LICCER

LICCER Model Technical Report

Account of technical backgrounds of the LICCER model

Report No. 4.2 (final 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 trans-national 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 framework and the model are described in detail in this report. The model aims on decision-support in the early stage of transport planning. A guideline will further elaborate on the use and aim of the model.

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

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1.2 Reason for the LICCER model

Energy use and greenhouse gas (GHG) emissions are typically associated with vehicles operation. Road infrastructure, however, also involves energy use and GHG emissions as a consequence of production and construction of road elements (e.g. roads, bridges and tunnels), operation of the road (e.g. for lighting and maintenance) and end-of-life processing after a road becomes obsolete. All these stages together form the life cycle of road infrastructure.

Several researchers have estimated the share of road infrastructure in the total energy use and GHG emissions from road transport system (i.e. road infrastructure plus direct emissions during traffic operation). The estimates vary from about 3 % of the total GHG emissions in the Netherlands (Pers. Com. Evert Schut, 2013), to about 22% of the total energy used for road transport system (Jonsson, 2007). Literature does not provide consistent indications about the share of road infrastructure in the total, but it is likely that this share will also depend on local conditions. For instance, traffic density in the Netherlands will on average surpass by far traffic density in Nordic countries. Local conditions also involve topography, share of rock, and the involved consumption of material intensive structures like bridges, underpasses and tunnels. More importantly, in case of upgrading existing roads, the energy use and GHG emissions related to the new road infrastructure may supersede the energy use and GHG emissions from the *change* in traffic movements. In general, however, changes in infrastructure reflect changes in traffic density. Consequently, life cycle energy use and GHG emissions from road infrastructure should not be neglected during road infrastructure planning decisions.

Energy use and GHG emissions are just among a range of other potential environmental impacts associated to road infrastructure. In order to ensure that all environmental implications are taken into account before a decision is approved, the European Union requires the performance of Environmental Assessments (European Commission, 2012). Current practice does show, however, that impacts such as life cycle GHG emissions and energy use from the construction of road infrastructure are often omitted from Environmental Assessments (Finnveden and Åkerman, 2011; Hilden et al., 2004).

Miliutenko et al. (2013) analysed road infrastructure planning processes in four countries (Sweden, Norway, Denmark and the Netherlands), and confirmed that life cycle energy use and GHG emissions are (often) not included in Environmental Assessment in the Netherlands, Sweden and Denmark (Miliutenko et al., 2013). A life cycle perspective, if included at all, is typically used later in the planning process. It is then usually not part of an Environmental Assessment, but used stand-alone for assessing the environmental impacts of (detailed) construction designs. In this stage different LCA models are used, such as DuboCalc in the Netherlands; Anavitor and/or LCcalc in Sweden; and ROAD-RES in Denmark. Only the Netherlands has an obligatory requirement for using LCA in the procurement stage, valid for the national highway network.

Norway is the only country with a formalized way of using life cycle considerations during the early stages of the road infrastructure planning process. This is done with the help of the Norwegian EFFEKT model that is developed for this purpose by the Norwegian National Road Administration. The EFFEKT model is a tool for estimating life cycle energy use and GHG emissions in road projects, as part of EIA cost-benefit analysis in feasibility studies of new road projects (Sandvik and Hammervold, 2008). There is a need for developing a similar tool as EFFEKT for assessment of life cycle energy use and GHG emissions in the early stages of the road infrastructure planning process for other countries, including Sweden, Denmark and the Netherlands. This is where LICCER is designed to contribute.

1.3 Important model notions

As described in literature reviews by Miliutenko (2009) and Muench (2010), several studies have been performed on the assessment of life cycle impacts of road transport infrastructure (e.g. Stripple (2001), Jonsson (2007), Karlsson and Carlson (2010), Birgisdottir (2006) and others). Even though these studies are often difficult to compare with each other, similar trends can still be observed. For instance, all of these studies concluded that production of construction materials have the highest share in energy use and GHG emissions during the life cycle of roads and bridges (excluding direct emissions from vehicles) (Hammervold et al., 2009; Muench, 2010). This may not be the case for roads and tunnels where tunnel operation has the highest share (due to energy use and GHG emissions for lighting and ventilation) (Karlsson and Carlson, 2010; Miliutenko et al., 2012). All elements other than the road itself notably contribute in all cases, and there is thus a need for a life-cycle perspective.

When assessing planned road infrastructure a life-cycle perspective is important in order not to sub-optimise or miss important changes. The LICCER model focuses on life cycle cumulative energy consumption and GHG emissions. Energy consumption is a major precursor for GHG emissions and subsequent climate change, but also for other important environmental impacts, e.g. acidification and eutrophication. These environmental impacts have a strong correlation with energy use as they are largely caused by the emissions from fuel combustion (Huijbregts et al., 2006). Such environmental impacts may therefore be underestimated or neglected in road planning in absence of any life cycle considerations.

It is decided to develop the LICCER model with inspiration from the Norwegian EFFEKT model. The EFFEKT model has already been developed, and is now implemented for use in the early stage of road planning for similar purposes (Straume, 2011). The LICCER model will have to be prepared, however, for use also in other countries with a different set of country-specific norms and default values for road infrastructure. Those countries initially are Sweden, Denmark and The Netherlands, but may in the future also include other countries. It is therefore decided to develop a LICCER model that is more flexible with respect to input values and road element design options than what is offered in EFFEKT model. LICCER furthermore sometimes uses other calculation rules than what is found in EFFEKT. This is necessary in order to develop a LICCER model that is suitable for other countries.

1.4 Model use

The aim of the LICCER project is to develop an easy to use model, including user guidelines, based on existing tools and methodologies for Life Cycle Assessment of road infrastructure. The model is at present limited to assessing life cycle cumulative energy consumption and GHG emissions, but could be expanded to host other impact categories in the future.

The model is to be used at the early stage of the planning process where different options are identified and screening evaluation is performed, as shown on Figure 1, based on Toller (2012).

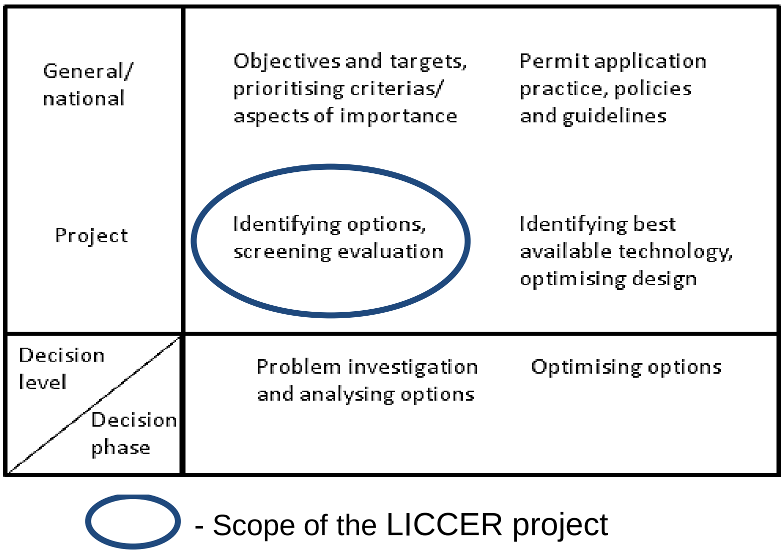


Figure 1: Framework for decision making showing the scope of LICCER project

The LICCER LCA-model is developed as a Microsoft-Excel tool, and offers a method to calculate the annual *energy use* (i.e., cumulative energy consumption) and the related annual *greenhouse gas (GHG) emissions* (i.e. CO_2-equivalents) over the life cycle of the road project. This enables to include these indicators in the early stage of the planning process for examining the environmental quality of different location alternatives for a new road corridor.

The model includes site-dependent aspects of the planning such as the choice of road elements (e.g. plain road, bridge or tunnel) and how they may vary accordingly. The model quantifies energy use and related GHG emissions in all life cycle stages of road infrastructure and indicatively also for traffic during operation after the road is constructed (see chapter 2.3). Life cycle stages of road infrastructure refer to production and construction of road elements (e.g. roads, bridges and tunnels), operation (e.g. for resurfacing, lighting and maintenance) and end-of-life processing after a road becomes obsolete). Energy use includes energy needed for producing material (such as pavement materials) and secondary energy carriers (such as electricity and fuel). Production and construction cover all life cycle material and energy inputs that are expected to play a significant role with respect to influencing the life cycle energy use and the life cycle GHG emissions.

The LICCER model enables National Road Agencies and other stakeholders to compare different road corridor alternatives in decision-making processes. Moreover, the knowledge from this project can be a useful input in Strategic Environmental Assessment (SEA) that considers the whole transportation system (including land, water and air transport), as it will give a differentiated information on the energy use and GHG emissions to be expected from road infrastructure. The knowledge obtained from the LCA model can also serve as a basis for more detailed assessments on how to design a specific road, as the energy use and GHG emission related hotspots of the overall road (infrastructure and traffic) system will be identified. Most likely, after a time of having regularly used the LICCER model in planning projects, road planners will have developed a much better understanding of such issues – and what to avoid and what to try to include more of in road planning projects – with a good chance of improved decision support and better solutions in the road transport sector.

Recommendations on how to use the model in the EIA processes are provided in a separate LICCER Model Guideline Report. This document provides the technical documentation of the LICCER model.

2 Life Cycle Assessment Methodology

2.1 Life Cycle Assessment

The LICCER model is based on Life Cycle Assessment (LCA) methodology following ISO 14044.

LCA is a systems analysis tool that takes into account potential environmental impacts of a product or service throughout the whole life cycle from raw material acquisition to transport, production and use, as well as the impact from activities in the end-of-life stage (ISO 14040, 1997). According to the definition by UNECE (2007), "LCA may be applied within the whole process of decision-making: identification of issues and impacts, analysis context and baseline, contributing to development of alternatives, assessment of impacts, comparing the options".

LCA methodology consists of four main phases; see Figure 2 (ISO 14040, 1997): 1) defining of the goal (why) and scope (how) of the study (including determining the boundaries and the functional unit); 2) inventory analysis that involves data collection about every life cycle stage, and therefrom calculating the environmental burdens associated with the whole life cycle; 3) impact assessment; and 4) interpretation of the results.

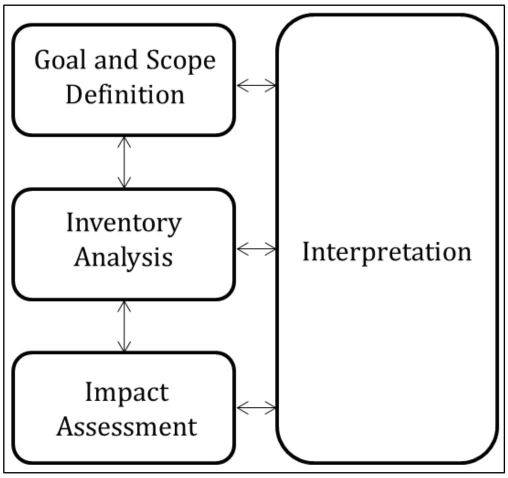


Figure 2: Life cycle assessment framework; phases of LCA

2.2 Goal of the LICCER model analysis

The main *objective* of using the LICCER model is to provide planners with information about the annual cumulative energy consumption and greenhouse gas (GHG) emissions related to the choice of new road corridors in a new road project. The model also deals with extensions of existing roads, and continued use of existing roads. This information can be used in the early stage road planning where the decision is made regarding choice of new road corridors in a new road project. The LICCER model shall provide quantitative information on how new road corridor alternatives (routes) influence the life cycle energy use and GHG emissions. The new road corridor alternatives shall, if possible, be compared with the reference alternative in which no new road infrastructure is constructed (i.e., the existing road is to be used also in future, without adding new infrastructure elements). The LICCER model accounts for energy use and GHG contributions from the whole life cycle of the project, including production, construction, operation and end-of-life stages, and include contributions from both the road infrastructure and the traffic on the road during operation. The model provides default values that are relevant for the country where the road project is located. The model also offers the opportunity to users for running the model with project specific values, replacing the default values, if and when available, for increased flexibility and getting to as correct results as possible. The purpose of the LICCER model is to offer to road planners a quantitative basis for better understanding of how solutions in new road projects could be chosen in order to reduce the life cycle cumulative energy consumption and GHG emissions.

