. As Alternative 1 is largely a tunnel solution, tunnel components here dominate the total infrastructure GHG emissions.

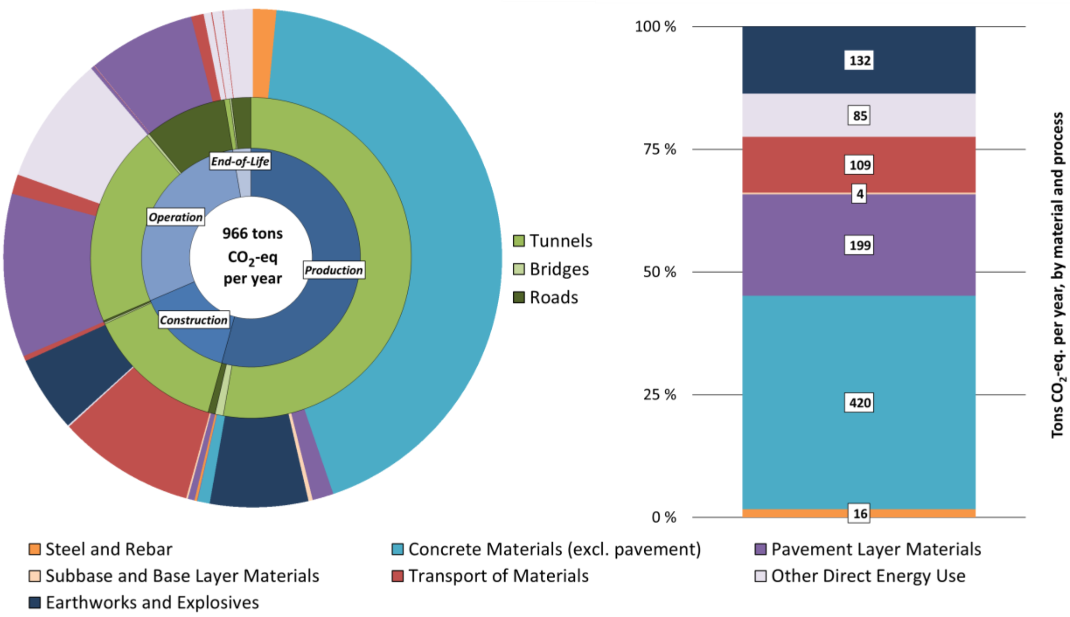


Figure 5. Contribution analysis for and greenhouse gas (GHG) emissions for Alternative 1

