LICCER

LICCER Model Case Study Report

Application of the LICCER-model to a Norwegian road section crossing the Oslo fjord

Report Nr 5.2

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Preface

This report is the basis of a student project at NTNU, by Ole Magnus Iversen. It has been extended with the help of inputs from the LICCER team and serves as the Norwegian case study report for the LICCER project, Report No. 5.2. We would like to thank the efforts of Ole Magnus Iversen for his input into this report.

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1 Introduction

1.1 Project context

Life Cycle Considerations in EIA of Road Infrastructure (LICCER) is a research project of the cross-border funded joint research programme **"ENR2011 ENERGY – Sustainability and Energy Efficient Management of Roads"**

"ENR2011 ENERGY – Sustainability and Energy Efficient Management of Roads" is a transnational joint research programme that was initiated by "ERA-NET ROAD II – Coordination and Implementation of Road Research in Europe" (ENR2), a Coordination Action in the 7th Framework Programme of the EC. The funding partners of this cross-border funded Joint Research Programme are the National Road Administrations of Germany, Denmark, Ireland, Netherlands, Norway, Sweden and United Kingdom.

The *aim* of the LICCER project was to develop an easy to use model, consisting of a modular framework and guidelines, based on existing tools and methodologies for Life Cycle Assessment of road infrastructure. The developed model does not follow a modular approach, however, but fully integrates modelling of road elements (i.e. road, bridges and tunnels). The model aims on decision-support in the early stage of transport planning. The framework, use and aim of the model are further described in the user guideline and the technical report.

The LICCER project duration: 01/01/2012– 31/12/2013

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1.2 Background to this report

Environmental impacts from the road transport sector are often associated with the vehicles on the road. However construction, operation and maintenance of the road infrastructure should not be neglected. Estimates show that the road infrastructure can stand for up to 22% of the total energy use of a specific road transport system (Jonsson, 2007). However, GHG-emissions and energy consumption from road infrastructure are often not considered in early planning of road infrastructure (Finnveden and Åkerman, 2011; Hilden et al., 2004). By including only impacts directly related to traffic, the basis for decision can be misleading, especially for bigger resource demanding road projects (Öman et al., 2012).

Life cycle assessment (LCA) is a methodology that can be used for quantification of the environmental impacts of a product system throughout the whole life cycle, from extraction of raw materials to waste treatment (Baumann and Tillman, 2004). LCA has been used to evaluate the environmental impacts of road infrastructure since the 1990's (Carlson, 2011), but so far it has not been common to actually include LCA in early planning stages. The LCA is rather performed when location of the road has already been chosen (Kluts and Miliutenko, 2012).

The project LICCER (Life Cycle Considerations in EIA of Road Infrastructure) aims to develop a life cycle model (the LICCER-model) for assessment of GHG-emissions and energy use in early planning of road infrastructure. Early planning is defined as choice of road corridor and choice of construction type, i.e. road element – plain road, tunnel or bridge. The LICCER-model will enable national road agencies and other stakeholders to compare different road corridor alternatives in the decision-making process (Brattebø et al., 2013).

Development of the LICCER-model started in January 2012. A final version of the model is expected to become available in the beginning of 2014. Before finalising the model it is necessary to test its applicability and robustness, in order to evaluate its usability for decision making. The applicability of the model is defined as user friendliness, and relevant content and relevant results for decision making in early planning stages. Robustness of the model is in this report understood as its possibilities to show differences between road corridors, and its sensitivity for assumptions and parameters. Both can be evaluated through identification of assumptions and parameters to which the model output is the most sensitive and the uncertainty in these parameters and assumptions.

This report presents results from a case study performed for a Norwegian road, aiming to evaluate applicability and robustness of the LICCER-model. The model is applied to a case study of selection of road corridors in early planning of road infrastructure, and a sensitivity analysis is performed in order to identify parameters and assumptions to which the model output is most sensitive. This case study was completed with a version of the LICCER model that was nearly complete but may show some irregularities with the completed model.

2 Methodology

2.1 Life cycle assessment

The LICCER-model is based on life cycle assessment methodology following the ISO 14040 standard. Life cycle assessment (LCA) is a framework for assessment of resource use and environmental impacts throughout the life cycle of a product or a service, from acquisition of raw materials via production and use stages to waste management (ISO 14040:2006). An LCA study usually consists of four stages applied in an iterative process (Baumann and Tillman, 2004; ISO 14040:2006). Figure 1 below shows an outline of the LCA procedure.

1. Goal and scope definition. The goal is related to the context of the study, such as why it is performed and who will use the result. The scope of the study is related to choices made in modelling, such as options to model, choice of functional unit, impact categories, system boundaries and data quality requirements.
2. The life cycle inventory (LCI) includes description and quantification of the resources used throughout the life cycle and the resulting emissions.
3. The emissions and resource use are then related to environmental problems in the life cycle impact assessment (LCIA), i.e. environmental loads such as emissions of CO_2 and SO_2 are translated into potential environmental impacts such as climate change, acidification, etc.
4. Finally the results are evaluated in relation to the goal and scope, in order to reach conclusions and provide recommendations.

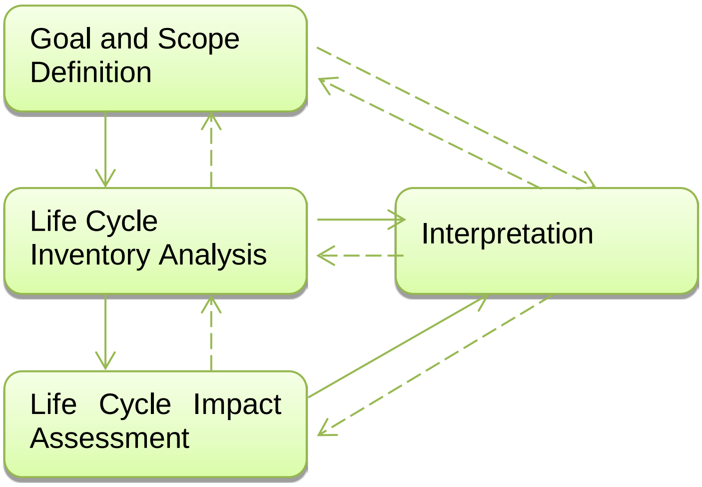


Figure 1: Overview of the LCA-procedure.The arrows indicate the order in which the procedural steps are performed. The broken arrows indicate possible iterations. (Adapted from Baumann and Tillman, 2004).

2.2 The LICCER-model

The LICCER-model is specifically designed for use in early stages of road infrastructure planning. In this stage, decisions still have to be taken on the exact location of the road in combination with required road elements (e.g. tunnels and bridges). The LICCER-model can thereby be used in the choice of route selection and choice between construction types (e.g.

road, bridge or tunnel). A brief overview of the model is provided below. The model is described in detail by Brattebø et al. (2013).

The LICCER-model is developed as an MS-Excel tool that should be easy to use and transparent in terms of background data and calculations. With the LICCER-model it is possible to quantify energy use (cumulative energy demand) and GHG-emissions (CO_2-equivalents) in all life cycle stages of the road, from material production to demolition. Additionally also impacts from traffic on the road are taken into account. Different types of roads, bridges and tunnels are included in the model, as well as supporting road furniture such as guardrails and road lighting.

The methodological choices in the case study are limited by the choices already made in the development of the LICCER-model. This implies that the functional unit, system boundaries, background data and the environmental impacts assessed are the same as in the LICCER-model.

The functional unit in the LICCER-model is "road infrastructure enabling annual transport between “A” to “B” over an analysis time horizon of a defined number of years” (Brattebø et al., 2013). The LICCER-model calculates the annual GHG-emissions and energy consumption as the average values per year for the analysis time horizon. As the yearly traffic on the road is increasing with time it was decided to use the average annual impacts in the LICCER-model and not the value over the whole analysis period. All calculations are adjusted to the service life of the road elements. In this case study an analysis period of 40 years is chosen, as it is the common dimensioning period for roads in Sweden. The service life of road elements in Norway is often chosen as 40 years for roads and 60 years for bridges and tunnels, hence these values are used in the case study.