2.3 Scope of the LICCER model

One of the important steps in the LCA procedure is defining the functional unit, which is a reference unit that describes the quantitative and qualitative performance of a product system (Weidema et al., 2004). The object of an assessment determines the functional unit, but the *functional unit* for analysis of new road infrastructure may take the form of:

> "Road infrastructure enabling annual traffic between "A" and "B" over an analysis time horizon of a defined number of years."

The road infrastructure alternatives providing this function may be the road infrastructure as it is now (the common reference alternative), or any new road corridor alternative with new infrastructure elements. The road infrastructure will be used over a longer period of time, and it is therefore necessary to estimate the future change (possibly growth) in traffic and to adjust all calculations for the service life of road infrastructure components in order to express all data on a yearly basis.

In the LICCER LCA model is limited to calculating cumulative energy consumption (in GJ/year) and the related GHG emissions (in kg CO_2-eq/year) over the whole life cycle of the road project. Other environmental impacts are not included. The model will calculate results in *annual average values for the analysis time horizon*. It is decided to use the annual average value over the analysis time horizon, not the value for the whole service life of the road, due to the fact that the yearly traffic on the road normally will increase with time and may be difficult to estimate far into the future.

The system boundaries of the analysis are defined as shown on Figure 3, where the main life cycle stages included for road infrastructure system and traffic on road during operation are as following:

- Production stage of road infrastructure (cradle to gate upstream activities for production of resource inputs, i.e. from raw material acquisition to the point of supply/sales of each input material commodity
- Construction stage of road infrastructure (on site construction activities and earthworks, transport of input material commodities from point of supply/sales to the construction site, and project internal transport work);
- Operation of road infrastructure (operation activities of resurfacing, transport work of resurfacing materials, and electricity for lighting, ventilation and water pumping);
- End-of-life of road infrastructure (demolition and removal of pavement, base and sub-base materials, concrete structures (excl. in tunnels), earthworks, and transportation of removed materials to permanent or reuse depots);

- Traffic on road during operation (energy use and related GHG emissions for consumption of gasoline, diesel, biofuel and electricity in light and heavy vehicles operating on the analysed road corridor after it has been constructed).

The model offers only a simplified method for calculation of energy use and GHG emissions from traffic on the road during operation. It does not take into account the influence of road design on the energy use and GHG emissions from traffic (for instance due to rolling resistance of the pavement), however, the model-user may insert project-specific values for fuel consumption per kilometre for different vehicle types. Local conditions (such as vertical gradients, travel speed and rolling resistance) may give input to the choice of such project-specific values.

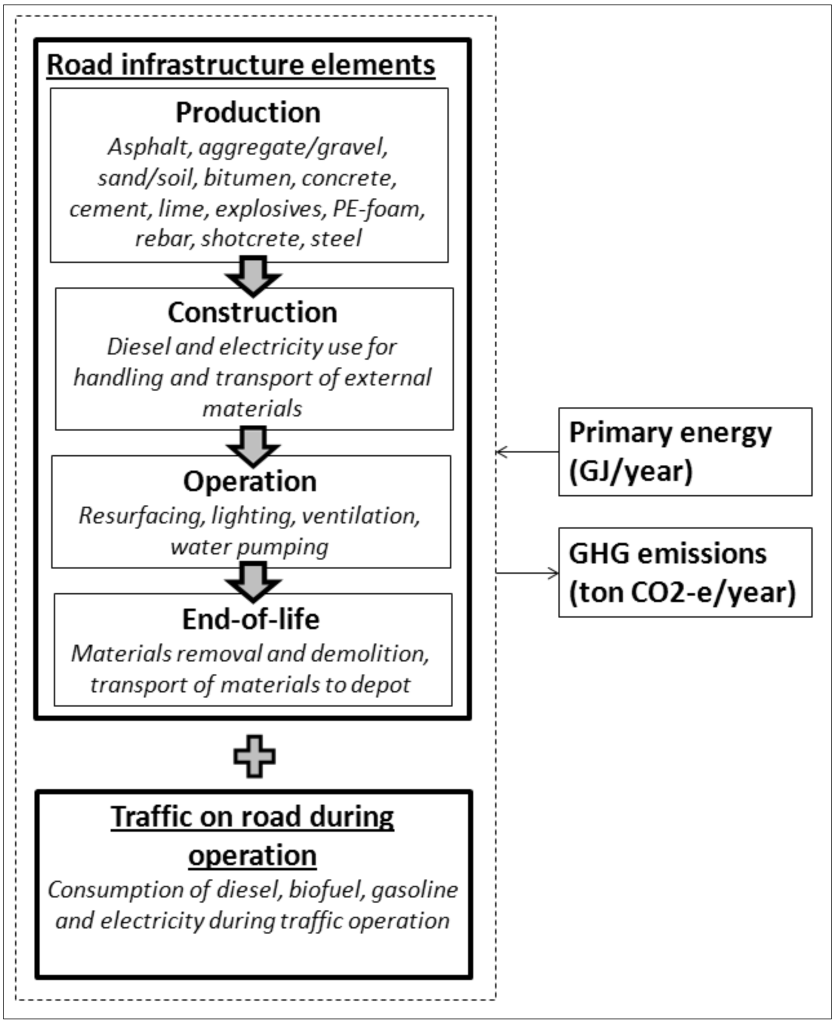


Figure 3: Simplified system boundaries in the LICCER model

3 Model structure and database

3.1 Overview of the model

Figure 4 illustrates the overall LICCER model structure. As shown, the LICCER model is based on project input variables for which the data is to be filled into the model by the user, and default model internal mathematical algorithms in combination with default values for model internal parameters and coefficients. The LICCER model also has the flexibility for replacing these default values for model internal parameter settings by project-specific values provided by the user (i.e. project relevant input data and specification of alternatives).

Based on this input, the LICCER model will offer:

i) Default values on service life of road infrastructure components, transport distances for materials and masses, fuel consumption for selected road construction activities, base material and pavement mixes, tunnel cross-section variables, specific material consumption and GHG emissions and energy use data for Sweden and Norway. The user will have an opportunity to specify his own data for these model internal parameters (in case project-specific values are known)

ii) A calculation engine, i.e. the mathematical algorithms, that calculates system-wide physical inventory flows (like total use of materials, diesel fuel, transport work, and electricity) to quantify life cycle energy use and GHG emissions

iii) Presentation of results.

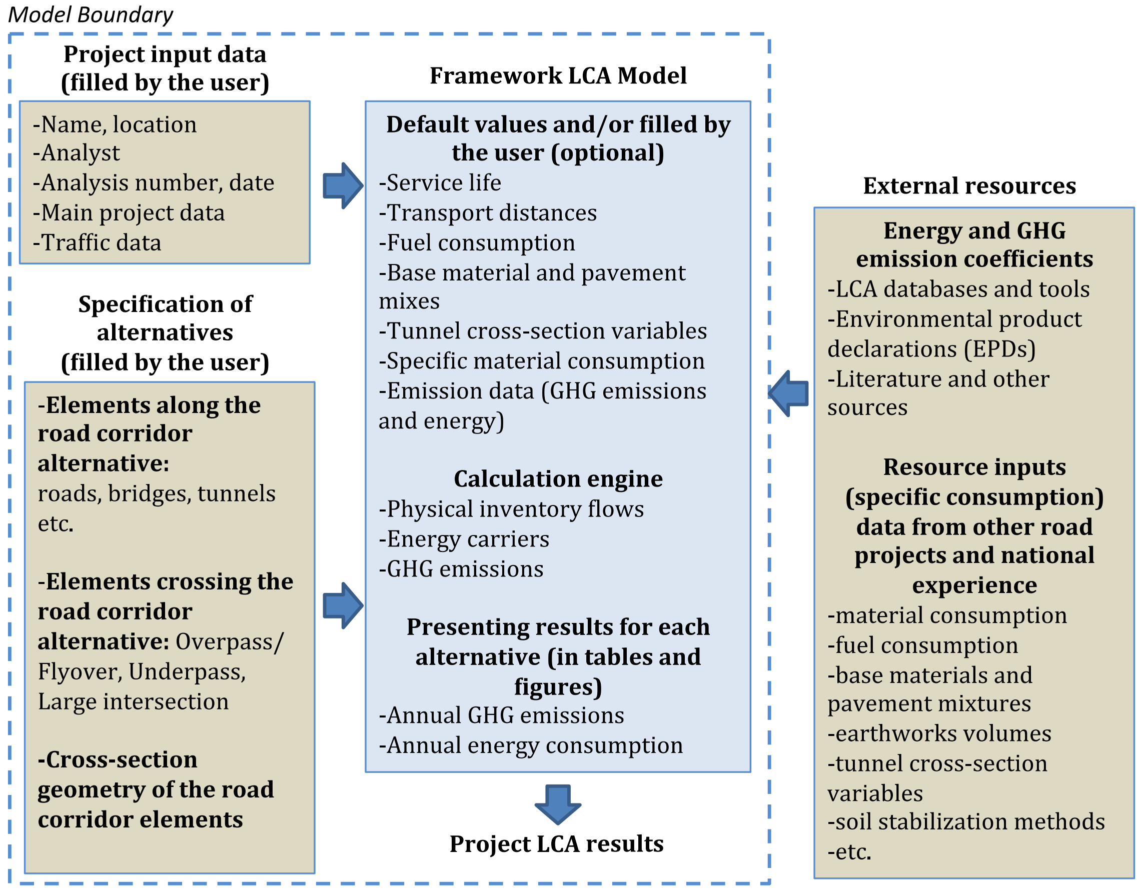


Figure 4: Overall LICCER model structure

3.2 Road corridor elements

A given road project can include a small number of *road corridor alternatives*, i.e. different alternatives for location and architecture of the road corridor. Each road corridor alternative may have a different total length, and may contain a different *combination of road elements*. The following road elements are considered in the model:

- Existing road (EXR)
- New road (NR)
- Extended road (ER)
- Road below groundwater (RBG)
- Aqueduct (AD)
- Underpass (UP)
- Tunnel (T)
- Dual Tunnel (DT)
- Underwater tunnel (UWT)
- Underwater dual tunnel (UWDT)
- Steel bridge or overpass (SBR)
- Concrete bridge or overpass (CBR)

The reference alternative by definition consists of continued use of today's road corridor, if possible, including the present given road infrastructure system consisting of the combination of existing road, existing road below ground water, existing aqueduct, existing underpass, etc.

Moreover, the following crossing elements (which may cross the longitudinal direction of the road corridor of any of our road corridor alternatives) are also considered:

- Steel Overpass/Flyover
- Concrete Overpass/Flyover
- Underpass
- Large intersection

For each road element within a given road corridor alternative the user will need to specify a cross-section geometry of the road infrastructure elements, as well as site characteristics regarding earthworks (for soil and rock), transport volumes during construction, etc.

Based on the specified road elements, consumption of materials and energy carriers in each of the *different life cycle stages of the project* will be calculated.

3.3 Materials and energy carriers

The LICCER model calculates annual cumulative energy consumption and GHG emissions related to all material flows for each road corridor alternative and all life cycle stages of the infrastructure project (production, construction, operation and end-of-life), as well as indicatively for traffic on the road during operation. Table 1 lists the direct consumption of material and energy carriers that are accounted for.