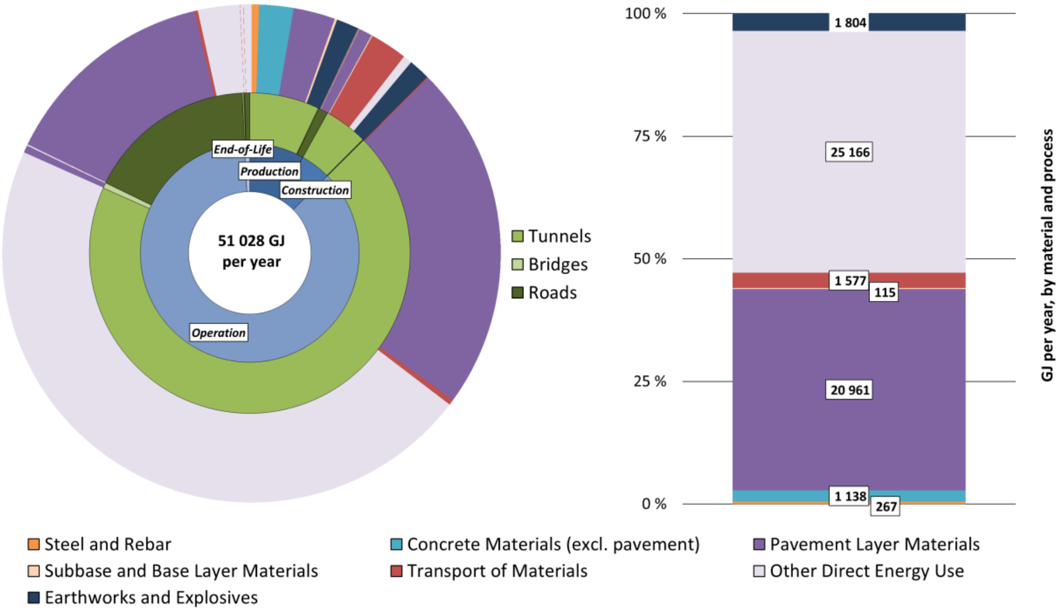


Figure 6. Contribution analysis for cumulative energy demand (CED) for Alternative 1

The CED results for Alternative 1 are also dominated by tunnels, in the form of "other direct energy use". This energy use comes from the very high electricity demand of the ventilation and lighting systems to be used in a new underwater tunnel (23,448 GJ). Interestingly, the large operational energy of tunnels does not lead to high GHG emissions due to the very low carbon intensity (20 g CO_2-eq/kWh) of the Norwegian electricity supply, which is more or less hydropower based. Replacement of pavement layer materials in tunnels (11,393 GJ) and roads (7,138 GJ) during the operation stage are the next two large contributors to CED in Alternative 1.