Figure 2 below provides an overview of the LICCER-model’s system boundaries. The main life cycle stages included are the following:

- **Production**: includes production of bitumen and aggregates, as well as other materials needed for road construction. The inventory data for the production stage includes excavation of raw material, transportation of materials and processing of these materials to construction components. This constitutes background data in the model and is gathered from national datasets, databases and the LCA-literature.
- **Construction**: is in the LICCER-model taken into account by transportation of materials to the construction site, in addition to diesel consumption for earthworks and construction of tunnels.
- **Operation**: includes maintenance of the road surface by reasphaltation (including production of materials and transportation of these materials to the construction site), and operational activities such as road lighting, ventilation of tunnels and pumping of water from tunnels.
- **End-of-life**: includes demolition of the road superstructure, bridges and guardrails, earthworks necessary to restore the land area back to natural conditions and transportation of materials to landfill and depots. Recycling and reuse of materials in the end-of-life stage is left outside the system boundary of the analysis.
- **Traffic**: includes consumption of gasoline, diesel, biofuel and electricity in light and heavy vehicles on the road.

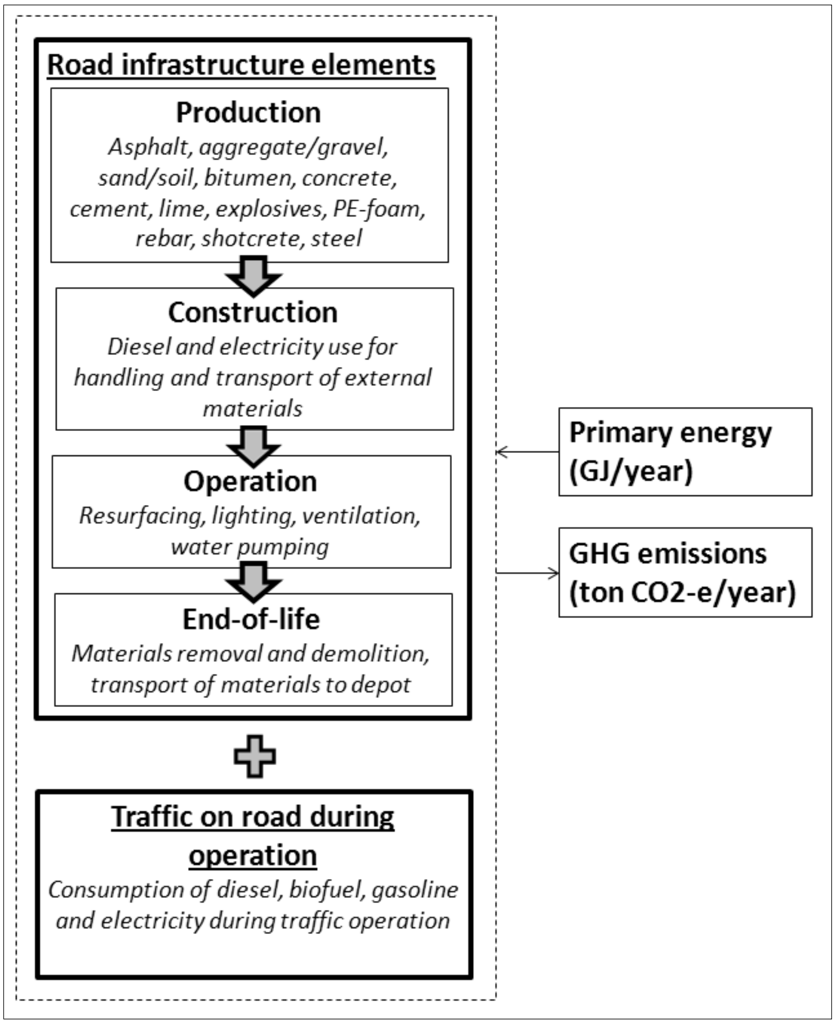


Figure 2: Simplified system boundaries in the LICCER model (Brattebø et al., 2013).

The LICCER-model includes a set of model-parameter default values used to calculate environmental impacts based on the data inserted by the user. This default data include transportation distances, specific material, electricity and fuel consumption, and emission and energy factors. Norwegian data is used specifically for fuel consumption in the traffic use stage, material consumption and for all road infrastructures. Greenhouse gas (GHG) emissions and primary energy parameter default values are derived mostly from the Norwegian EFFEKT database and from research by the LICCER team. A full list of data sources can be found in the model under the 'DataSources' tab.

2.3 Description of the Norwegian case

The project chosen for the Norwegian case study is the planning of a new road section crossing sea-water south of the capital city of Oslo, known as the Oslo fjord crossing. The project is chosen as a case for the LICCER model as it includes multiple road types and complex road designs which can be evaluated with the LICCER model. The Oslo fjord crossing is a project currently under the 'Concept study' planning stage (KVU – Konseptvalgutredning), and offers a real-world example to test the applicability of the LICCER-model.

The Oslo fjord crossing has the possibility for many alternative road corridor choices that can be made by road planning authorities. This case considers just two of the possible alternatives. The two alternatives have the same beginning and end points and both serve the function of providing a mode of Oslo fjord crossing for 7000 vehicles daily. Figure 3 shows the proposed crossing alternatives overlaid on a map of the area. Alternative 2, the green line in Figure 3, represents the reference alternative with a present road and an extended tunnel with greater capacity and enhanced safety for traffic than what is offered by the current road.

Alternative 1 represents a new road with two bridges, to be located within the red shaded area. The details regarding possibilities of crossing the Oslo fjord in the red shaded area is yet not open to the public, but data has been provided for a bridge crossing example as shown in Figure 3. The collective starting point from the west is point A; where Highway 23 meets Road 11 (Fylkesveg 11; see point A in Figure 3). The shared end point to the east is point C; the meeting of Highway 23 with National Highway 6 at Vassum crossing (E6; see point C in Figure 3). Both routes share a common road piece irrespective of route choice, i.e. from point B to C in Figure 3, which extends for 3550 meters through the Frogn- and Vassum-tunnels, Bråtan bridge, and a small distance on Highway 23.

The daily traffic on the reference alternative, i.e. Alternative 2, is 12000 vehicles per day and is greater than on the new Alternative 2 due to other roads collectivizing in this area. The additional 5000 vehicles thus are kept out of the results so that only the 7000 vehicles using the proposed crossings will be accounted for in the analysis.

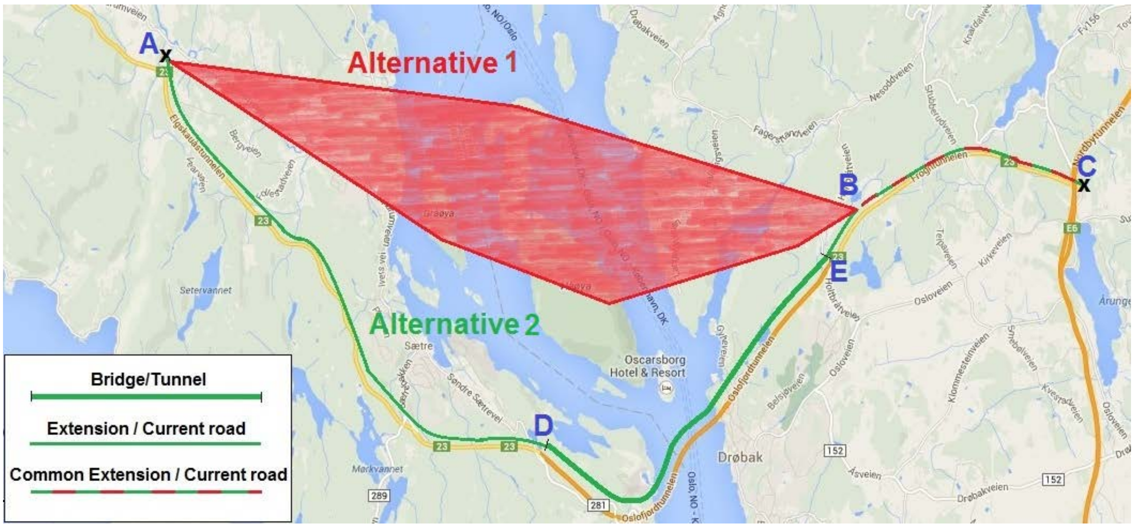


Figure 3: Map of proposed Oslo fjord crossings

Alternative 1: The first alternative (hereby known as Alternative 1 or Alt.1) is the proposed construction of a multiple bridge crossing over or near Hå Island (Håøya) and travelling north from today's underwater tunnel crossing (the Oslo fjord tunnel) until meeting the E6 at the Vassum crossing. For the case study, Alternative 1 is between A and B composed of one new steel bridge, one new concrete bridge, and three sections of new road being built. In addition to the new infrastructure, the current two-lane sections of road between B and C must be extended to four lanes to accommodate the extra traffic. The actual route of the bridge crossing not yet decided in the planning process, and the process is not yet public, therefore its exact location cannot be shown in this report. Hence the road corridor location of Alternative 1 is hidden within the red shaded are in Figure 3. Table 1 and Table 2 below show the road elements and their lengths included in the analysis for each road section in Alternative 1. Table 14 to Table 16 in the appendix summarize the road elements by construction type. In total, Alternative 1 is **18010 meters** long.