Table 1: Direct resource inputs included (cells in grey) in the model analysis

		Elements along the road corridor				**Elements crossing the road corridor**		**Traffic**
Input type	Unit	New road, Extended road	Aqueduct, Underpass, Road below groundwater	Tunnel, Dual Tunnel Underwater tunnel, Underwater dual tunnel	Steel bridge or overpass, Concrete bridge or overpass	Steel Flyover, Concrete Flyover	Crossing underpass, Large Intersection	
Asphalt membrane	ton							
Aggregate, gravel	ton							
Sand/soil	ton							
Bitumen	ton							
Concrete	ton							
Cement in soil stabilization	ton							
Lime in soil stabilization	ton							
Explosives	ton							
PE-foam	ton							
Rebar	ton							
Shotcrete	ton							
Steel	ton							
Diesel	m^3							
Electricity	kWh							
Biofuel	m^3							
Gasoline	m^3							
Transport of materials	tonkm							

3.4 Energy use and emission coefficients of resource inputs

For the secondary energy carrier *electricity* the model will ask the user to select between the national electricity mix of Norway, Sweden, Denmark and the Netherlands, or alternatively the Nordic electricity mix (NORDEL) and the European electricity mix. The LICCER model eventually aspires to be filled with default model internal values for each of these different electricity mixes, with region-dependent predefined (default) energy use and GHG emission coefficient values for all resources in Table 1. As part of the present LICCER project, however, the database only contains model internal values for the Norwegian and Swedish electricity mix and (partially) for the Norwegian and Swedish resources. The restriction in project time and resources, and use of case studies only in Norway and Sweden, is the reason for this limited scope of data during the project. The model is basically ready, however, for hosting default model internal values for other countries as soon as the country-specific input values or coefficients are available to be inserted into the model. Once the values are available it is very easy and quick to populate the model with the given data. Also, the model can already be used for any road project, regardless of where it is located, if the user provides project-specific values for all model parameters.

The life cycle energy use will include the indirect energy use for the production of materials and energy carriers as resource inputs (e.g. MJ = MJ/ton * ton). These calculations will include the choice of a given electricity mix (as explained above).

Greenhouse gas (GHG) emissions are calculated on the basis of *emission coefficients* (ghg_i) for each direct physical resource input. For instance, the GHG emissions ($GHG_{Concrete}$, in kg CO_2-eq) related to the production of concrete is the mass (in kg) of concrete consumed multiplied with the emission coefficient ($ghg_{Concrete}$) for concrete (in kg CO_2-eq per kg):

$$GHG_{Concrete} = Mass_{Concrete} * ghg_{Concrete}$$

The model offers default values for the emission coefficients of each material and energy carrier consumed, such as for concrete, on the basis of national datasets. In the current version of the model such datasets are given for Norway and Sweden, on the basis of the national values (when available) already approved and used by the NRAs. These calculations include the choice of a given electricity mix, since the emission coefficient value of a given material depends on the electricity mix. If a road project consumes quantities of a material (e.g. concrete) of a type with an emission coefficient very different from the default value, the model-user may correct for this by providing project-specific values.

3.5 Analysis time horizon and service life

The model calculates the annual life cycle energy use and GHG emissions for each of the road corridor alternatives in a defined road project over a given *analysis time horizon* (ATH) that is freely chosen by the user (e.g. ATH = 25 years). The various components of a road element are assumed to have a *service life* (T_{SL}), which may be shorter or longer than the analysis time horizon, e.g. 40 or 60 years. Country-specific default values for service life are provided for Sweden and Norway. Those default values are based on what the National Road Administrations consider as recommended service life values for the different road element types in this kind of LCA analysis.

The user can also set the service life for each element according to project specific values.

Frequency of asphalt pavement resurfacing is calculated on the basis of the Annual Average Daily Traffic (AADT) value of the given road, using a regression function based on Swedish regulations.

All life cycle energy use and GHG emission contributions from elements in the project need to be normalized to the service life of each element, as well as to the chosen analysis time horizon, divided by the number of years in the analysis time horizon. Results are given in GJ/year and kgCO_2-eq/year.

3.6 Traffic during operation of the road

The LICCER model also calculates the energy use and GHG emissions from *yearly traffic* (AT_t

= $AADT_t \cdot 365$) on the road, according to a default country-specific or a user-defined project-specific assumed traffic mix (% light vehicles, % truck and % truck with trailer) and fuel mix (% gasoline, % diesel, % biofuel and % electric). The Annual Average Daily Traffic in a given year t in future ($AADT_t$) is calculated assuming a constant yearly traffic increase from the starting point in year zero $AADT_0$.

The model will calculate energy use and GHG emissions that is a result of *differences in traffic* between each new route alternative within the project and the reference alternative, which is Alternative 0 if the existing road can serve the expected traffic increase in future. If not, one of the new route alternatives (Alternative 1) may be chosen as reference.

4 Road elements and life cycle stages

4.1 Architecture and input variables of road elements

In the early planning stage, a road project may consider several alternative road corridors, and there also will be an existing road system that by definition is referred to as the reference alternative. One road corridor alternative may include different in-series road elements (e.g. new road, extended road, tunnels, and bridges). Each of these is below summarized in some detail.

The model contains default values, but allows for varying conditions to be set by the user for each road element and for different construction parameters such as material consumption.

There are several input variables within each road element that need to be specified as model input by the user of the LICCER model, in the 'RoadDesign' tab:

- number of elements of a given type within the alternative (N_E)
- road length (L_i), road width (W_i), and number of lanes (N_n)
- pavement layer height and material type (H_{PV} and M_{PV})
- base layer height and material type (H_{BL} and M_{BL})
- sub-base layer height and material type (H_{SBL} and M_{SBL})
- share length including lighting, side and centre guardrails (SHL_{LG}, SHL_{SG} and SHL_{CG})
- earthworks definitions; soil volumes and fuel used for earthworks (Q_{ES}, Q_{ERS}, and Q_{BLR})
- soil stabilization methods ($SOIL_{STAB}$)
- concrete use ($Q_{CON\text{-}OTH}$)
- tunnel walls and lining methods
- quantity of traffic from outside ($AADT_{OUTS}$) and length of such traffic (L_{OUTS})

Some of these inputs (such as road length, road width and number of lanes, share of lighting and guardrails, and earthworks and soil stabilization methods) will be unique for a given road project. Others inputs (such as sub-base, base and pavement layer height and material type) may often be determined by national road construction guidelines and practices. Hence, input data will have to be collected from different sources. More information about sub-base, base and pavement layers are given below.

When working in the 'Comparison' mode, comparing each of the new road corridor alternatives with the reference, the model forces the user to apply the same inputs for components of the same type, for the whole length of the project. This means that if there is a road corridor alternative with three tunnels in a project, all three tunnels have to have the same number of lanes, width, and pavement composition and tunnel lining. Results relative to the reference alternative are then given in the 'Comparison' tab.

In order to add flexibility, the user may also choose to work with the 'Adding-Up' mode of the model where all the new road corridor elements are now defined as in-series sections within one and the same new route alternative, which can now be compared with the reference alternative. In the ‘Adding-Up’ mode the user may well use different input values (such as number of lanes, width, pavement composition and tunnel lining) for each of the three alternatives (here; in-series sections). Results are now given in the ‘Adding-Up’ tab.

4.1.1 Road layers

The model treats the road layers as different layers and is concerned with the quantities, production and application of the materials as a whole. The model treats the common road layer structure as shown in Figure 5. The user needs to define and input to the model the pavement layer, base layer and sub-base layer.

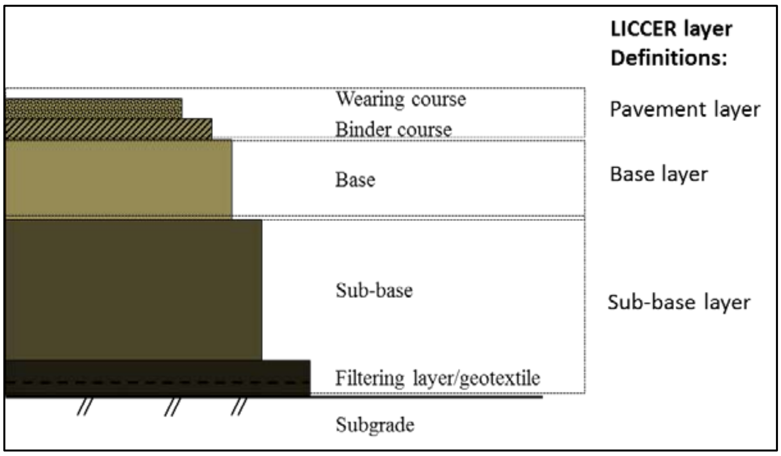


Figure 5: LICCER road layers structure

Pavement layer

The pavement layer is treated as a singular layer where sub-layers such as wearing course and binder course are not explicitly shown in the model but implicitly understood as included. The material consumption is calculated from the road length (L_i) according to a specified width and depth of pavement layer in paved lanes.

The pavement layer also represents a special case in the road layers, as there is generally a requirement to resurface the pavement layer over time due to general wear and tear. The resurfacing frequency, or the service life of pavement layer subject to resurfacing, is default calculated as a function of average daily traffic (AADT). The model has a default depth of pavement layer subject to resurfacing, but the user can also change this according to project-specific values. The model treats the material consumption of the resurfacing layers as determined by how often the road requires resurfacing.

The user has the opportunity to deviate from predefined default values, and define himself the depth and blend of the pavement layer according to share of bitumen, concrete and/or aggregate/gravel. If the user does not choose to define these material blends, they will be set as default according to common practice in the selected country.

Base and sub-base layer

The base and sub-base layers are separate layers in the model, but calculated in the same way. Generally comprising of aggregate or sand, the base and sub-base layers form the foundation of the road. The materials used in the model are user defined and can be set as 100% aggregate, 100% sand or a user defined blend (where a percentage share of bitumen can also be included in the base layer). The sub-base layer is expected to include a filtering layer (as seen in Figure 5), but geotextile is not included in the specifications and calculations. The model calculates the material use of the sub-base and base layers by layer depth, layer area and material density, out of which default density values are given while the user has to input the depth and with of layers as well as length of elements in which the layers occur.

4.1.2 Lighting

Road lighting is defined as the amount of road length requiring illumination. The user chooses how much of the road is lit as a percentage of road length. The material requirements in infrastructure for road lighting have not been included in the LICCER model due to their relative insignificance, but energy (electricity) use during the operation stage is included.

4.1.3 Guardrails

Centre and side guardrails are represented in the model as both concrete and steel guardrails. The user has the opportunity to define how much of the road length has guardrails and what type of material (concrete or steel) the guardrails are made from. The material calculations use pre-set values for materials per meter length of road with guardrail, but the user can also provide project-specific values.

4.1.4 Earthworks

The earthworks represent all movement of earth during construction processes of a certain road length and are defined in three ways:

1) Simple soil excavation – the use of machinery to move soil requiring no further treatment
2) Ripped soil excavation – using secondary machinery to loosen soil for excavation
3) Blasted rock – using explosives to blast rock and moving blasted rock

In addition to these earthworks, tunnel systems also need other earthworks that will be examined in section 4.2.5.

Earthworks can be a very important source of energy use and GHG emissions in road construction, depending upon local soil/rock conditions and the local topography. The user has to estimate the volume in cubic meters of soil or rock for the earthworks required, as well as expected transport distances for earthworks. Based on these inputs, and other default model values, the model calculates the earthwork masses, the amount of fuel used in moving earth, the amount of transportation required for removed earth, and in the case of blasted rock, how much explosives are used. The user alternatively has the opportunity to specify directly the *total fuel consumption in earthworks,* if such estimates are known (since in some situations this may from experience be more feasible than estimating the cubic meters volumes of soil and rock). If the user directly inputs total fuel consumption in earthworks, the model will ignore other earthworks volume inputs.

4.1.5 Soil stabilization

Soil stabilization is treated in the model as a soil volume that needs to be stabilized by a method, to be selected by the user, over the length of each element of the road corridor. The user choses a stabilization method from a menu of predefined type of stabilization methods and inputs the estimated cubic meters of soil that need this stabilization. The model then calculates the consumption of stabilization materials.