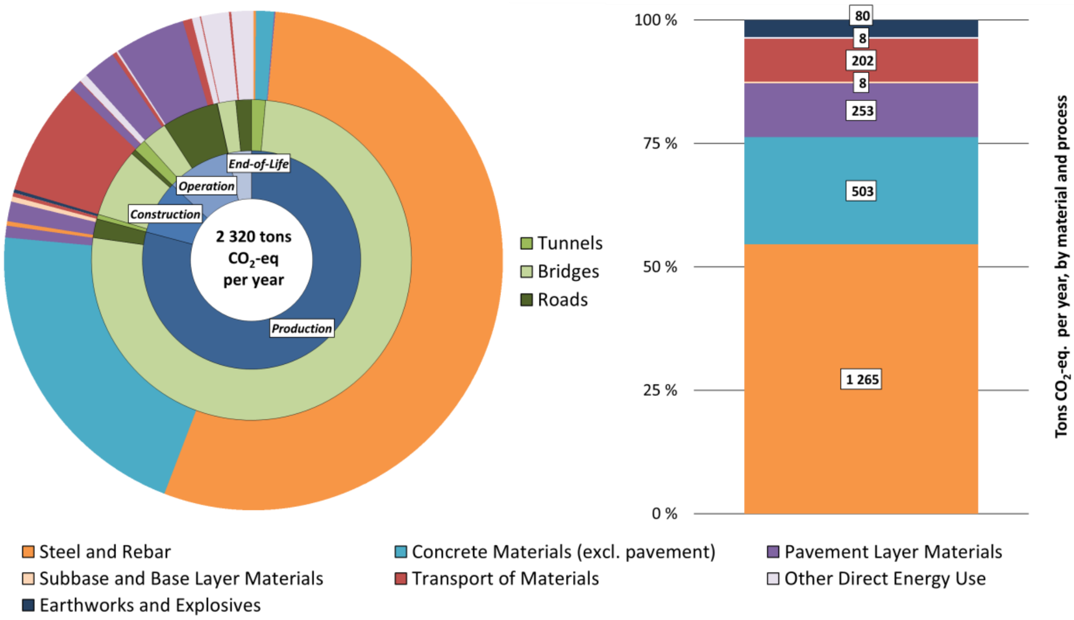


Figure 7. Contribution analysis for greenhouse gas (GHG) for Alternative 2

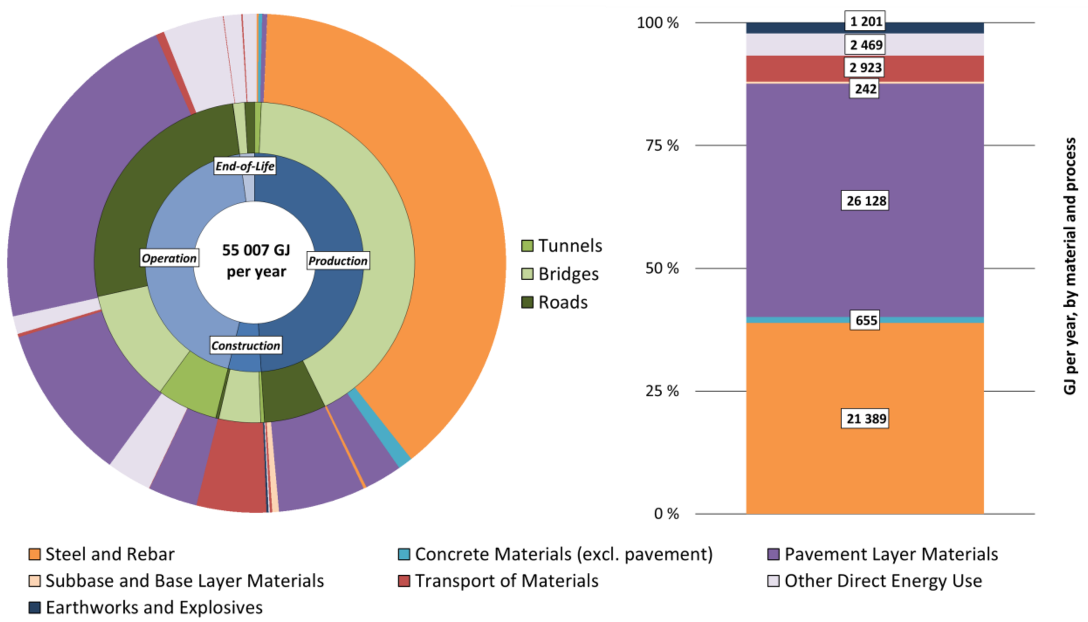


Figure 8. Contribution analysis for cumulative energy demand (CED) for Alternative 2

Figure 7 shows the contributions to GHG for infrastructure components in Alternative 2. The production stage has the highest annual GHG emissions (1825 tons), with bridges contributing the greatest impact (1743 tons) in this stage. The materials that contribute to these production emissions on bridges are steel and rebar (1225 tons) and concrete materials (476 tons). Steel production is particularly polluting as the main material component of the bridges. Other components that contribute significantly to the GHG emissions are transport of bridge materials (160 tons) and the replacement of pavement layers during operation on roads (106 tons) and bridges (49 tons). Bridges are the main component of Alternative 2 and therefore have the highest infrastructure emissions.

Figure 8 shows the CED results for Alternative 2, which are also dominated by steel and rebar production for bridges (21,240 GJ) as steel production is very energy intensive. Replacement of pavement layer materials in roads (11970 GJ) and bridges (5591 GJ) during operation followed by material production of pavement layer materials in roads (3094 GJ) and transport of bridge materials (2313 GJ) have the highest energy demand. Pavement layer materials include the embodied energy in bitumen used in the layers, and the heating of the asphalt, which contributes significantly to the high CED value in both alternatives.

Overall, the infrastructure in Alternative 1 (the route with an extended tunnel) requires less energy to build and maintain, and it produces less GHG emissions annually, however, Alternative 1 should not be chosen over Alternative 2 (the route with two bridges). This is because the GHG emissions and CED contributions due to traffic in this case study are outweighing the benefits of reduced infrastructure emissions. Alternative 2 is shorter than Alternative 1, which means that less fuel is used for traffic to cross the Oslo fjord between the same two points.

4. Discussion and implications

Alternative 2 is clearly the best choice for reducing the annual GHG emissions and CED in the Oslo fjord crossing case study, and the results have several implications for road planners. The main implication of this case study is that impacts of traffic are more important than the impacts related to infrastructure. This indicates that life cycle assessment of road projects, at the early stages of planning, should always include (and maybe have its main focus on) traffic, and it is likely that route planners should prioritize shorter route lengths if possible. This may not, however, be the conclusion in other cases when driving distances of alternative routes are not significantly different or if (some of) the routes contain long lengths of bridges and/or tunnels without largely influencing driving distance.