Table 1: Section A to B road infrastructure length, Alternative 1

Length of road elements (m)	Total sections	Total combined length (m)
New road	3	10400
Steel bridge	1	1500
Concrete bridge	1	2560

Table 2: Section B to C road infrastructure length, Alternative 1

Length of road elements (m)	Total sections	Total combined length (m)
Existing road	2	1300
Existing tunnel	2	1988
Existing Concrete bridge	1	262
Extended road	2	1300
Tunnel	2	1870
Concrete bridge	1	262

Alternative 2: The second alternative (Alternative 2, or Alt.2) is the continued use of the current Highway 23 (between Point A and Point D), then the building of a new underwater tunnel parallel to the existing underwater tunnel (between Point D and E, and finally an extension of an existing 2-lane road and tunnel to a 4-lane road and tunnel (between E and B, and between B and C), to allow for more daily traffic. There is also the expansion of a two-lane road into four lanes along its length. Table 3 to Table 5 below show the road elements and their lengths included in the analysis for each road section in Alternative 2. Table 17 to Table 19 in the appendix summarize the road elements by construction type. In total, the Alternative 2 is **24400 meters** long.

Table 3: Section A to D road infrastructure length, Alternative 2

Length of road elements (m)	Total sections	Total combined length (m)
Existing road	3	7390
Existing tunnel	3	3610

Table 4: Section D to E road infrastructure length, Alternative 2

Length of road elements (m)	Total sections	Total combined length (m)
Existing underwater tunnel	1	7306
Underwater tunnel	1	7400

Table 5: Section E to C road infrastructure length, Alternative 2

Length of road elements (m)	Total sections	Total combined length (m)
Existing road	2	3750
Existing tunnel	2	1988
Existing Concrete bridge	2	262
Extended road	2	3750
Tunnel	2	1870
Concrete bridge	1	262

2.4 Data inventory

A significant amount of project-specific data was gathered for the case study. Data gathered includes the tunnel profiles and method of earthworks required, pavement and sub-base layer depths, share length with guardrails, road geometry, project lifetime and daily traffic measurements. Tunnel profile information came from technical specifications documents for the current Oslo fjord tunnel (Statens vegvesen, 1997) and from proposal documents for the new tunnel section (Statens vegvesen, 2013a). Steel bridge profile information comes from personal communication with road authorities (Statens vegvesen, 2013b) while material consumption comes from two other Norwegian bridges; data from the Tresfjord Bridge was used for concrete (Statens vegvesen, 2012c) and data from the Hardanger Bridge was used for steel (Statens vegvesen, 2012b). Other data comes from personal communication or basic assumptions.

Table 6: Width of new road elements for Oslo fjord crossing alternatives

Width of road elements (m)	Alt.1	Alt.2
Existing road (2 lane)	10.0	10.0
Extended/New road (2 lane)	-	12.0
Extended/New road (4 lane)	20.0	12.0
Small concrete bridge	8.0	8.0
Wide concrete bridge	19.0	-
Steel bridge	19.0	-
Tunnels	9.5	9.5
Underwater tunnels	-	10.5

The width of the road elements are presented in Table 6. All roads use a same asphalt depth of 0.08m for driving surfaces and while subbase and base depth varies from 0.120m combined up to 0.620m. 0.045m of asphalt is removed during each re-asphaltation. As well, it is assumed that all road lengths have 100% road light coverage. New roads and extended roads have 100% steel side guardrail coverage. Tunnels are concrete lined and require a mass of 0.13 m^3 per m^2 tunnel area. Total earthworks are calculated by the model according to the calculated tunnel geometry, which is also calculated by the model. Earthworks for tunnels are considered to be blasted rock.

Alternative 1 is based on a more material-intensive bridge in Norway and has some material consumption parameters that differ from the default values in the LICCER model. The new bridge is assumed to be built as a long steel suspension bridge crossing the fjord. The consumption variables that were changed in the simulation for Alternative 1 are summarized in Table 7 below.

Table 7: Alternative 1 material consumption parameters

Material consumption parameter	Unit	Alt.1	EFFEKT default
Concrete, concrete bridges	m3/m2 surface area	2.00	1.31
Concrete, steel bridges	m3/m2 surface area	0.77	0.71
Rebar, concrete bridges	ton/m2 surface area	0.54	0.22
Rebar, steel bridges	ton/m2 surface area	0.19	0.11
Steel, steel bridges	ton/m2 surface area	1.12	0.22

The analysis time horizon is 40 years while the service life of roads is 40 years and of tunnels and bridges 60 years. Annual daily traffic increases by 1.5% per year over the analysis time horizon of the project, starting at 7000 vehicles per day ending with 12698 vehicles per day. All other background data come from the LICCER model default values.

3 Results

3.1 *Inventory of materials used*

The LICCER-model constructs an inventory of all materials based on road and project parameters. These are quantified in the calculations section. There is a base set of default values which includes transportation, material properties (i.e. density), material consumption for construction, as well as cumulative energy and GHG emission factors. The material consumption for Alternatives 1 and 2 are summarized in Table 8 below.

Table 8: Material consumption for new infrastructure in road corridors.

Material	Unit	Alt.1	Alt.2
Asphalt membrane	ton/year	34.48	0.70
Aggregate/gravel, base layer	ton/year	658.27	1 201.49
Aggregate/gravel, subbase layer	ton/year	2 426.67	405.05
Aggregate/gravel, pavement layer	ton/year	737.69	335.40
Sand/soil, base layer	ton/year	-	-
Sand/soil, subbase layer	ton/year	-	-
Sand/soil, for soil replacement	ton/year	-	-
Bitumen, base layer	ton/year	-	-
Bitumen, pavement layer	ton/year	33.63	15.29
Asphalt mixing	ton/year	-	-
Concrete, pavement layer	ton/year	-	-
Concrete, concrete bridges	ton/year	4 018.31	84.74
Concrete, steel bridges	ton/year	877.80	-
Concrete, tunnel portals	ton/year	63.77	71.38
Concrete, tunnel wall elements	ton/year	-	-
Concrete, tunnel lining (cast on site)	ton/year	246.06	1 045.81
Concrete, other	ton/year	-	-
Concrete, guardrails	ton/year	-	-
Cement, soil stabilization	ton/year	-	-
Lime from lime pillars, soil stabilization	ton/year	-	-
Explosives	ton/year	-	25.81
PE-foam, tunnel lining	ton/year	-	-
Rebar, bridges	ton/year	528.01	-
Rebar, tunnel wall elements	ton/year	-	-
Rebar, tunnel portals	ton/year	4.82	5.40
Rebar, tunnel lining	ton/year	-	-
Rebar, other	ton/year	-	-
Shortcrete, tunnel lining	ton/year	138.80	589.94
Steel, guardrails	ton/year	-	-
Steel, tunnel securing bolts	ton/year	1.58	6.70
Steel, steel bridges	ton/year	532.00	-

3.2 *Annual GHG-emissions and energy consumption*

The infrastructure portion of the results for the Oslo fjord crossing analysis is shown in Figure 4. The results show the gross total annual GHG emissions and the gross total annual energy consumption for Alternatives 1 and 2. Results are organized according to the four lifecycle phases included in the LICCER model. The figure on the left shows annual GHG emissions (in tons of CO_2-equivalents per year), while the figure on the right shows annual energy use (in GJ per year). These are results for one average year over the entire 40 year analysis time horizon of the project.