The four types of soil stabilization that are included in the model are as follows:

1) In-situ stabilization – applying cement as a stabilizing agent by blending with the soil to a required depth
2) Mass stabilization – applying cement as a stabilizing agent without removing the top layer of soil
3) Lime-cement columns – lime and cement are premixed and injected into moist soil to a certain depth where it forms into columns
4) Soil replacement – the replacement of soil with more stable soil from another source

In-situ, mass and lime-cement column stabilization are calculated according to the materials used, transportation of the materials, and the energy used in applying these methods, according to what is reported by Rydberg and Andersson (2003). Soil replacement is calculated according the energy used in application and the transportation of the replaced soil and the new material as well as the amount of material required.

4.1.6 Concrete use and tunnel walls and lining methods

Concrete is used in different types of road infrastructure. Important areas of use are bridges, tunnels, roads below groundwater, aquaducts and underpasses. The model automatically calculates the use of reinforced concrete in bridges. For tunnels, the consumption of concrete (with and without reinforcement) is a direct result of the chosen lining methods and the area of the inside walls/ceiling, which is the product of tunnel cross-section arch length and tunnel length). The user needs to select from a pull-down menu the tunnel lining method, and on this basis the model automatically calculates the consumption of concrete (and/or shotcrete), by first calculating the area and volume of lining materials inside the tunnels and the area and volume of tunnel portals at the tunnel entrances.

For roads below groundwater, aquaducts and underpasses the consumption of reinforced concrete is not necessarily a direct function of the road cross-section geometry, since there are many different designs and thereby a higher variation in specific consumption level (cubic meter of concrete per m road lane length). When a project includes such elements (road below groundwater, aquaducts, underpasses) the user therefore should directly estimate and input the cubic meters of reinforced concrete per m lane length.

4.1.7 Traffic from outside

Some parts of the road project may serve extra traffic from outside, in addition to the traffic within our project. New road infrastructure on such parts of the road project will contribute to the overall energy use and GHG emissions. However, these contributions should only partly be allocated to our project. Since the new road also in this case serves extra traffic from outside, a part of the traffic's contributions to energy use and GHG emissions should be allocated to the outside system. For each type of element along the road corridor the user is asked to input the length (L_{OUTS}) that also serves traffic from outside and the quantity of such traffic ($AADT_{OUTS}$), if this is expected to occur.

Think of a situation where our road project between "A" and "B" is 25 km long and has a yearly traffic of 8000 vehicles, but a shorter intermediate distance from "C" to "D" (both located in between A to B) also serves 5000 extra vehicles from outside, entering at C and leaving at D, or vice-versa. Hence, the total traffic on the road from C to D is 13,000 vehicles. In such a situation it would not make sense to allocate all the energy use and GHG emissions of the road infrastructure to our project and our 8000 vehicles only; 8/13 parts of the burdens should be allocated to our project and 5/13 parts of the burdens should be allocated to the outside system.

4.2 Main elements of the road infrastructure

4.2.1 Existing road

Existing roads (EXR) are roads that are already receiving traffic today. Existing roads are considered infrastructure that is already built and are primarily used for calculation of traffic.

The LICCER model handles existing roads in two ways by calculating entire stretches of existing road with all existing road structures separated in a single section, or by including a simplified existing road row in all new infrastructure sections. An existing road can be considered for all road types within the LICCER model as Alternative 0 or just for the consideration of traffic in the other alternatives.

Existing roads are defined by their length and width and with specifications inputted by the user. The LICCER model calculates the components of an existing road by neglecting material production and construction of road infrastructure elements and calculating only operation and end-of-life stages, including production of materials used in the operation stage. Traffic use is also included in the existing road structure.

Existing roads are made up of driving lanes (DL), paved hard shoulders (HS), central reserve including guardrail (CR), cycling/pedestrian lanes (CPL), soft shoulders including guardrails (SS) and road ditch (RD).

4.2.2 New road and extended road

New roads (NR) and extended roads (ER) are the most basic road types in the LICCER model. A new road is defined as a basic (plain) road type requiring a paved road surface and base/sub-base layers, earthworks, guardrails, and lighting. An extended road is defined in the same way as a new road except that it is an extension (e.g. a widening) of an existing road while a new road is an entirely new construction. New roads and extended roads can be as small as a single lane driveway to as large as a multiple lane highway, as according to how the user will input the project specifications. The LICCER model calculates the components of new road and extended road in the same way, based on user inputs as explained in section 4.1.

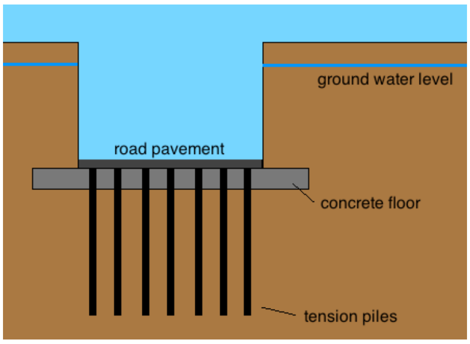
New road and extended roads are made up of driving lanes (DL), paved hard shoulders (HS), central reserve including guardrail (CR), cycling/pedestrian lanes (CPL), soft shoulders including guardrails (SS) and road ditch (RD).

Example 1: New roads or extended roads

4.2.3 Road below groundwater

The LICCER model offers the opportunity of including a road that is situated below groundwater, since these road types may be found in low-lying countries such as the Netherlands. Roads built below groundwater levels are designed by constructing a waterproof concrete shell, and the use of concrete can be very significant in order to resist buoyancy forces. There may be several design solutions. With respect to energy use and GHG emissions, however, it is concluded that the important input factors are the required earthworks and soil stabilization, and consumption of reinforced concrete, for which the user is asked to input the estimated use consumption (CON_{OTH}). The consumption of rebar in concrete is calculated within the model, by use of a default coefficient value.

Roads below groundwater are made up of driving lanes, hard shoulders, central reserve and cycling/pedestrian lanes.



Example 2: Road below groundwater

4.2.4 Aqueduct

The aqueduct (AD) is a type of tunnel or underpass of waterways seen most often in low-lying countries such as the Netherlands. An aqueduct involves channelling water within a constructed channel, under which a stretch of the road underpasses. An aqueduct may therefore be seen as a variant of an underpass. However, since there may be many different designs involved, and aqueducts have their own design criteria, the LICCER model specifies the aqueduct as an individual element of the road project. Information on aqueduct construction and material usage is not readily documented. Therefore, the user may provide project specific values for aqueducts.

Aqueducts are made up of driving lanes, hard shoulders, central reserve and cycling/pedestrian lanes.

Example 3: Aqueducts

4.2.5 Underpass

An underpass (UP) is a road construction that travels underneath existing infrastructure. Additional earthworks and additional use of concrete reinforcements when compared to new road infrastructure characterize underpasses. The LICCER model asks the user to input the additional concrete usage in the same way as for a road below groundwater and an aqueduct. This method of allowing the user to define the concrete usage in underpass is provided given the many varying types of underpasses. This would give sufficient flexibility to the user, regardless of the many different designs one could think of.

Underpasses are made up of pre-defined driving lanes, hard shoulders, central reserve and cycling/pedestrian lanes.

Example 4: Underpasses

4.2.6 Tunnel, dual tunnel and underwater tunnel

Tunnels (T) are road constructions that are dug underground and lined with a casing to prevent soil collapse and rock falling down on the road. The tunnels in the LICCER model are predefined according to their by default assumed consumption of earthworks, tunnel wall elements (CON_{TWE}), concrete tunnel portals (CON_{TP}), tunnel vault lining (CON_{TL}), paved road surface. Tunnels may also substantially differ in their operation stage where electricity is consumed by tunnel ventilation (EL_{VT}) in addition to the lighting (EL_{LT}). Underwater tunnels are tunnels normally located in (subsea) rock under a body of water, such as when crossing under water a river, a fjord or part of a sea. The underwater tunnels have the same input variables as regular tunnels, except here electricity for water pumping (EL_{WPUT}) is also included, and there may be higher requirements for ventilation since an underwater tunnel may have a large vertical gradient and its lowest level deep below sea level. Dual tunnels and underwater dual tunnels represent the same as singular tunnels except that there are two tunnels side by side. Hence, dual tunnels consume much more input materials and energy than singular tunnels, on a lane meter or AADT basis.

Example 5: Tunnels and underwater tunnels

The earthworks and material use calculations for tunnels come from simple regression functions, derived from data about different tunnel classes in Norway, to define the tunnel cross-section area and the vault's arch length according to particular profiles. Table 2 shows the different tunnel classes in Norway and the corresponding width, cross-section area and arch lengths (SVV 2010).

Table 2: Cross-section area and arch length for tunnel classes in Norway

	Tunnel Class			
	A	**B**	**C and D**	**E and F**
Tunnel profile	T5,5	T9,5	T10,5	2 x T9,5
Total width (m)	5,5	9,5	10,5	2 x 9,5
Cross-section area (m^2)	42,59	70,89	79,08	2 x 70,89
Tunnel vault arch length (m)	17,73	21,66	22,75	2 x 21,66

Given such data for different tunnel classes (SVV 2010), as shown in Table 2, it is possible to develop a linear regression function that calculates the cross-section area and vault arch length of any tunnel on the basis of its total width, with a R^2 correlation coefficient close to 100%. On this basis the LICCER model calculates the volume and masses of rock that must be blasted and transported away per unit length of a tunnel, from the total width of the tunnel. This is also the basis for estimation of the consumption of input resources for making the tunnel (e.g. explosives, electricity, diesel, PE foam, concrete, shotcrete and rebar).

The LICCER model also defines tunnel portals for the same classes as shown in Table 2, with given lengths, and thus calculates the consumption of concrete and reinforcement steel in the portals.

Tunnel earthworks are calculated slightly differently than earthworks in other road elements, as they include fuel used for uploading blasted or excavated materials from inside the tunnel.

For the different types of tunnels the user needs to choose the vault lining method and soil stabilization method (if any), and input the share length of soil and rock as well as the volume of soil to be stabilized.

Tunnels and underwater tunnels are made up of driving lanes, hard shoulders, central reserve and cycling/pedestrian lanes.

4.2.7 Steel bridge/overpass and concrete bridge/overpass

Bridges and overpasses provide a unique challenge to the LICCER model due the difficulty of classifying bridges and overpasses into a single or a few well-defined design schemes. Bridges and overpasses can be defined as structures that use an elevated design to avoid obstacles on the driving surface. In principle an overpass and a bridge are not different as they both are constructed to elevate the road surface above an obstruction or gap. The LICCER model thus calculates their material use and impacts in the same way.

Example 6: Bridges and overpasses

Due to the fact that there are many different bridge design classes used in road construction, and a lack of documentation of their respective typical consumption of masses, it is just not possible to propose well-defined "average" default values for consumption of materials for different bridge or overpass designs. The LICCER model is intended for use in analysing energy use and GHG emission of different road corridor alternatives in early stage planning, where specific information about involved bridge or overpass structures are probably not available. It is therefore decided to establish default data on a more rough level, referring to typical values for the specific amounts of important materials per m^2 of bridge surface area. As an example we refer to empirical data from the Norwegian EFFEKT model and Straume (2011); see Table 3.

Table 3: Material consumption per m^2 bridge surface area for concrete and steel bridges

Material	Unit	Concrete bridge	Steel bridge
Concrete	m^3/m^2	1,31	0,71
Steel	ton/m^2	0	0,22
Rebar	ton/m^2	0,22	0,11
Asphalt membrane	m^2/m^2	1,00	1,00

The LICCER model calculates material use for bridges and overpasses from this table for Norway, from the surface area (m^2) of the bridge or overpass, according to the method that is already accepted and adopted in the EFFEKT model. A similar table is used for Sweden, based on Swedish bridge design experience. The same principle can be used for bridges in other countries, however, since bridge design and construction norms may differ from country to country, one would expect somewhat different specific material consumption values in different countries, as well as for very different bridge designs. If a project involves many bridges or long bridges, the user is encouraged to estimate and input his own project-specific values, as far as possible, in order to provide more accurate results. In such situations project-specific values could be collected from other built bridges of not too different length and height. This method is used in the LICCER model due to a desire to model bridges in a way that is flexible and not overly complicated for the user.