Few full road infrastructure LCA studies, such as Stripple (2001) and Treloar et al (2004), have included traffic as part of the overall analysis. An analysis without traffic risks being insufficient and can lead to flawed decision-making in road construction planning. As a general rule of thumb, the longer the route and the higher traffic intensity it has, the greater the emissions and energy use due to traffic. These factors can also be influenced due to route incline/decline, speed limits, vehicle types and fuel mix, all representing factors which would require a more complex traffic analysis than what is undertaken in this study. The traffic calculations used in this analysis, using what is available in the LICCER model, contain a simplified traffic algorithm based on national average fuel consumption in road vehicles and traffic mixes as proposed in Statens vegvesen (2014c). However, the analyst may change these assumptions if sufficient data for such exist, when using the LICCER model

In addition to including traffic in the analysis, this study utilizes a functional unit that differs from other studies in that it fulfills the function of traffic traveling between two endpoint locations and serves the same total amount of traffic. This methodology is helpful for planners given that route selection follows the same methodology and each alternative can be compared to one another in a way that is useful for decision makers. When using such a project-specific functional unit, however, results cannot be easily compared to those of other projects, or other unrelated routes. Previous LCA studies on road infrastructure have chosen functional units that compare road alternatives and sections in terms of meter length of built road (Barandica, Fernandez-Sanchez, Berzosa, Delgado and Acosta, 2013), (Huang, Hakim, & Zammataro, 2013), fixed road dimensions and fixed traffic (Treloar, Love, and Crawford, 2004), or fixed time horizons (ECRPD, 2010). Given the complexity of road projects and the difficulties with compiling data on multiple alternatives in pre-construction and planning phases, it is critical that the functional unit is chosen in line with the objectives of the study and not with generic information.

Despite these methodological differences between this study and most other studies, it is of interest to compare some of the results with studies that include traffic. In Treloar et al (2004), the energy use per stretch of road was calculated to be 14% for construction and maintenance and 86% from vehicle traffic over the 40 year lifetime of the project (after removing energy use from vehicle production). In Stripple (2001), infrastructure emissions ranged from 9 to 11% depending on the surface type used while traffic made the balance of the energy use. For Alternative 1 in this study, 6% of cumulative energy demand came from infrastructure and 94% from traffic. For Alternative 2 in this study, the same results are 11% and 89%, respectively. This is very close to the same ranges reported by both Treloar and Stripple, and reinforces the importance of including traffic in LCA analysis of road projects.

Cumulative energy demand and greenhouse gas emissions from infrastructure are indeed smaller in scope than emissions from traffic, but they are not altogether insignificant, particularly when comparing relative differences between alternative road corridors. If tailpipe emissions from vehicles continue to decline, infrastructure will also take up a greater share of road emissions. The infrastructure GHG impacts are heavily influenced by where materials are produced, what energy source is used to produce materials and how much transport occurs. Critical to the Norwegian case is the use of electricity from low-carbon intensive hydropower, which delinks operational energy use (i.e. ventilation in tunnels and road lighting) from GHG emissions. Ventilation in long tunnels, like in Alternative 1, would likely have much higher GHG emissions in a country that has a more carbon intensive electricity system than Norway.