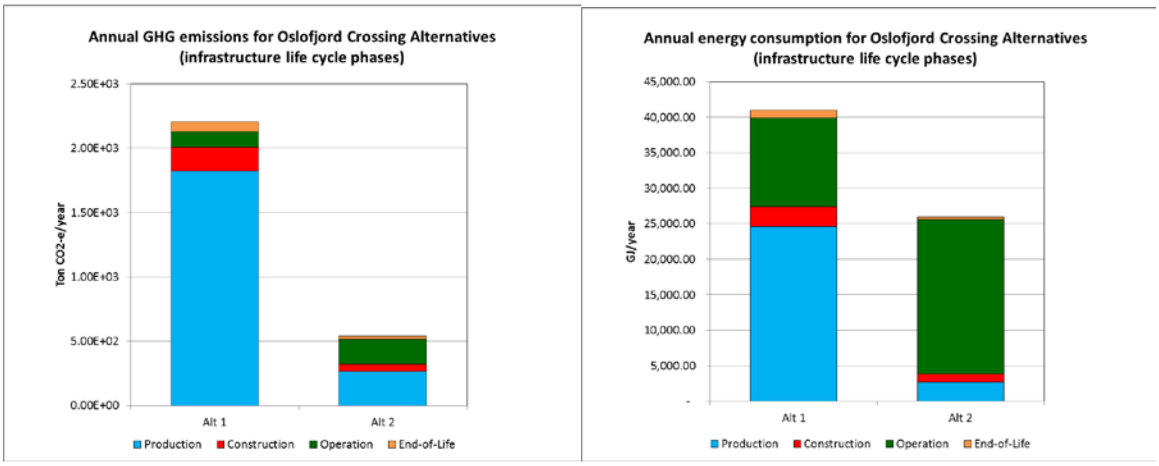


Figure 4: GHG emissions and energy consumption by lifecycle phase'

Total annual GHG emissions for Alternative 1 are 2204 tons CO_2-equivalents per year total across all phases, with the production phase dominating the emissions. The total for Alternative 1 is more than four times the total for Alternative 2, which has 541 tons of CO_2-equivalent emissions per year. The emissions difference in production between Alternative 1 and 2 predominantly comes from the production of large amounts of steel needed for the bridges in Alternative 1. Other large contributors to GHG emissions are asphalt production and earthworks.

Total annual energy consumption for Alternative 1 is also greater than for Alternative 2, with a total annual energy use over all lifecycle phases of 41001 GJ per year for Alternative 1. This energy use for Alternative 1 is dominated again by production mostly due to the energy used in steel production. Alternative 2 has a total annual energy use of 25959 GJ per year, with the largest contribution coming from operation. Both Alternative 1 and 2 have large energy consumption results in the operation phase. Alternative 1 and 2 both have high contributions from operations due to the replacement of the asphalt driving layers over time. The largest energy consumer in the operation phase for Alternative 2, however, is due to the constant need for lighting and ventilation in the tunnel. The share of energy is much higher than the share of GHG emissions in operation due to the fact that energy used in operation of infrastructure comes mainly from hydropower, which in Norway is much less GHG-intensive than where material production occurs.

Figure 5 shows the annual GHG emissions and annual energy consumption results by groups of material type. Steel contributes to the largest share of GHG emissions by material for Alternative 1, more than double all other contributions combined. Concrete also contributes to large GHG emissions for both alternatives, but to a lesser degree than steel. The concrete use and steel use for the bridges is very high due to the considerable length of the bridges.

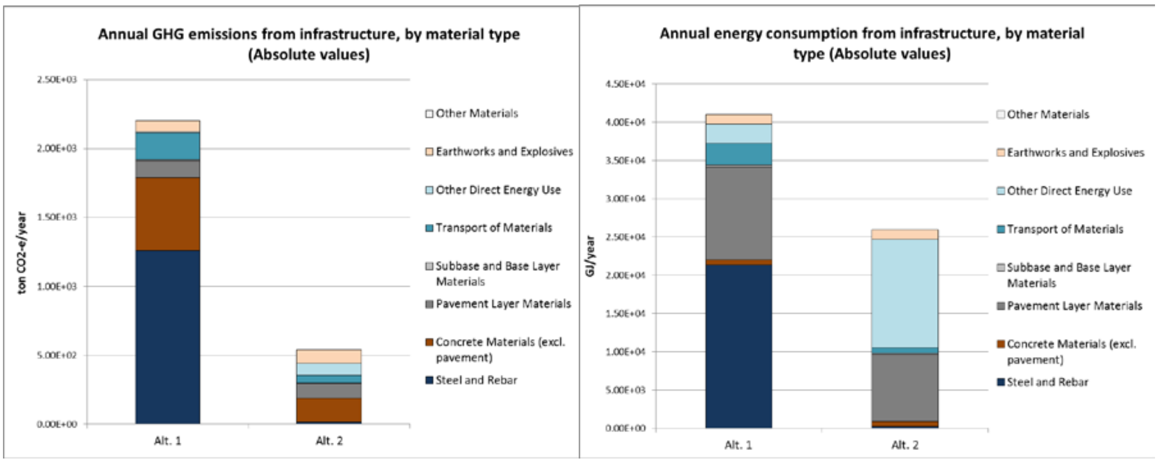


Figure 5: Annual GHG emissions and energy consumption, by material types

The annual energy consumption results in Figure 5 also show that Alternative 1 has a much greater energy use in infrastructure components, but now the pavement layer materials make up a significant amount of energy use. The energy use in pavement layers comes largely from the production of bitumen in asphalt and asphalt membrane on bridges. Alternative 2 has the largest annual energy consumption in the 'Other Direct Energy Use' category, which is largely from constant lighting and ventilation in the tunnel system.

In addition to energy use and GHG emissions from infrastructure, the LICCER-model also accounts for traffic along the two alternative routes. Figure 6 shows the results of the analysis including traffic. The figure on the left shows annual GHG emissions (in CO_2-equivalents) while the figure on the right shows annual energy use (in GJ). These are results for one average year over the entire 40 year analysis time horizon of the project, combined for all lifecycle stages.

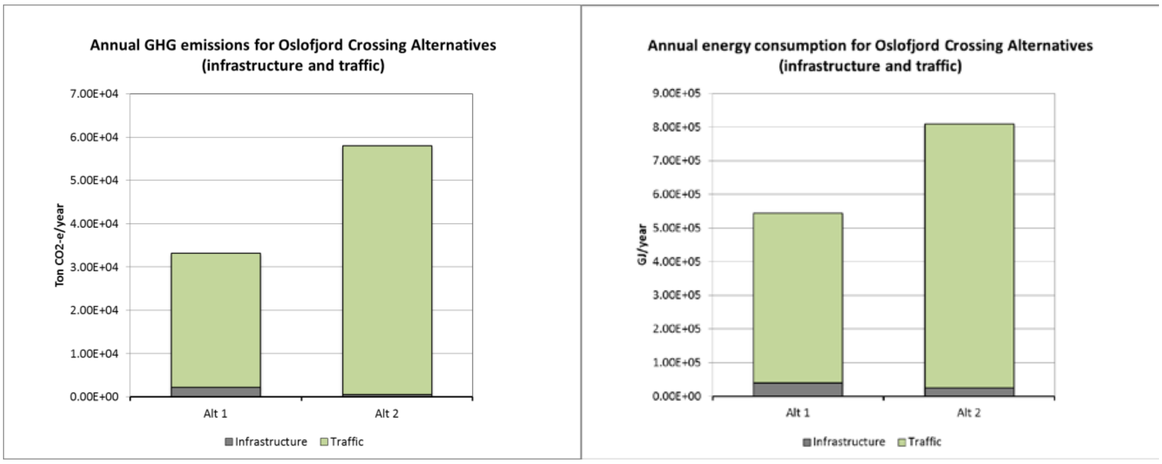


Figure 6: GHG emissions and energy consumption from combined infrastructure and traffic

The graph on the left side of Figure 6 shows that while Alternative 1 had much higher infrastructure GHG emissions, Alternative 2 has much higher traffic GHG emissions, which influences totally the overall results. Alternative 1 has 33 166 tons CO_2-equivalents per year due to traffic while Alternative 2 has 58 047 tons CO_2-equivalents per year. The graph on the right side also follows the same pattern, with Alternative 2 having a total annual energy use due to traffic of 808 385 GJ per year and Alternative 1 has 543 873 GJ per year. These very large differences are due to the road length in Alternative 2 being far longer than for Alternative 1.

Alternative 1 is 18010 metres long and Alternative 2 is 24400 metres long. This additional 6390 metres of length means that more fuel is used to get from one point to the other. As more fuel is used, this is an increase in direct energy use and emissions from combustion. Alternative 2 has nearly 50% more energy use and almost 75% more GHG emissions due to traffic because of the road length difference.

Figure 7 shows the annual GHG emissions and energy consumption corresponding to traffic type. Both Alternative 1 and 2 assume the same traffic level, type and fuel consumption variables.