For bridges the user needs to choose the soil stabilization method and volumes (if relevant), and input estimates for share lengths and volumes for earthworks (soil, ripped soil and rock)..

Bridges and overpasses are made up of driving lanes, central reserve and cycling/ pedestrian lanes.

4.2.8 Crossing structures

Crossings structures are construction elements that cross the main route as defined by the project, but such structures are not part of the main road lengths of the project. Consider an old road that has been in use before the decision to build a new road has been made. For the new road to be built, it must avoid the old road by crossing over or underneath the old construction with a fly-over or underpass. If the new road is not built, there will be no need for the crossing fly-over or underpass to be built. The fly-over or underpass is not part of the new road's driving surface, but materials and energy will be consumed in the construction of the fly-over or underpass to enable the new road. Therefore, the consumption of material and energy carriers, and the associated GHG emissions of the fly-over or underpass must be allocated to the new road construction and included in the model calculations.

Example 7: Crossing structures

The LICCER model deals with four types of crossing structures and they are:

1) Steel overpass/fly-over – a bridge-like crossing made from steel
2) Concrete overpass/fly-over – a bridge-like crossing made from concrete
3) Underpass – a crossing which travels underneath the project road
4) Large intersection – a large crossing of two or more roads on the same gradient

The LICCER model separates road crossings from the main project road lengths in the sense that it does not include traffic calculations for them. Similar to bridges, there is also a challenge related to how different crossings can vary in design and construction. The LICCER model asks the user to enter the total paved surface area, total concrete use (from which also the amounts of rebar will be calculated), total steel use (for steel crossings) and total fuel used in earthworks. These are the only input variables for road crossings. If a project involves crossing structures to such an extent that the user thinks they may significantly influence the model results, the user should try give as good estimates for these input factors as possible and use them in the input sheets. However, the user may also want to totally neglect crossing structures, if they do not exist or only in small quantity. The model anyway offers an opportunity to deal with such crossing structures in a flexible way, which also accounts for the most important input variables regarding energy use and GHG gas emissions.

4.3 Life cycle stages

The LICCER model is built to include different life cycle stages in a project as is commonly done in LCA. The model calculates energy and material use in each of these stages individually and then combines them together in the life cycle results. The following subsections describe each of the life cycle stages included in the LICCER model.

4.3.1 Material production of road infrastructure

The production stage is where the (embodied) energy use and GHG emissions of all main material inputs for new road infrastructure are quantified. The production stage includes extraction of raw materials, processing of raw materials and transportation to processing facilities, and production of materials or manufacturing of construction components to the point (the ‘gate’) where they are ready for purchase in the construction stage. The production stage is where all materials are produced for use on the road project.

4.3.2 Construction of road infrastructure

The construction stage accounts for the building of the road project infrastructure with machinery and labour using materials from the production stage. The construction includes all fuels used in machinery, transportation from the processing facilities (the ‘gate’) to the construction site, earthworks, project-internal transportation of masses, and electricity used on site during construction.

4.3.3 Operation of road infrastructure

The operation stage accounts for the period of time when the road infrastructure is in use and for interim maintenance on the road. The latter includes the materials used in resurfacing and maintenance, including transportation of these materials. Operation includes the electricity used for road lighting and for ventilation in tunnels. The LICCER model does not calculate emissions and energy use from the annual (change in) traffic on the road as part of the operation stage, but rather includes this information as a separate life cycle stage (see 4.4). The reason for this is to highlight the contributions of change in traffic independent from contributions of new road infrastructure. When an existing road corridor (the reference alternative) is adjusted, the new road corridor may induce a change in traffic relative to the existing road due to different road lenght.

4.3.4 End-of-life management of road infrastructure

The end-of-life (EOL) stage accounts for selected activities at the end of the service life of road elements when the road infrastructure is no longer in use and demolished. This includes fuel used for material removal and road deconstruction, in transportation of materials to landfill and/or recycling depots, and in earthworks to restore the land area back to natural conditions. It is assumed that vault lining materials inside tunnels are just left behind. It is also assumed that road infrastructure materials deposited (or landfilled) will not cause any GHG emissions from the deposit. Any kind of material recycling or reuse is left outside the system boundary of the analysis, assuming that the possible benefits and costs of such recycling and reuse are fully allocated to the other system in which they are used.

4.4 Traffic during operation

The traffic on roads during their operation is considered in the LICCER model as separate from the road infrastructure operation stage. Traffic movements obviously occur, however, at the same time as other road infrastructure operation and maintenance activities in the project. It is common to assume that the energy use and GHG emissions from traffic supersede the energy use and GHG emissions from the road infrastructure. Infrastructure is therefore sometimes considered to be unimportant compared to traffic itself. This may be different, however, in case of adjusting existing road corridors. Then the adjustment may cause a *change in traffic* (relative to the existing traffic) that creates a comparable increase or decrease in energy use and GHG emissions. This is useful information in road infrastructure planning. The change in traffic therefore is separated from the infrastructure in order to enable comparison of both.

The model calculates energy use and GHG emissions from yearly traffic on the road, according to a traffic mix made up of different vehicle types. Yearly traffic is the average traffic per year over the defined analysis horizon. The traffic mix is a blend of light vehicles and trucks with and without trailers, with a fuel mix based on biofuel, electricity in electric vehicles, diesel and gasoline.

The vehicle types included are:

- Trucks with trailer (TRwT)
- Trucks without trailer (TRnT)
- Electric powered light vehicles (LVT_{ELEC})
- Diesel powered light vehicles (LVT_{DIE})
- Gasoline powered light vehicles (LVT_{GAS})

These fuel and vehicle mixes are on specifying the region of a project by default determined by national statistical averages, but the values can be modified by the user if the vehicle fleet in a specific project is estimated to have a different mix of fuel and vehicle types compared to the national average. In addition, the LICCER model includes as a default the present share of biofuel in diesel and gasoline, but the user can also replace these with project-specific for an assumed future share of biofuel at the end of the analysis time horizon. This is then used to calculate the quantity of traffic during operation on biofuel.

One feature of the LICCER model, as mentioned in section 4.1.7, is to allocate part of the resource inputs of the road infrastructure, and their associated energy use and GHG emissions, to traffic “from outside”, if this is expected to occur. This allocation method does not, however, influence the calculations of life cycle energy use and GHG emissions from traffic within our project, it only splits the energy use and GHG emissions from road infrastructure in two parts; one allocated to our project and one to traffic from outside.

5 Results Interpretation

5.1 Types of results

The LICCER LCA-model calculates and reports results that are presented in tables and graphs. The aim is to present results so that the planners get insight into:

- Which new route or road corridor alternatives are better than others, regarding cumulative energy consumption and GHG emissions when accounting for contributions from the road infrastructure as well as (the change in) traffic on the road during operation
- How does each new alternative perform in this respect relative to the reference alternative of continued use of today's road system, i.e.:
    - o What is the relative contribution of individual road infrastructure elements (e.g. plain roads, tunnels, bridges)
    - o What is the relative contribution of the different life cycle stages (production, construction, operation, end-of-life)
    - o What is the relative contribution of road infrastructure versus traffic on the road during operation
    - o What is the relative contribution of different material inputs and different fuels
    - o What is the inventory of resource inputs (materials and energy carriers) within each alternative and how are they consumed in each of the different road elements (plain roads, tunnels, bridges, etc.)
    - o What are the absolute contributions of each alternative (Alternative 0, 1, etc.)

All the above questions are illustrated by calculating the cumulative energy consumption (GJ/year) and GHG emissions (kgCO_2-eq/year) of a given road project. The next section gives an overview of the different LICCER outputs. These outputs are in consecutive sections presented and discussed.

5.2 Overview of LICCER-output results

All LICCER-output results are expressed per functional unit *representing 1 year of operation*, *on average for the defined analysis time horizon*, regardless of the defined service life of the different road infrastructure components. This means that the total contribution of the road infrastructure over the specified service life is allocated to one year of operation, and then the contributions from traffic on the road during one year is added to the allocated contribution from infrastructure.

The functional unit makes it possible for road planners to examine in a systematic and transparent way how each route or road corridor alternative performs regarding energy use and GHG emissions, and what are the reasons for such performance profiles. This helps to understand what are the important parts of the system, how they influence the overall performance profiles and how to improve road projects with respect to location and architecture of a new road corridor. This is of vital importance in environmental evaluation of road projects in road planning, since different new route or road corridor alternatives may give significantly different contributions from infrastructure investments as well as different contributions from the change in traffic during operation due to changes in travel distances between a new alternative and the reference alternative.

The LICCER model has the ability to model up to 3 different new road corridor alternatives for a given road project, and compare this to a reference alternative that commonly represents the continued use of today's road infrastructure system. The results are presented in three different ways:

1. Individual presentation and breakdown of aggregated results for each alternative, separately.

   These results are given in separate tabs **‘Result-Alt.X’** where per alternative the corresponding life cycle contributions to annual cumulative energy consumption and GHG emissions of the main components and life cycle stages of the road infrastructure are given, and of the annual total including traffic on the road during operation (this mode shows results related to absolute traffic on the road and not results related to change in traffic relative to the reference alternative).

2. Presentation and breakdown of aggregated results for each new alternative can be viewed in comparison to the reference alternative, when the user has chosen the ‘**Comparison’ mode for analysis**. This mode is to be chosen when alternative 1, 2 and 3 represent *individual new alternative road corridors*, which are to be compared with a reference alternative. Each road corridor alternative may on the local level take a somewhat different route.

   These results are given in a tab **‘Comparison’** that reports the difference (Δ) between life cycle energy use and GHG emissions of each of the new alternatives (1, 2 and 3) and the reference alternative (0 or 1). The best alternative is the one with the lowest (Δ) value. Due to the importance of traffic during operation, this value can also be negative (which is indeed a benefit!) if a new route gives a much shorter driving distance than in the reference alternative, and the benefits from less annual traffic overrides the annual life cycle energy use and GHG emissions from the production and construction of road infrastructure in the new alternative.

   Results are also presented in the form of absolute energy use and absolute GHG emissions organized by lifecycle phase (in the form of tables) and material and traffic type (in tables and graphs) for each alternative.

3. Presentation and breakdown of aggregated results for the sum of an in-series of new road sections together constituting a new road corridor alternative can be viewed in comparison to the reference alternative, when the user has chosen the ‘**Adding-Up’ mode for analysis**. This mode is to be chosen when alternative 1, 2 and 3 are *in-series sections of one new route of the road corridor*, which can be compared with a reference.

   These results are given in a tab **‘Adding-Up’** that reports the difference (Δ) between energy use and GHG emissions of the sum of the new alternatives (1, 2 and 3) and the reference alternative (0 or 1). These results can be used, and should only be used, if the user wishes to define the new alternatives as in-series sections of one new route or road corridor alternative, and compare this with the reference.

   In this mode it is also possible to include an existing road, or part of an existing road as one section (0) of a new road project now including up to 4 in-series sections (0, 2, 3 and 4). In this case the new road is not analysed relative to a reference.

   Results are also presented in the form of absolute energy use and absolute GHG emissions organized by lifecycle phase (in the form of tables) and material and traffic type (in tables and graphs) for each alternative/section.

5.3 Aggregated results for each alternative

To understand how results can be interpreted, one can look at an example for a hypothetical road project E6 “A” to “B” with one road corridor alternative called the “Southern road corridor” or alternative “1A” for short. Alternative 1A has been populated with example data just for the purpose of showing how results for each alternative are presented and can be interpreted. The aggregated results for each route alternative are given in the ‘Result-Alt.X’ tabs, and commented below. Please note the data used in Chapter 5.3 here are the same as those of the real Swedish road example that is used in Chapter 5.4 that refer to the Test Values populated into the model itself. The reason why we here use a hypothetic road project is that it allows showing results for a road project with all possible road elements (existing road, new road, extended road, road below groundwater, aquaduct, underpass, etc.) involved.