When doing LCA calculations in the early planning phases of a new road, several model variables are known with low accuracy and many assumptions will have to be made under uncertainty. Despite this, it is in the early planning important decisions can be made that may significantly reduce the cumulative energy demand and GHG emissions. There is an inherent difficulty in knowing the exact material and construction requirements of a new road, which can easily undermine the quality of analysis results. A sensitivity analysis of critical materials in infrastructure can shed light on the relative uncertainty of the results. In our study, steel production, concrete production and earthworks were chosen for a sensitivity analysis, due to their respective importance in the results. Steel is a critical material for Alternative 2, and a 10% reduction in steel consumption will reduce the overall GHG emission of infrastructure in Alternative 2 by 3.7%. This is important because the bridge design used in this analysis comes from another existing Norwegian bridge, but this other bridge may not be of the same design as the ones to be built in the Oslo fjord crossing project. A 10% decrease in concrete production climate impacts leads to a 4.3% decline in GHG emissions of infrastructure in Alternative 1 and 2.2% decrease for Alternative 2. Although concrete is a critical element for both alternatives, concrete use in Alternative 1 is primarily in tunnels and the construction of tunnels follow straightforward construction guidelines which the inventory model is built upon. This means that there is less uncertainty in concrete consumption in Alternative 1 than concrete consumption in Alternative 2. Earthworks were also important for each alternative. Reducing the fuel consumption in earthworks machinery by 50% reduced GHG emissions from infrastructure for Alternative 1 by only 2.1%, signifying that there is not much GHG emission savings to be made by reducing total earthworks in this case study. Again, this might be different in other road projects.

Some maintenance activities are not included in the LICCER model, such as snow clearing, road line painting, and additional maintenance activities as reported in Stripple (2001). This is a methodological weakness of the model; however, such processes are not expected to be of significant importance when choosing between road corridors in early phase road planning. Likewise the impact of manufacturing road vehicles and construction machinery fall outside the scope of this analysis. Cass and Mukherjee (2011) concluded that construction manufacturing equipment had a range of climate impacts between 0.4% and 0.8% of total infrastructure emissions, signifying generally low importance on overall results. There is, however, evidence to suggest that the impact of road vehicle production could be as high as 28% of the climate impact of a road project (including infrastructure and traffic) (Treloar et al, 2004), but this is likely highly variable and with less practical meaning to potential road planners.

Other assumptions regarding future traffic mix and future fuel use in this study come from national statistics for current Norwegian roads. This indicates that usage of alternative fuels and vehicle types such as biodiesel and electric vehicles are almost certainly underestimated in the future. The assumption to use present day fuel mix and vehicle mix reflects the absence of reliable future projections of traffic. A more robust traffic calculation methodology would improve the results of this analysis, but do not deter from the importance of traffic impacts in the overall results.

A further development of the model could include expanded impact categories that assess impacts to water, resource depletion and biological and human health. Expanded impact categories could be used to strengthen the decision making process in addition to other non-LCA decision metrics such as economic and social cost-benefit analysis and life cycle costing. The model itself is only as relevant as the weighting criteria in which decision makers consider the climate impacts and energy demand of a road project and is thus a support tool for decisions.

5. Conclusion

This paper presents an LCA case study of a road construction project with two alternative road corridor locations in the early planning phase. The results were calculated with the LICCER model, while the input data came from previously constructed projects and national road construction standards. The overall observation is that utilizing LImodels for estimation of CED and GHG emissions in early stage road planning are indeed possible, despite the inherent challenges of poor access to inventory data of high accuracy. Using such LCA tools may provide useful information to decision makers during the planning process, which in turn can influence the overall CED and GHG emissions.

The contributions to CED and GHG emissions from the road infrastructure of the two alternative road corridors we examined in this case study are mainly from the production and operation stages of the road's life cycle. This is mainly due to the consumption of concrete and tunnel ventilation during operation in Alternative 1 and steel used in bridges in Alternative 2. Although the bridge alternative has higher infrastructure impacts, the overall impact when including traffic shows that it is the better option for road planners who wish to reduce overall CED and GHG emissions, due to a shorter driving distance.

The results of this study indicate that the annual CED and GHG emissions of transport infrastructure are important, but that energy consumption and emissions from traffic may easily outweigh their importance. Traffic calculations should therefore be included in the LCA analysis of road infrastructure and road projects, and calculation methods should be chosen so that the relative uncertainties of infrastructure-related and traffic-related contributions are dealt with relative to their overall contribution. Methodologies for future studies should be adjusted to include as complete as possible data on total route length, present and future growth in traffic and mix of the vehicle fleet, as well as specific fuel consumption per vehicle type and the future expected fuel mix. Adopting this methodology will allow decision makers to include the most relevant and important details in aiding the route selection process and allow results to be comparable. Using the results of this study should also help road planning authorities shape their policy towards reducing the CED and the associated GHG emissions of road projects.