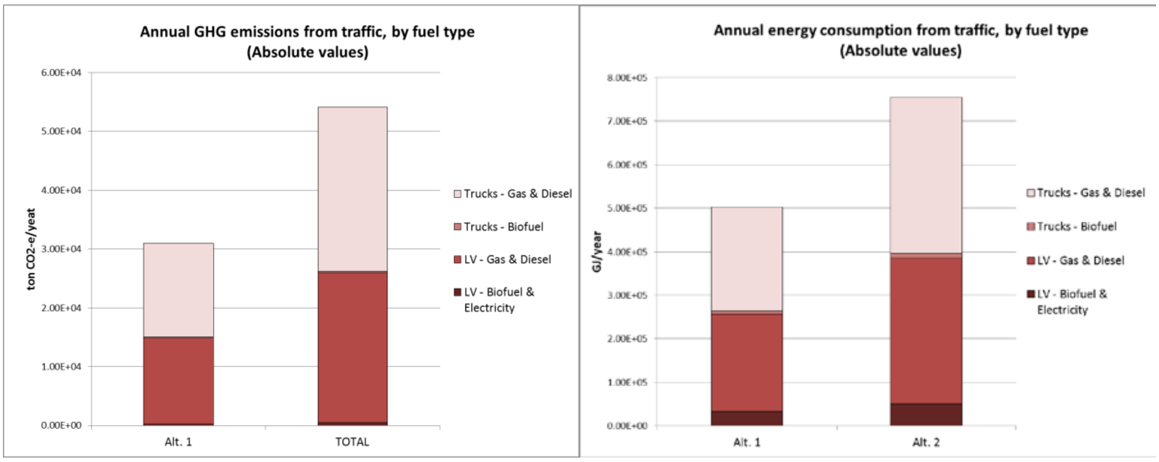


Figure 7: Annual GHG emissions and energy consumption due to traffic

The graph on the right shows that largest share of traffic comes from gas and diesel light vehicles and trucks, in almost equal parts. The GHG emissions due to biofuels and electricity are almost negligible but this is due to the very small rate of assumed biofuel and electricity vehicles in use. The annual energy consumption graph on the right of Figure 7 shows that the electric and biofuel vehicles are a small portion of all vehicle traffic on the two alternative routes.

Figure 6 and Figure 7 show the critical importance of including traffic results in an analysis of new road constructions. Traffic is the largest proportion of both alternatives for GHG emissions and energy use over the lifecycle of a road project. For more complete information of the total annual GHG emissions and energy use for Alternative 1 and 2, please see Table 20 and Table 21 in the appendix.

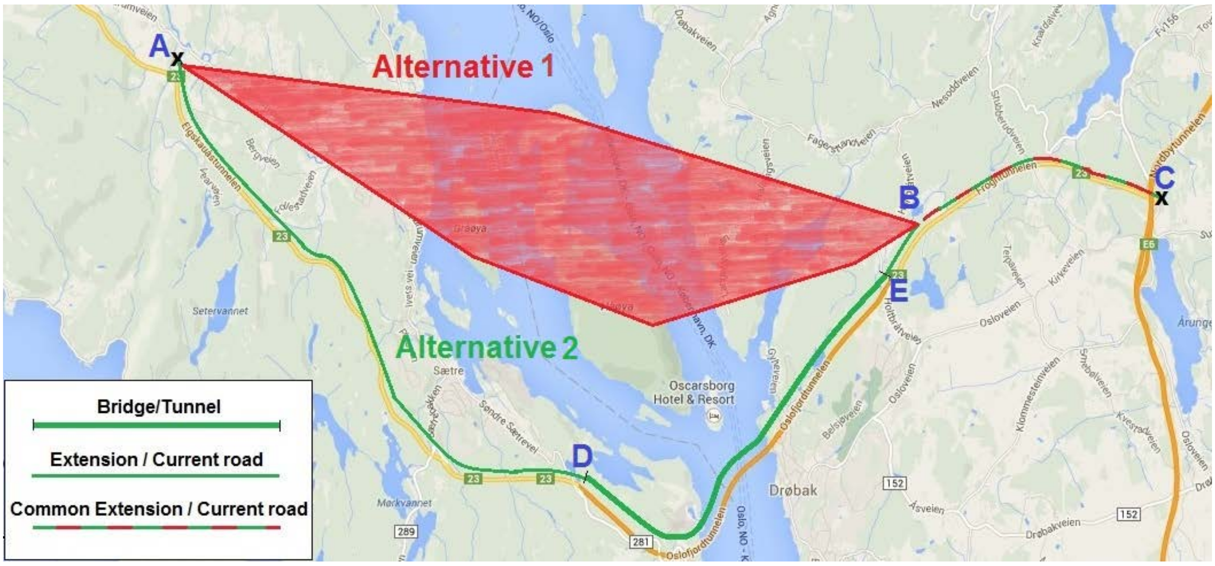
4 Discussion and conclusions

4.1 Influence of assumptions on results

The results calculated from the model require explanation and discussion to fully appreciate their meaning. The case provided two alternative methods to cross the Oslo fjord using different infrastructures and using some assumptions. These assumptions are made for various reasons, but mostly for simplifying the analysis. The idea of this case study is to show the flexibility and applicability of the LICCER model when handling complex road systems and multiple alternatives.

The discussion begins by stating the functional unit, which in this case study (and LICCER results in general) is to serve the expected traffic between two points over a fixed number of years. Alternative 1 and Alternative 2 were not of the same length, but they provided the same function of crossing the Oslo fjord for 7000 vehicles per day (at the beginning of the proposed project). The functional unit thus must be divided between a fixed beginning- and end-point, which is common for different alternatives when using the model in the way this case describes. This issue may become more complicated when traffic levels are different along different stretches of the route.

This case study included a series of road sections for each alternative as described in Chapter 2.3, partly with different traffic. This required a more complex calculation and compilation of results. To help with the explanation, here is Figure 3: Map of proposed Oslo fjord crossings, once more.



Alternative 1 was comprised of sections A→B→C. Daily traffic on section A→B was 7000 vehicles at starting point of the project while from B→C daily traffic was 12000 vehicles as other roads connect to this stretch. Alternative 2 was comprised of sections A→D→E→B→C. Daily traffic on sections A→D→E was 7000 vehicles while it was 12000 vehicles from E→B→C. The case study is first and foremost concerned with the crossing structures, meaning the bridges and tunnels. Thus the extra traffic (5000 vehicles traffic from outside) had to be allocated outside the analysis in order to complete a proper comparative analysis for the whole project. The analysis was done by organizing each stretch of road into the Adding-Up mode of the LICCER model and running separate calculations for the higher road traffic by allocating out the additional 5000 vehicles per day. After carrying out all the separate road stretch calculations, results for each alternative were compiled in a separate spreadsheet and finally compared against each other. This method satisfies the condition that the integrity of the functional unit remains while only accounting for the traffic that uses the two crossing alternatives.

Two important assumptions are made with respect to traffic in the case study analysis. In reality, fuel efficiency in vehicles is expected to increase over time and vehicles of all types are expected to use less fuel during the project lifetime. The case study, however, does not take into account the probably of increasing efficiency improvements in fuel consumption through the lifetime of the project. This first assumption was made to simplify the analysis in the absence of reliable data and leads to likely overestimate of fuel consumption in the results. The second traffic assumption was that the share of biofuel and electric powered vehicle use would be static throughout the lifetime of the case study. According to most projections, the number of renewable and electricity powered vehicles will increase over the next forty years. This assumption means another likely overestimation of GHG emission results.

Another important component of the analysis in the case study is the assumption that both projects have the same lifetime. The analysis assumed an analysis time horizon of 40 years, with 40 years of service life for roads and 60 years for bridges and tunnels. This means that only the first 40 years of the 60 years of service life for bridges and tunnels are accounted for in the analysis and end results. If the service life of bridges and tunnels was also chosen to be 40 years, to match the service life of roads in the project, there would be a corresponding increase in annual GHG emissions and energy use in the results.

The parameters used in the LICCER-model can be defined by the user when proper information is available. When this information is not available, or when others reasons are asking for that, there is a set of default parameter values to be used. However, these default values have inherent assumptions that can change results. For example, the effects of lighting in a tunnel are dependent upon the technology chosen. Today’s implemented technology for lighting is not particularly efficient when compared to emerging technology to be used in future, such as LED lighting. The use of background data in analysis means that parameter conditions for a project are embedded within the model in the form of per unit material consumption, transport distance, emissions coefficient, etc. These embedded default parameters are not always correct for a specific project and thus must be carefully checked by the user.