In this hypothetical example the road project E6 “A” to “B” is a project with 11 times 1.0 km length, namely for each of the 11 road elements listed in section 3.1 (new road, extended road, road below groundwater, aqueduct, underpass, tunnel, dual tunnel, underwater tunnel, underwater dual tunnel, steel bridge and concrete bridge). This gives a total length of 11.0 km. The road has an average AADT (Average Annual Daily Traffic) of 8500 vehicles over a 20 years analysis horizon, and it has 3 driving lanes, 2 hard shoulders and a central reserve, in total giving a road width of 13 meters excluding road ditches. There are also some crossing structures included, and the service life of all infrastructure main components is 40 years and resurfacing with removal of old and adding of new asphalt takes place every 8 years.

The results page for alternative 1A begins with a table on the right hand side of the ‘Result-Alt.1’ tab that summarises the basic information included in the analysis as shown in Figure 6.

INFORMATION ABOUT THE ANALYSIS:	
Name of project:	E6 "A" to "B" - Hypothetic project No. 1
Name of analyst:	Ola Normann
Analysis No:	Run 2 - C
Date:	31.05.2013
Analysis mode:	Comparison mode
Alternative 1:	1A
Alternative name:	Southern road corridor

Figure 6: Analysis overview in alternative 1A

5.3.1 Greenhouse gas emission results

In Table 4, the first four rows show the compiled values of annual GHG emissions in each of the four separate life cycle stages (Production, Construction, Operation and End-of-Life) for the different road infrastructure element types. These values are summed-up in the Infrastructure row, to give the infrastructure emissions from all life cycle stages broken down to each element. The Traffic row gives the emissions from traffic during operation for each element, and the Total row gives the total emissions (infrastructure plus traffic) for each element. The right-hand side column gives the sum of emissions for all elements of the project.

The lower part of the table reports the percentage shares of GHG emissions by each stage and element as ‘% of life cycle GHG emissions for infrastructure’ (i.e. as sum of each stage; Production, Construction, Operation and End-of-Life). Life cycle energy use of infrastructure and energy use of traffic are also given as % of the total of infrastructure and traffic together (i.e. ‘% of total’ being the total for Infrastructure and Traffic).

Table 4: Annual GHG emissions table

PHASE	(unit)	Existing road	New road	Extended road	Road below g.w.	Auqaduct	Underpass	Tunnel	Dual tunnel	U.w. tunnel	U.w. dual tunnel	Steel bridge	Concrete bridge	Crossing structures	SUM all elements
Production	ton CO2-e/year	0.00E+00	0.00E+00	1.47E+01	0.00E+00	0.00E+00	0.00E+00	6.28E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.10E+01
Construction	ton CO2-e/year	0.00E+00	0.00E+00	7.32E+00	0.00E+00	0.00E+00	0.00E+00	1.41E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.73E+00
Operation	ton CO2-e/year	0.00E+00	0.00E+00	2.03E+01	0.00E+00	0.00E+00	0.00E+00	2.70E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.06E+01
End-of-Life	ton CO2-e/year	0.00E+00	0.00E+00	1.45E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.45E+01
Infrastructure	ton CO2-e/year	0.00E+00	0.00E+00	5.68E+01	0.00E+00	0.00E+00	0.00E+00	7.96E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.48E+01
Traffic	ton CO2-e/year	0.00E+00	0.00E+00	4.96E+03	0.00E+00	0.00E+00	0.00E+00	6.54E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.61E+03
Total	ton CO2-e/year	0.00E+00	0.00E+00	5.01E+03	0.00E+00	0.00E+00	0.00E+00	6.62E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.68E+03
Production	% of infrastructure	0.00	0.00	22.65	0.00	0.00	0.00	9.69	0.00	0.00	0.00	0.00	0.00	0.00	32.35
Construction	% of infrastructure	0.00	0.00	11.29	0.00	0.00	0.00	2.17	0.00	0.00	0.00	0.00	0.00	0.00	13.46
Operation	% of infrastructure	0.00	0.00	31.38	0.00	0.00	0.00	0.42	0.00	0.00	0.00	0.00	0.00	0.00	31.79
End-of-Life	% of infrastructure	0.00	0.00	22.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.39
Infrastructure	% of total	0.00	0.00	1.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	1.14
Traffic	% of total	0.00	0.00	87.33	0.00	0.00	0.00	11.53	0.00	0.00	0.00	0.00	0.00	0.00	98.86
Total	% of total	0.00	0.00	88.33	0.00	0.00	0.00	11.67	0.00	0.00	0.00	0.00	0.00	0.00	100.00

Below the GHG emissions results table is the chart in Figure 7, which shows the first four rows in Table 4 in graphical form.

The annual life cycle emissions shown here reflect, as mentioned above, a hypothetic example where Alt.1 contains a varied road length of each element. It is interesting to see the very large emissions caused by several road element types, and the generally dominant contributions from production. The sum of all GHG emissions from road infrastructure is given in a separate chart, as shown in Figure 8 below.

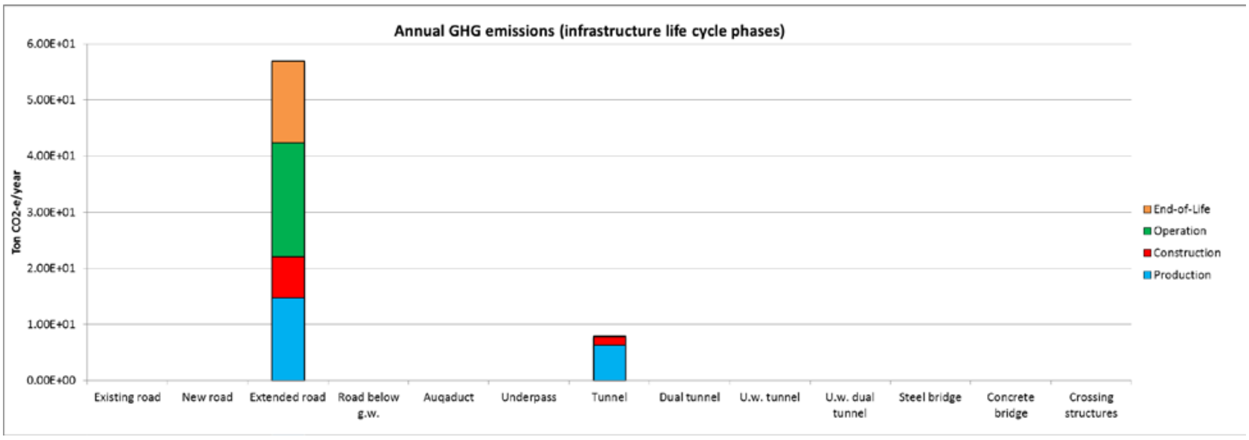


Figure 7: Annual GHG emissions from infrastructure elements

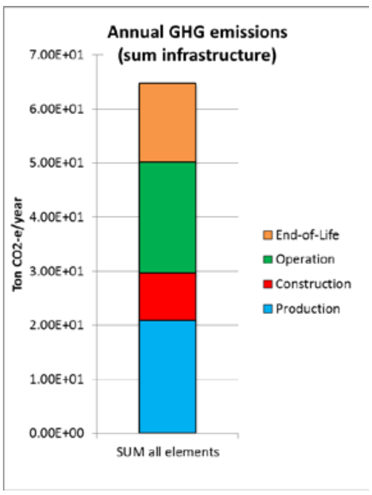


Figure 8: Annual GHG emissions from road infrastructure life cycle stages

Figure 9 and Figure 10 are the graphical representations of rows 5 – Infrastructure, 6 – Traffic and 7 – Total (with infrastructure and traffic together) from Table 4. From these results one can see the overall large importance of traffic during operation, in this case accounting for 89,4 % of the total annual emissions, as also verified in Table 4.

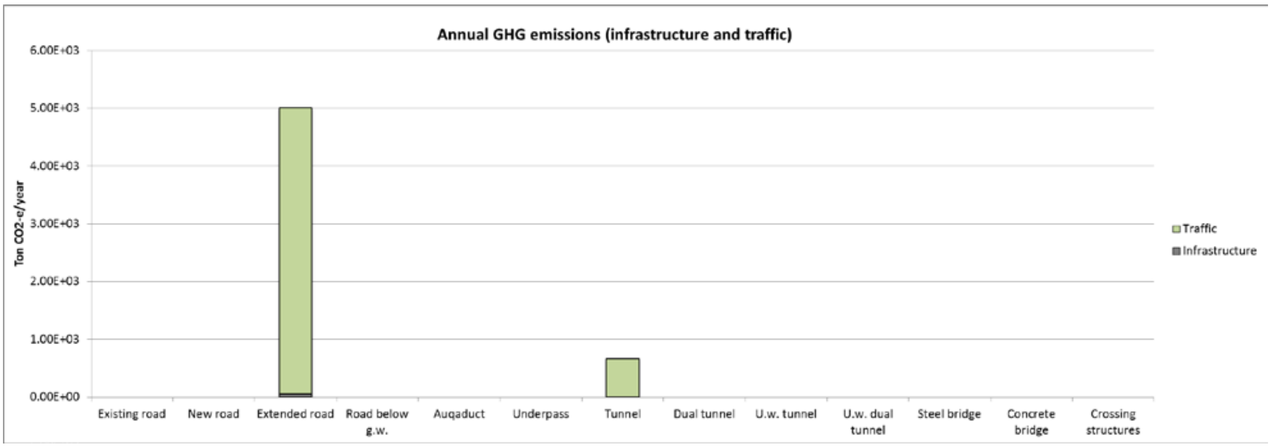


Figure 9: Annual GHG emissions from road infrastructure elements and traffic

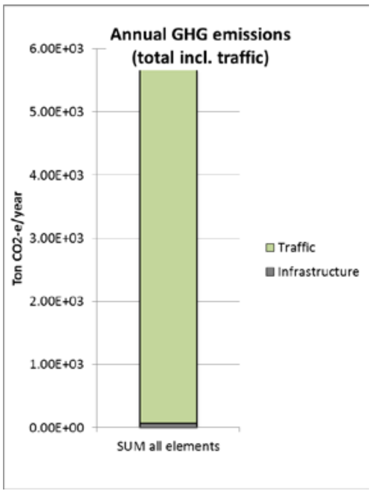


Figure 10: Annual GHG emissions, including traffic, totalled over all road infrastructure elements

5.3.2 Life cycle energy use results

The energy use results table is structured in the exact same way as the GHG emissions table, where columns represent the different road elements and rows represent different stage and different contributions to energy use. Table 5 shows the same format as Table 4 and is found in the results tab of the LICCER model directly below GHG emissions results. The results come from Alt.1 in test case.