The overall observation is that simplified LCA methods for estimation of CED and GHG emissions in early stage road planning is indeed possible and may provide useful inputs to decision making at stages where potential environmental impacts can be avoided.

Acknowledgements

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Appendix A

The following tables are presented as part of the background data included in the analysis. This data can also be found in the LICCER technical report in Brattebø et al (2013).

Table A shows the traffic mix and average fuel and energy consumption of vehicles included in the traffic analysis.

Table A. Traffic mixes and average fuel consumption of vehicles assumed in LICCER model

Fuel consumption from traffic in use phase	Unit	Value
Diesel fuel, traffic use phase, Trucks, no trailer	liter/10km	1,92
Diesel fuel, traffic use phase, Trucks, with trailer	liter/10km	3,00
Diesel fuel, traffic use phase, Light vehicles	liter/10km	0,54
Gasoline fuel, traffic use phase, Light vehicles	liter/10km	0,73
Electricity, traffic use phase, Light vehicles	MJ/km	1,61
Share of truck traffic, no trailer	% of AADT	18,6
Share of truck traffic, with trailer	% of AADT	4,4
Share of light vehicle traffic	% of AADT	77,1
Share light vehicles on diesel fuel, traffic use phase	% of light vehicles	53,2
Share of biofuel in diesel/gasoline fuel today	% of total fuel use	3,5
Share of electric cars in use today, Light vehicles	% of light vehicle stock	0,2

Appendix B

Table B shows the per unit CO_2-e emissions of materials and energy sources used in the analysis.

Table B. Greenhouse gas emissions of materials and energy used in the LICCER model

Specific greenhouse gas emissions of materials	Unit (kg CO_2-e)	Value
Aggregate	kg/ton	2,39
Bitumen	kg/ton	430,00
Asphalt membrane	kg/ton	206,00
Aggregate/Gravel in reasphaltation	kg/ton	2,39
Bitumen in reasphaltation	kg/ton	430,00
Asphalt mixing	kg/ton	5,99
Sand / Soil	kg/ton	2,39
Concrete	kg/m3	236,00
Diesel	kg/m3	3190,00
Biofuel	kg/m3	691,00
Electricity	kg/kWh	0,02
Explosives	kg/ton	2380,00
Gasoline	kg/m3	2750,00
Gravel	kg/ton	2,39
PE-foam	kg/ton	2470,00
Rebar (reinforcement steel)	kg/ton	754,79
Rockfill	kg/ton	1,80
Shotcrete	kg/m3	454,64
Steel	kg/ton	1610,00
Lime, soil stabilization	kg/ton	780,00
Cement	kg/ton	748,00
Transport work	kg/tkm	0,13

Appendix C

Table C shows the per unit CED of materials and energy production used in the analysis.

Table C. Energy consumption materials and fuels used in LICCER model

Total energy consumption per unit of resource input	Unit	Value
Aggregate	MJ/ton	73,5
Bitumen	MJ/ton	52 000
Asphalt membrane	MJ/ton	6 900
Bitumen in reasphaltation	MJ/ton	52 000
Asphalt mixing	MJ/ton	390
Sand/soil	MJ/ton	73,5
Concrete	MJ/m3	261
Diesel	MJ/m3	47 850
Biofuel	MJ/m3	23 433
Electricity	MJ/kWh	4,53
Explosives	MJ/ton	28 750
Gasoline	MJ/m3	42 790
Gravel	MJ/ton	73,5
PE-foam	MJ/ton	86 540
Rebar (reinforcement steel)	MJ/ton	14 324
Rockfill	MJ/ton	24,7
Shotcrete	MJ/m3	3 040
Steel	MJ/ton	25 710
Cement	MJ/ton	5 484
Lime in soil stabilization	MJ/ton	5 300
Transport work	MJ/tkm	1,82