4.2 Sensitivity analysis

In this case study, as previously mentioned, two other long and newly built bridges in Norway (Hardanger bridge and Tresfjord bridge) were used as models for the proposed two bridges in Alternative 1. These two model bridges have greater steel and concrete consumption per m2 of bridge surface area than what is common for most (shorter) bridges in Norway, in the LICCER-model represented by bridge default values collected from the EFFEKT model. The implications for this selection can be shown in the results of a sensitivity analysis as shown in Figure 8, Figure 9, and Figure 10. The sensitivity analysis uses the exact same project specifications for all values including length and bridge area, service life and amount of daily traffic. The only changes made in the scenario analysis is the replacement of Alternative 1 bridge material consumption values for steel and concrete with the default values as used in the LICCER-model from EFFEKT.

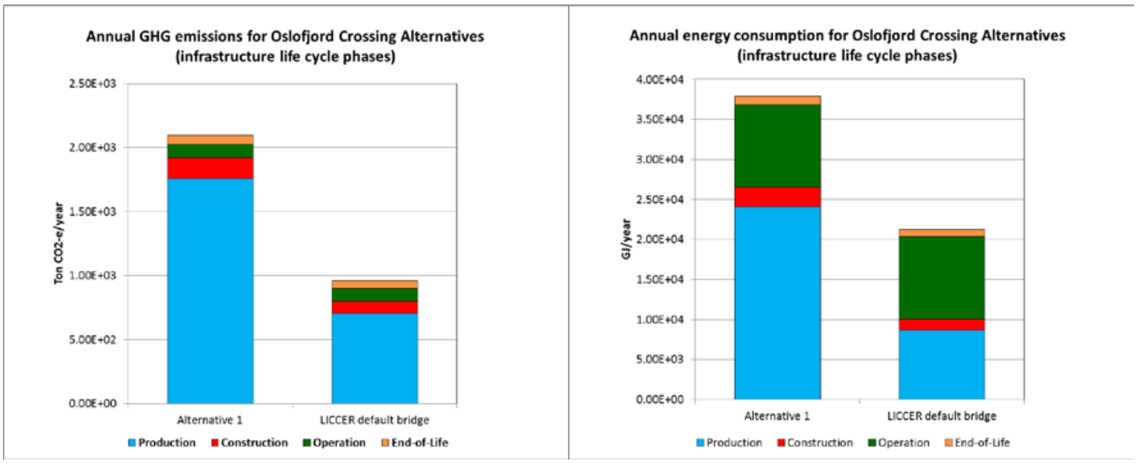


Figure 8: Annual GHG emissions and energy consumption for Alternative 1 bridge parameters and LICCER default bridge parameters in infrastructure by phase

Figure 8 shows the results of the sensitivity analysis organized according to lifecycle phase. In the graph on the left, the annual GHG emissions from the Alternative 1 and the LICCER default bridge are shown side by side. Immediately evident is the very large emissions associated with the bridge assumptions in Alternative 1, which is more than double results for the LICCER default bridge. The emissions difference between operation, construction and end-of-life do not differ all that much (or not at all) between the two alternatives. However, emissions associated with production are considerably higher in Alternative 1.

The graph on the right shows a similar pattern with annual energy use, where Alternative 1 dominates annual energy use from the production process while all other processes remain relatively equal. Figure 9 clarifies why these differences occur.

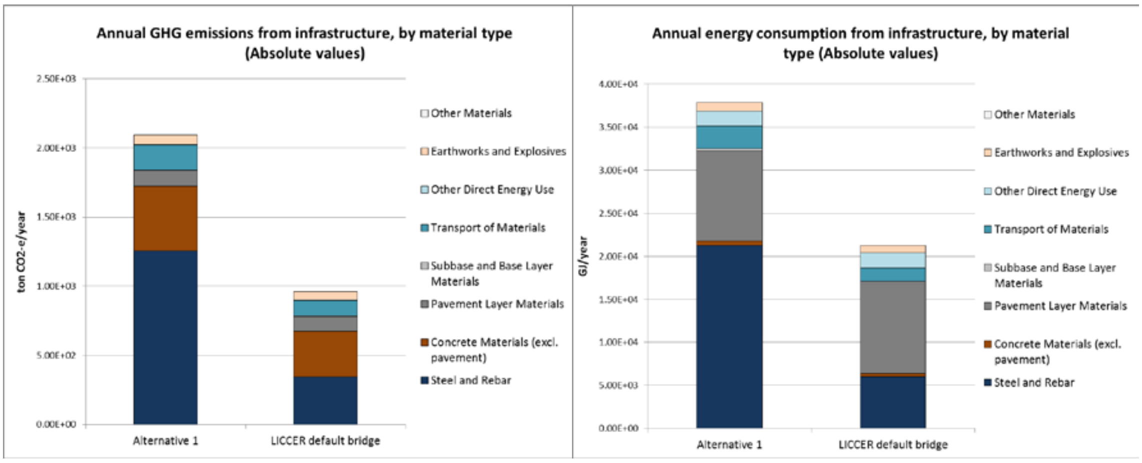


Figure 9: Annual GHG emissions and energy consumption for Alternative 1 bridge parameters and LICCER default bridge parameters in infrastructure by material type

The bridge assumptions in Alternative 1 requires more steel and concrete use than the average default LICCER bridge, as it is taller than a typical short bridge with which the reference data included in the LICCER model (from EFFEKT). Consequently, per unit length, the emissions and energy use from steel are much greater for Alternative 1 than for the LICCER default bridge. Not surprisingly, as all other material consumption requirements were left unaltered, there is no difference between them in the scenario analysis in Figure 9 shows.

Figure 10 takes the sensitivity analysis one step further by including traffic.

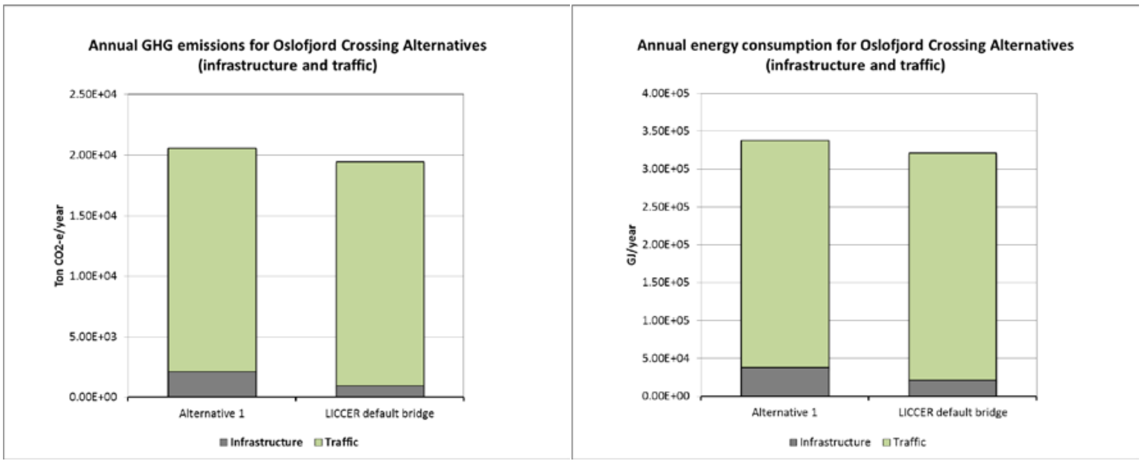


Figure 10: Annual GHG emissions and energy consumption for Alternative 1 bridge parameters and LICCER default bridge parameters when including traffic

Again, as all other project specifications remain the same, there is no difference between annual GHG emissions and energy use due to traffic.

Another consideration for the LICCER model that is not explicitly included is the lack of topographical information. There is an expectation that for a road section that is more “hilly” in comparison to a road section that is flat, fuel consumption from traffic will be greater. As an explicit part of the LICCER model, the only fuel consumption data that is included is data that comes from national datasets and thus takes only an average fuel use for the country chosen. Precise traffic emissions and energy use from a challenging topography, i.e. a road with many slopes, would not necessarily be well described analysis results using the LICCER model default fuel consumption values.

As a sensitivity exercise, the same analysis for the tunnel section D→E for Alternative 2 was re-modelled with an increase of 20% fuel consumption across all vehicles types due to the vertical gradient of the underwater tunnel. For an increase of 20% fuel consumption across all vehicle types, there was a 19.5% increase in total emissions and a 17.9% increase in total energy use for combined traffic and infrastructure for the tunnel project. Emissions and energy use due to traffic were correspondingly 20% higher than without the added fuel consumption.