Table 5: Annual life cycle energy use table

PHASE	(unit)	Existing road	New road	Extended road	Road below g.w.	Auqaduct	Underpass	Tunnel	Dual tunnel	U.w. tunnel	U.w. dual tunnel	Steel bridge	Concrete bridge	Crossing structures	SUM all elements
Production	GJ/year	0.00E+00	0.00E+00	6.79E+02	0.00E+00	0.00E+00	0.00E+00	5.70E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.36E+02
Construction	GJ/year	0.00E+00	0.00E+00	1.13E+02	0.00E+00	0.00E+00	0.00E+00	7.49E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.88E+02
Operation	GJ/year	0.00E+00	0.00E+00	1.49E+03	0.00E+00	0.00E+00	0.00E+00	5.67E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.55E+03
End-of-Life	GJ/year	0.00E+00	0.00E+00	2.14E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.14E+02
Infrastructure	GJ/year	0.00E+00	0.00E+00	2.50E+03	0.00E+00	0.00E+00	0.00E+00	1.89E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.68E+03
Traffic	GJ/year	0.00E+00	0.00E+00	1.28E+05	0.00E+00	0.00E+00	0.00E+00	1.69E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.45E+05
Total	GJ/year	0.00E+00	0.00E+00	1.30E+05	0.00E+00	0.00E+00	0.00E+00	1.70E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E+05
Production	% of infrastructure	0.0	0.0	25.3	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	27.4
Construction	% of infrastructure	0.0	0.0	4.2	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	7.0
Operation	% of infrastructure	0.0	0.0	55.4	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	57.6
End-of-Life	% of infrastructure	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0
Infrastructure	% of total	0.0	0.0	1.7	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.8
Traffic	% of total	0.0	0.0	86.7	0.0	0.0	0.0	11.5	0.0	0.0	0.0	0.0	0.0	0.0	98.2
Total	% of total	0.0	0.0	88.4	0.0	0.0	0.0	11.6	0.0	0.0	0.0	0.0	0.0	0.0	100.0

The same format that was used for showing table results in GHGs is followed in Figure 11, Figure 12, Figure 13, and Figure 14 below.

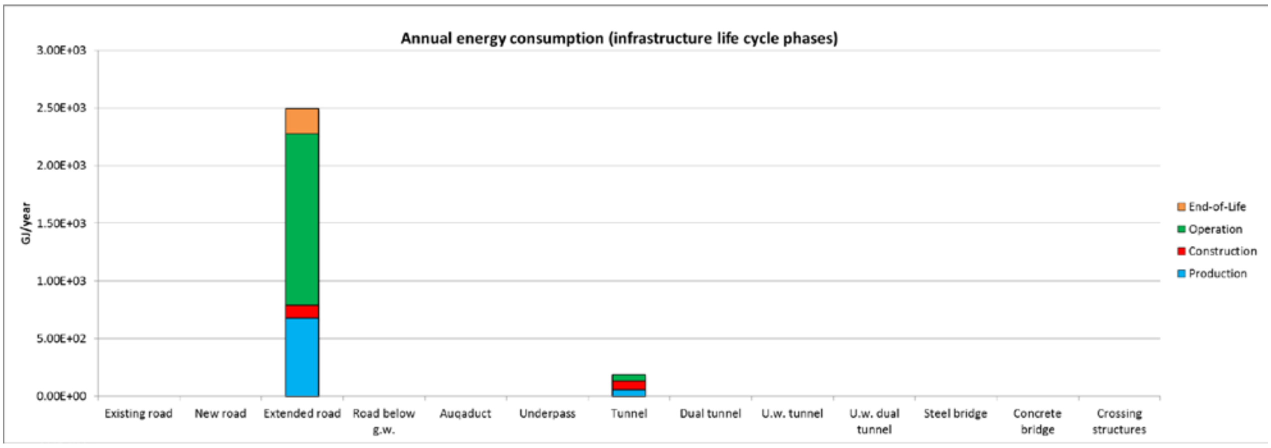


Figure 11: Annual life cycle energy use from road infrastructure elements

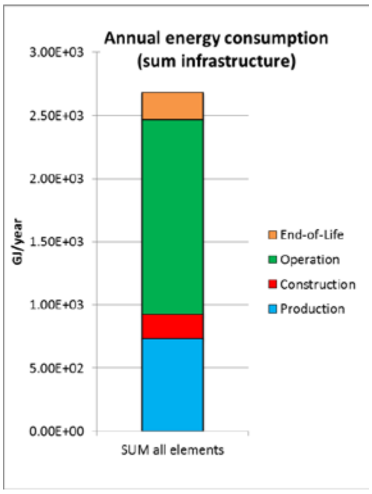


Figure 12: Total annual life cycle energy use from road infrastructure life cycle stages

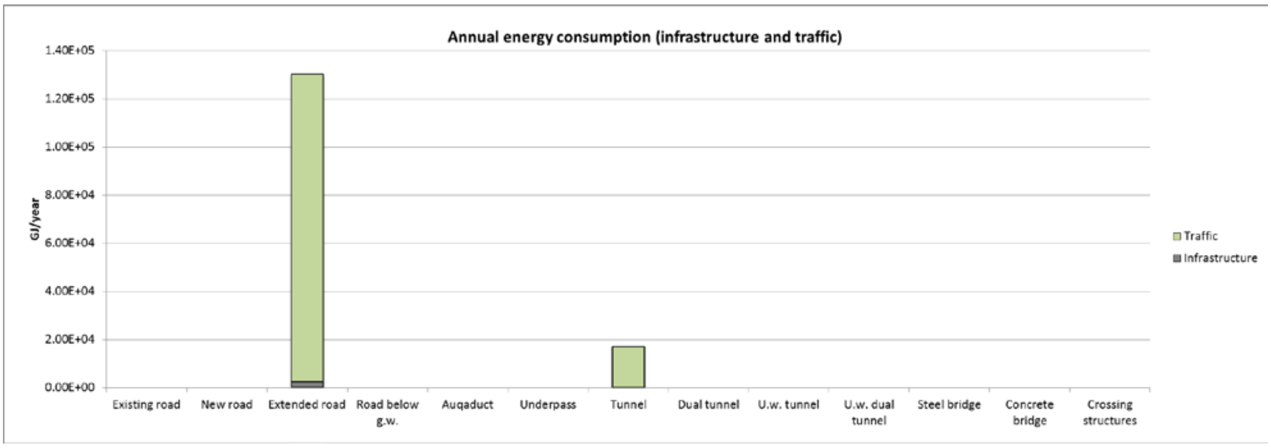


Figure 13: Annual life cycle energy use from road infrastructure elements and traffic

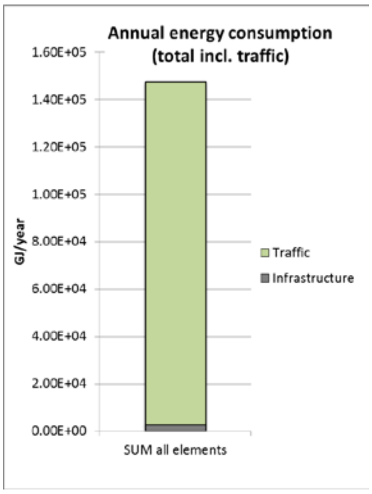


Figure 14: Annual life cycle energy use, including traffic, totalled over all road infrastructure elements

If the user wants to examine more in details what are the causes of results, there are detailed information available in the 'Calculations' tab of the model, where values for the consumption of input materials and energy carriers in every part of the system (life cycle stages and road elements) are reported, as well as their corresponding GHG emissions and energy consumption values. These tables offer opportunities for a complete in-depth analysis of why model results become as they do, and understanding what specific parts of the system turn out to be the most important ones.

5.4 Results from 'Comparison' mode analysis

The results from comparison of different alternatives relative to the reference alternative are given in the 'Comparison' tab, where also key information about the analysis is reported; see Figure 15. In this example three new alternatives (1, 2 and 3, each with a name) are compared to the reference alternative (Alt. 0) of continuing using today's road. Please notice that the data in Chapter 5.4 here are collected from a real Swedish road example that refers to the Test Values populated into the model itself.

INFORMATION ABOUT THE ANALYSIS:		
Name of project:	Road 55, Yxtatorpet to Malmkšping. LICCER Case Study.	
Name of analyst:	Ola Norman	
Analysis No:	Run 1	Comparison mode
Date:	31.12.2013	
New alternatives:	Alt. 1	Improvements
	Route 1	
	Alt. 2	Middle
	Route 2	
	Alt. 3	West
	Route 3	
Reference:	Alt. 0	Continuing use of current road
	Today's road	

Figure 15: Analysis overview of 'Comparison' mode

For Alt.1 the main assumptions about the road composition, lengths and geometry data are from the Test Values included in the model. Alt. 0 is 7574 metres long; Alt. 1 is 8574 metres, Alt.2 is 7034 metres, and Alt.3 is 6794 metres.

In this example the reference alternative is Alt.0, which has no new road infrastructure to be produced and constructed, only operated and end-of-life managed.

Similar to in the previous section we will illustrate some results for life cycle energy use and GHG emissions, however now also showing the difference between each new alternative and the reference alternative.

5.4.1 Greenhouse gas emission results

Table 6 shows how results are reported for annual GHG emissions.

Table 6: Annual GHG emissions in 'Comparison' mode

PHASE	(unit)	Alt. 0	Δ Alt. 0	Alt. 1	Δ Alt. 1	Alt. 2	Δ Alt. 2	Alt. 3	Δ Alt. 3
Production	ton CO2-e/year	0.0E+00	0.00E+00	4.00E+01	4.00E+01	5.04E+01	5.04E+01	3.77E+01	3.77E+01
Construction	ton CO2-e/year	0.0E+00	0.00E+00	1.05E+01	1.05E+01	2.46E+01	2.46E+01	2.15E+01	2.15E+01
Operation	ton CO2-e/year	1.7E+01	0.00E+00	2.47E+01	7.95E+00	2.17E+01	4.94E+00	2.13E+01	4.53E+00
End-of-Life	ton CO2-e/year	7.5E+00	0.00E+00	1.50E+01	7.51E+00	1.77E+01	1.02E+01	1.44E+01	6.86E+00
Infrastructure	ton CO2-e/year	2.4E+01	0.00E+00	9.03E+01	6.60E+01	1.14E+02	9.01E+01	9.49E+01	7.06E+01
Traffic	ton CO2-e/year	5.0E+03	0.00E+00	5.61E+03	6.54E+02	4.60E+03	-3.53E+02	4.45E+03	-5.10E+02
Net total	ton CO2-e/year	5.0E+03	0.00E+00	5.70E+03	7.20E+02	4.72E+03	-2.63E+02	4.54E+03	-4.40E+02
Production	% of Infrastructure	0.0	N.A.	44.3	N.A.	44.0	N.A.	39.7	N.A.
Construction	% of Infrastructure	0.0	N.A.	11.7	N.A.	21.5	N.A.	22.7	N.A.
Operation	% of Infrastructure	69.1	0.00	27.4	47.41	19.0	29.49	22.4	27.05
End-of-Life	% of Infrastructure	30.9	0.00	16.6	99.92	15.5	135.67	15.1	91.33
Infrastructure	% of Net total	0.5	0.00	1.6	271.86	2.4	371.05	2.1	290.99
Traffic	% of Net total	99.5	0.00	98.4	13.20	97.6	-7.13	97.9	-10.30
Net total	% of Net total	100.0	0.00	100.0	14.46	100.0	-5.29	100.0	-8.83

The third column in the table gives the annual GHG emissions of Alternative 0. Since this alternative means a continued use of today's road, no new road elements are added. Therefore there will be no Production or Construction activities and the emissions from these stages are zero. However, there will be emissions from Operation and End-of-Life, since the existing road will also have to be resurfaced and demolished at the end of its service life.

Further to the right in the table are given three pair of columns, one pair for each new route alternative. The left hand side of the pair gives the results for the given alternative in itself, which is just a copy of results from the corresponding 'Result-Alt.X' tab. The right hand side of the pair gives the difference value in GHG emissions between this alternative and the reference alternative (i.e. Δ = Alt.X – REF.). In this case, the reference alternative will be Alternative 0.

The rows in the lower part of the table give the annual GHG emission of each new alternative as a percentage (i.e. = Alt.X/REF.*100%) of the corresponding reference alternative value. Here the percentage values for Production and Construction are not applicable (N.A.) due to the fact that these values (for Alt.0) are zero for these two stages.