The results of the sensitivity analysis are shown in Table 9 and Table 10 below.

Table 9: Sensitivity analysis for GHG emissions due to added fuel use in tunnel section D to E

PHASE	(unit)	Increased Fuel Use	Alternative 2 Tunnel	Difference
Infrastructure	ton CO2-e/year	376.18	376.18	0.0 %
Traffic	ton CO2-e/year	18 420.87	15 350.67	20.0 %
Net total	ton CO2-e/year	18 797.04	15 726.85	19.5 %

Table 10: Sensitivity analysis for energy use due to added fuel use in tunnel section D to E

PHASE	(unit)	Increased Fuel Use	Alternative 2 Tunnel	Difference
Infrastructure	GJ/year	2.93E+04	2.93E+04	0.0 %
Traffic	GJ/year	2.99E+05	2.49E+05	20.0 %
Net total	GJ/year	3.29E+05	2.79E+05	17.9 %

The sensitivity analysis shows that the use of default values can certainly mean less precise results and it is therefore prudent to find as good as possible project-specific values to use in LICCER-model calculations (unless there are reasons to refrain from project-specific values). The use of project-specific values is likely to be generally important for road elements that represent 'heavy structures' such as long and/or high bridges and long tunnels (likely to consume more concrete, rebar and steel in construction, or electricity for lighting and ventilation in operation, than what is assumed in the default values). Project-specific values could also be commonly used for fuel consumption from traffic.

4.3 Conclusion

The case study shows the LICCER model can be used to analyse complex road infrastructure and traffic situations in the early-stage planning of new road projects. The case study provided five separate route sections along two separate road corridor alternatives for the Oslo fjord crossing, and was designed to show the applicability of the LICCER-model for calculating the annual GHG emissions and energy use over a 40 years analysis time horizon. Combined with other analysis tools on the market, the LICCER-model can help road authorities reach a consensus on road infrastructure decisions.

On the basis of what was calculated and observed in this case study, it seems evident that traffic during the operation phase will be the largest contributor to annual GHG emissions and energy use for the alternative choices in the Oslo fjord crossing. Hence, it is important to search for a road corridor that represents the shortest possible driving distance. From the results in this case study the conclusion is that contributions from traffic is much more important than the contributions from road infrastructure, even though this case study includes long distances with heavy structure elements of bridges and/or tunnels. Despite this finding, national road administrations should of course also try to minimise the energy use and GHG emissions from the road infrastructure. One reason for this is that the relative contributions from infrastructure are likely to be higher in future than today, as fuel generation and vehicle technologies are expected to improve, using higher shares of biofuel and electric vehicles than what was assumed in this case study. As part of the early planning process for road infrastructure and road projects, the goal of the LICCER-model is to provide relevant information to influence decisions. This case study demonstrated that the model has sufficient flexibility to provide such information, also for a complex road project, and that the model is able to point to what are the important elements and factors within the life cycle of the road project.

The case study also clearly indicate that Alternative 1 has higher annual energy use and GHG emissions when including only the contributions from road infrastructure, due to the two long two bridges in this alternative, but that Alternative 2 has the highest overall annual energy use and GHG emissions when traffic is also included, simply because Alternative 1 is shorter. As part of the sensitivity analysis, Alternative 1 also considers a specific bridge type outside constraints of a typical Norwegian bridge. The results may become even more promising for Alternative 1 if less material-intensive bridge design solutions (closer to the default values for bridges, provided by the EFFEKT dataset) can be chosen.

The results of this case study give a clear recommendation to decision makers with regard to which alternative is less energy use and GHG emission intensive.

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APPENDIX – Background data in the LICCER-model

This appendix includes tables presenting the background data included in the LICCER-model that were used for the case study presented in this report.

Table 11: Emission factors used in the case study, data included in LICCER-model for Norway.

Material	*GHG-emissions*	*Unit*	*Reference*
Aggregate	2.39	kg/ton	EFFEKT (Norwegian electricity mix)
Bitumen	430.00	kg/ton	Idemat (2012)
Asphalt membrane	206.00	kg/ton	EFFEKT (Norwegian electricity mix)
Aggregate/Gravel in reasphaltation	2.39	kg/ton	EFFEKT (Norwegian electricity mix)
Bitumen in reasphaltation	430.00	kg/ton	Idemat (2012)
Asphalt mixing	5.99	kg/ton	Zapata (2005) (Norwegian electricity mix)
Sand / Soil	2.39	kg/ton	EFFEKT (Norwegian electricity mix)
Concrete	236.00	kg/m3	EFFEKT (Norwegian electricity mix)
Diesel	3190.00	kg/m3	EFFEKT (Norwegian electricity mix)
Biofuel	691.00	kg/m3	Øsftoldforskning (2009)
Electricity	0.02	kg/kWh	EFFEKT (Norwegian electricity mix)
Explosives	2380.00	kg/ton	EFFEKT (Norwegian electricity mix)
Gasoline	2750.00	kg/m3	EFFEKT (Norwegian electricity mix)
Gravel	2.39	kg/ton	EFFEKT (Norwegian electricity mix)
PE-foam	2470.00	kg/ton	EFFEKT (Norwegian electricity mix)
Rebar (reinforcement steel)	754.79	kg/ton	EFFEKT (Norwegian electricity mix)
Rockfill	1.80	kg/ton	EFFEKT (Norwegian electricity mix)
Shotcrete	454.64	kg/m3	Østfoldforskning (2013), Mie Vold
Steel	1610.00	kg/ton	EFFEKT (Norwegian electricity mix)
Lime, soil stabilization	780.00	kg/ton	Hammond, Jones (2011)
Cement	748.00	kg/ton	NORCEM EPD (2013), Standard cement
Transport work	0.13	kg/tkm	EFFEKT (Norwegian electricity mix)

Table 12: Energy factors used in the case study, data included in the LICCER-model for Norway.

Material	*Energy use*	*Unit*	*Reference*
Aggregate	73.5	MJ/ton	EFFEKT (Norwegian electricity mix)
Bitumen	52 000	MJ/ton	Idemat (2012)
Asphalt membrane	6 900	MJ/ton	EFFEKT (Norwegian electricity mix)
Bitumen in reasphaltation	52 000	MJ/ton	Idemat (2012)
Asphalt mixing	390	MJ/ton	Zapata (2005)
Sand/soil	73.5	MJ/ton	EFFEKT (Norwegian electricity mix)
Concrete	261	MJ/m3	EFFEKT (Norwegian electricity mix)
Diesel	47 850	MJ/m3	EFFEKT (Norwegian electricity mix)

Biofuel	23 433	MJ/m3	Øsftoldforskning (2009)
Electricity	4.53	MJ/kWh	EFFEKT (Norwegian electricity mix)
Explosives	28 750	MJ/ton	EFFEKT (Norwegian electricity mix)
Gasoline	42 790	MJ/m3	EFFEKT (Norwegian electricity mix)
Gravel	73.5	MJ/ton	EFFEKT (Norwegian electricity mix)
PE-foam	86 540	MJ/ton	EFFEKT (Norwegian electricity mix)
Rebar (reinforcement steel)	14 324	MJ/ton	EFFEKT (Norwegian electricity mix)
Rockfill	24.7	MJ/ton	EFFEKT (Norwegian electricity mix)
Shotcrete	3 040	MJ/m3	Østfoldforskning (2013), Mie Vold
Steel	25 710	MJ/ton	EFFEKT (Norwegian electricity mix)
Cement	5 484	MJ/ton	NORCEM EPD 2012, Standard cement
Lime in soil stabilization	5 300	MJ/ton	Hammond, Jones (2011)
Transport work	1.82	MJ/tkm	EFFEKT (Norwegian electricity mix)

Table 13: Specific material consumption used in the case study, data included in the LICCER-model for Norway

Material	*Value*	*Unit*	*Reference*
Asphalt, depth of layer replaced in each reasphaltation	0.050	m thickness replaced	EFFEKT
Asphalt membrane, bridge surface	26.00	kg/m2 surface area	EFFEKT
Concrete, concrete bridges	1.31	m3/m2 surface area	EFFEKT
Concrete, steel bridges	0.71	m3/m2 surface area	EFFEKT
Concrete, tunnel portals	31.50	m3/m Arch-T per tunnel	EFFEKT
Concrete, tunnel wall elements	0.90	m3/m tunnel length	SVV Håndbok 21
Concrete, tunnel vault cast lining	0.50	m3/m2 vault area	SVV Håndbok 21
Concrete, guardrails	700.00	kg/m railing length	Assumed, based on Producers' data
Cement, In-situ soil stabilization	0.06	ton/m3 stabilized soil	Recalculated from (Rydberg 2002)
Cement, Mass stabilizing in soil stabilization	0.08	ton/m3 stabilized soil	Recalculated from (Rydberg 2002)
Cement, Lime-Cement columns in soil stabilization	0.08	ton/m2 area	Recalculated from (Rydberg 2002)
Lime, Lime-Cement columns in soil stabilization	0.08	ton/m3 stabilized soil	Recalculated from (Rydberg 2002)
Diesel, transportation of masses in earthwork	0.035	liter/tkm mass transport	EFFEKT
Diesel, machinery for earthwork in road construction	0.80	liter/m3 loose materials	EFFEKT
Diesel, uploading blasted tunnel rock	0.15	liter/m3 loose materials	EFFEKT
Diesel, earthworks, blasted rock	0.80	liter/m3 loose materials	Assumed
Diesel, earthworks, simple soil excavation	0.80	liter/m3 loose materials	EFFEKT
Diesel, earthworks, soil ripping	0.80	liter/m3 loose materials	EFFEKT
Diesel, End-of-Life pavement removal	0.80	liter/m3 loose materials	EFFEKT
Diesel, End-of-Life base & subbase removal	0.80	liter/m3 loose materials	EFFEKT
Diesel, End-of-Life concrete structures demolition	5.00	liter/m3 concrete structure	Assumed
Diesel, End-of-Life earthworks	2.00	liter/m2 total road area	EFFEKT
Electricity, drilling/ventilation tunnel construction	450	kWh/m	EFFEKT
Electricity, lighting roads and bridges in use phase	26.5	kWh/year/m	EFFEKT
Electricity, lighting tunnel in use phase	26.5	kWh/year/m	EFFEKT
Electricity, ventilation tunnel in use phase	7.5	kWh/year/m	EFFEKT
Electricity, ventilation underwater tunnel in use phase	15.5	kWh/year/m	EFFEKT
Electricity, water pumping u.w.tunnel in use phase	18.0	kWh/year/m	EFFEKT
Explosives, road construction	1.00	kg/m3 rock in situ	EFFEKT
Explosives, tunnel construction	2.20	kg/m3 rock in situ	EFFEKT
PE-foam, tunnel vault lining	0.05	m3/m2 vault area	EFFEKT
Rebar, concrete bridges	0.22	ton/m2 surface area	EFFEKT
Rebar, other	0.12	ton/m3 concrete	EFFEKT
Rebar, steel bridges	0.11	ton/m2 surface area	EFFEKT
Rebar, concrete elements tunnel	0.12	ton/m3 concrete element	EFFEKT
Rebar, tunnel portals	2.86	ton/m arch length	EFFEKT
Rebar, tunnel vault lining	0.021	ton/m2 vault area	EFFEKT
Shortcrete, tunnel vault lining	0.08	m3/m2 vault area	SVV Håndbok 21
Steel, guardrails	0.021	ton/m guardrail	EFFEKT
Steel, securing bolts tunnel	2.00	kg/m2 vault area	EFFEKT
Steel, steel bridges	0.22	ton/m2 surface area	EFFEKT

Table 14: Fuel consumption of vehicles, data included in LICCER-model for Norway.

Type of fuel	*Fuel consumption*	*Unit*	*Reference*
Diesel fuel, traffic use phase, Trucks, no trailer	1.92	liter/10km	TØI 2009
Diesel fuel, traffic use phase, Trucks, with trailer	3.00	liter/10km	TØI 2009
Diesel fuel, traffic use phase, Light vehicles	0.54	liter/10km	TØI 2009
Gasoline fuel, traffic use phase, Light vehicles	0.73	liter/10km	TØI 2009
Electricity, traffic use phase, Light vehicles	1.61	MJ/km	TØI 2009

Table 15: Transport distance of materials to the construction site, data included in LICCER-model for Norway

Material	*Transport distance (km)*
Aggregate/gravel, all usage except pavement asphalt	20
Asphalt membrane	150
Asphalt, pavement (incl. bitumen and aggregate)	30
Sand/soil, all usage	20
Concrete, pavement	150
Concrete, bridges	150
Concrete, tunnel portals	150
Concrete, tunnel wall elements	150
Concrete, tunnel lining (cast on site)	150
Concrete, other	300
Concrete, guardrails	150
Cement, soil stabilization	300
Lime from lime pillars, soil stabilization	300
Explosives	150
PE-foam, tunnel lining	300
Rebar, bridges	500
Rebar, tunnel wall elements	500
Rebar, tunnel portals	500
Rebar, tunnel lining	500
Rebar, other	500
Shortcrete, tunnel lining	150
Steel, guardrails	500
Steel, tunnel securing bolts	500
Steel, steel bridges	500

Table 16: Length of current road infrastructure for Oslofjord crossing Alternative 1

Length of road elements (m)	*Total sections*	*Total combined length (m)*
Existing two lane road	2	1300
Existing tunnel	2	1988
Existing concrete bridge	2	262

Table 17: Length of road upgrades from two to four lanes for Oslofjord crossing Alternative 1

Length of road elements (m)	*Total sections*	*Total combined length (m)*
Extended road	2	1300
Existing tunnel extension	2	1870
Concrete bridge extension	1	262

Table 18: Length of new road constructions for Oslofjord crossing Alternative 1

Length of road elements (m)	*Total sections*	*Total combined length (m)*
New road	3	10400
New steel bridge	1	1500
New concrete bridge	1	2560

Table 19: Length of current road infrastructure for Oslofjord crossing Alternative 2

Length of road elements (m)	*Total sections*	*Total combined length (m)*
Existing two lane road	5	11140
Existing tunnel	2	5598
Existing underwater tunnel	1	7306
Existing concrete bridge	2	262

Table 20: Length of road upgrades from two to four lanes for Oslofjord crossing Alternative 2

Length of road elements (m)	*Total sections*	*Total combined length (m)*
Extended road	2	3750
Existing tunnel extension	2	1870
Concrete bridge extension	1	262

Table 21: Length of new road constructions for Oslofjord crossing Alternative 2

Length of road elements (m)	*Total sections*	*Total combined length (m)*
New underwater tunnel	1	7400

Table 22: Aggregated GHGs by material and fuel type for all lifecycle phases

Material/Fuel	*Unit*	*Alt.1*	*Alt.2*
Steel and Rebar	ton CO2-e/year	1 261.24	14.87
Concrete Materials (excl. pavement)	ton CO2-e/year	525.57	176.20
Pavement Layer Materials	ton CO2-e/year	125.16	106.54

Subbase and Base Layer Materials	ton CO2-e/year	7.37	3.84
Transport of Materials	ton CO2-e/year	194.67	54.90
Other Direct Energy Use	ton CO2-e/year	8.67	85.99
Earthworks and Explosives	ton CO2-e/year	81.29	98.79
Other Materials	ton CO2-e/year	-	-
LV - Biofuel and Electricity	ton CO2-e/year	269.85	471.27
LV - Gas and Diesel	ton CO2-e/year	14 602.62	25 502.58
Trucks - Biofuel	ton CO2-e/year	158.83	277.39
Trucks - Gas and Diesel	ton CO2-e/year	15 931.35	27 823.12
Total	ton CO2-e/year	33 166.62	54 615.48

Table 23: Aggregated energy consumption by material and fuel type for all lifecycle phases

	Unit	Alt.1	Alt.2
Steel and Rebar	GJ/year	21 350.18	249.72
Concrete Materials (excl. pavement)	GJ/year	682.03	622.38
Pavement Layer Materials	GJ/year	12 153.64	8 803.78
Subbase and Base Layer Materials	GJ/year	226.66	118.04
Transport of Materials	GJ/year	2 811.89	751.27
Other Direct Energy Use	GJ/year	2 557.16	14 123.54
Earthworks and Explosives	GJ/year	1 219.36	1 289.93
Other Materials	GJ/year	-	-
LV - Biofuel and Electricity	GJ/year	33 502.02	50 257.48
LV - Gas and Diesel	GJ/year	223 187.93	334 811.55
Trucks - Biofuel	GJ/year	7 211.98	10 818.92
Trucks - Gas and Diesel	GJ/year	238 970.23	358 487.11
Total	GJ/year	543 873.07	780 333.72