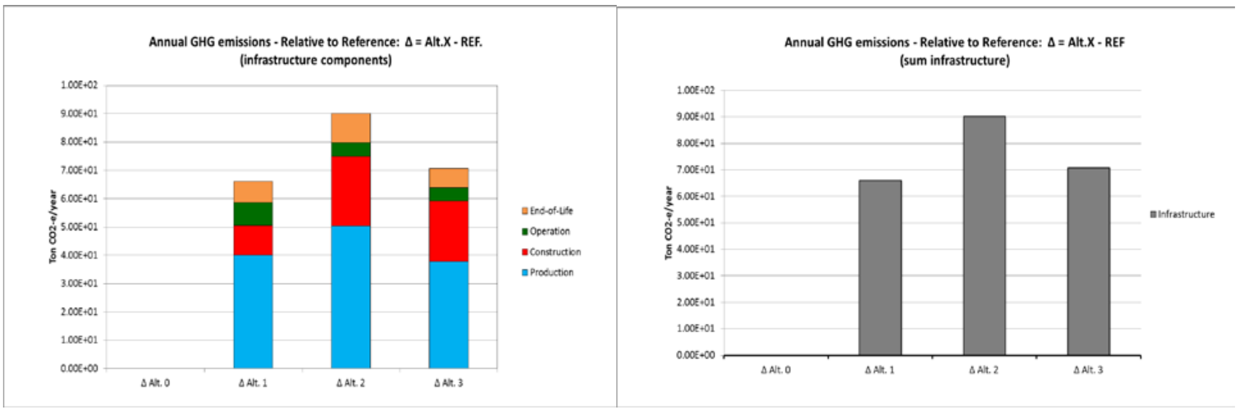
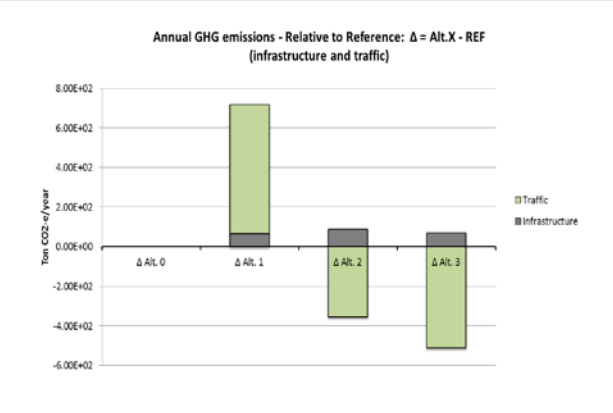


Figure 16: Annual GHG emissions for infrastructure in 'Comparison' mode

The results in Figure 16 can reflect the difference between each new road alternative and the reference alternative when examining the contributions from infrastructure only. The chart to the left shows the difference in GHG emissions from each life cycle stage. Please notice that the difference in emissions from Production and Construction will always be positive when Alt.0 is the reference, since there are no such activities in that alternative. The difference in emissions from Operations and End-of-Life, however, may be negative (below zero), if such activities involve less material handling and transportation in any of the new alternatives than in the reference alternative. The chart to the right in Figure 16 shows the net sum of different GHG emissions from road infrastructure for each alternative, relative to the reference.

From the results in Figure 16 it is clear that Production represent the dominant stage of the life cycle GHG emissions, for all alternatives. It is also obvious that in this example Alt.1 is the best alternative out of the three new route alternatives. However, all three give a positive difference for GHG emissions from infrastructure. This is also as expected, since there are no Production and Construction activities in the reference alternative.



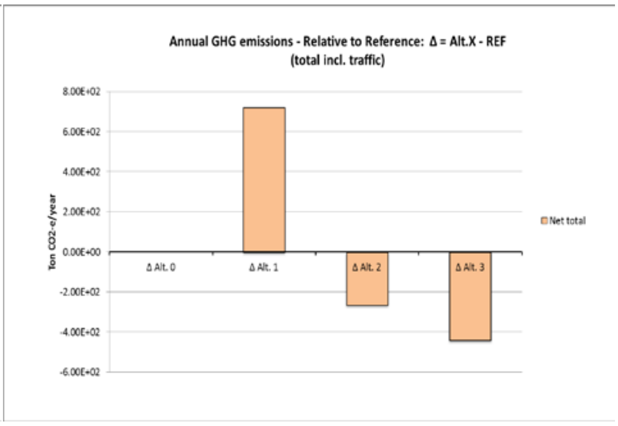


Figure 17: Annual GHG emissions for infrastructure and traffic in 'Comparison' mode

Figure 17 shows the results for difference in annual GHG emission relative to the reference alternative, when traffic during operation is included. The chart to the left presents the breakdown in relative results for infrastructure and traffic, so that their relative importance (and direction) is shown. In this example, there is a large difference in annual emissions from traffic for ΔAlt.1, since this alternative has a longer total road length. However, this is not the case for ΔAlt.2 and ΔAlt.3, which give lower emissions from traffic than in the reference alternative, respectively, due to the fact that Alt.2 and Alt. 3 have a shorter road length than Alt.0. The chart to the right in Figure 17 shows the net total (incl. traffic) difference in annual GHG emissions between each new route alternative relative to the reference. One can see that in this example there are significant total performance differences between the three new alternatives, with Alt.3 being the best and Alt.1 the worst. Hence, the length of a new road alternative influences whether it is better or worse than the reference due to the change in traffic.

Table 7: Absolute annual GHG emissions by material and traffic type

	Lifecycle GHG emissions from infrastructure, by material type	(unit)	Alt. 0	Alt. 1	Alt. 2	Alt. 3
	Steel and Rebar	ton CO2-e/year	0.00E+00	2.92E+00	1.94E+00	4.36E+00
	Concrete Materials (excl. pavement)	ton CO2-e/year	0.00E+00	4.86E+00	1.59E+01	8.38E-01
	Pavement Layer Materials	ton CO2-e/year	1.46E+01	4.56E+01	4.02E+01	4.02E+01
	Subbase and Base Layer Materials	ton CO2-e/year	0.00E+00	8.10E+00	1.12E+01	1.08E+01
	Transport of Materials	ton CO2-e/year	1.51E+00	9.94E+00	1.31E+01	1.03E+01
	Other Direct Energy Use	ton CO2-e/year	7.93E-01	1.49E+00	9.56E-01	9.56E-01
	Earthworks and Explosives	ton CO2-e/year	7.40E+00	1.74E+01	3.10E+01	2.74E+01
	Other Materials	ton CO2-e/year	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Subtotal	ton CO2-e/year	2.43E+01	9.03E+01	1.14E+02	9.49E+01
	Lifecycle GHG emissions from traffic, by fuel type	**(unit)**	**Alt. 0**	**Alt. 1**	**Alt. 2**	**Alt. 3**
Light Vehicles	Biofuel and Electricity	ton CO2-e/year	6.77E+02	7.66E+02	6.29E+02	6.07E+02
	Gas and Diesel	ton CO2-e/year	2.73E+03	3.09E+03	2.53E+03	2.45E+03
Trucks	Biofuel	ton CO2-e/year	4.82E+01	5.46E+01	4.48E+01	4.33E+01
	Gas and Diesel	ton CO2-e/year	1.50E+03	1.70E+03	1.40E+03	1.35E+03
	Subtotal	ton CO2-e/year	4.96E+03	5.61E+03	4.60E+03	4.45E+03
	Total	**ton CO2-e/year**	**4.98E+03**	**5.70E+03**	**4.72E+03**	**4.54E+03**

Table 7 refers to the absolute GHG emissions related to material type and traffic type for each of the alternatives. These results provide the user with more detailed information about a project without the need to aggregate information from the calculations tab. All material results here are considered for the entire life cycle while traffic is considered in the operation phase (from well-to-wheel). The results of this table are in Figure 18.

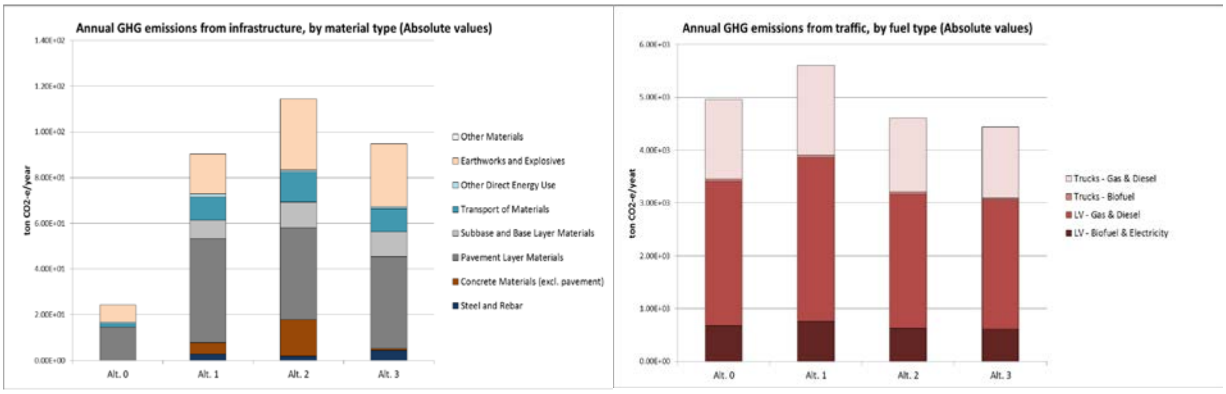


Figure 18: GHG emissions by material type and traffic type

The results are absolute values and separated inherently by infrastructure on the graph to the left, and traffic on the graph to the right. They are separated by the alternatives and not by life cycle stages that consider the GHG emissions through the entire lifecycle of the project. In the first table, the results show that the GHG contribution from infrastructure is the greatest in Alt.2, with grey section made up of pavement layer materials, being the dominant material contribution. In the right side figure, Alt.1 has the greatest emissions due to traffic with the ruby red representing gasoline and diesel light vehicles. It should be noted that the reference alternative (in this case Alt.0) are included in these results as they are absolute values without a reference.

5.4.2 Life cycle energy use results

As for GHG emissions, the model calculates differences in annual life cycle energy use for each new route alternative relative to the reference alternative. The results in our example are given in Table 8 and Figure 19 and Figure 20 below.

Table 8: Annual life cycle energy use in 'Comparison' mode

PHASE	(unit)	Alt. 0	Δ Alt. 0	Alt. 1	Δ Alt. 1	Alt. 2	Δ Alt. 2	Alt. 3	Δ Alt. 3
Production	GJ/year	0.00E+00	0.00E+00	1.63E+03	1.63E+03	1.67E+03	1.67E+03	1.55E+03	1.55E+03
Construction	GJ/year	0.00E+00	0.00E+00	2.17E+02	2.17E+02	3.76E+02	3.76E+02	3.27E+02	3.27E+02
Operation	GJ/year	9.52E+02	0.00E+00	1.41E+03	4.60E+02	1.19E+03	2.38E+02	1.20E+03	2.49E+02
End-of-Life	GJ/year	1.11E+02	0.00E+00	2.22E+02	1.11E+02	2.62E+02	1.51E+02	2.13E+02	1.02E+02
Infrastructure	GJ/year	1.06E+03	0.00E+00	3.48E+03	2.42E+03	3.50E+03	2.43E+03	3.29E+03	2.22E+03
Traffic	GJ/year	1.28E+05	0.00E+00	1.45E+05	1.69E+04	1.19E+05	-9.10E+03	1.15E+05	-1.31E+04
Net total	GJ/year	1.29E+05	0.00E+00	1.48E+05	1.93E+04	1.22E+05	-6.67E+03	1.18E+05	-1.09E+04
Production	% of Infrastructure	0.0	N.A.	46.9	N.A.	47.7	N.A.	47.0	N.A.
Construction	% of Infrastructure	0.0	N.A.	6.2	N.A.	10.7	N.A.	10.0	N.A.
Operation	% of Infrastructure	89.6	0.0	40.5	48.3	34.0	25.0	36.5	26.2
End-of-Life	% of Infrastructure	10.4	0.0	6.4	100.3	7.5	136.2	6.5	91.9
Infrastructure	% of Net total	0.8	0.0	2.4	227.8	2.9	229.0	2.8	209.2
Traffic	% of Net total	99.2	0.0	97.6	13.2	97.1	-7.1	97.2	-10.3
Net total	% of Net total	100.0	0.0	100.0	15.0	100.0	-5.2	100.0	-8.5

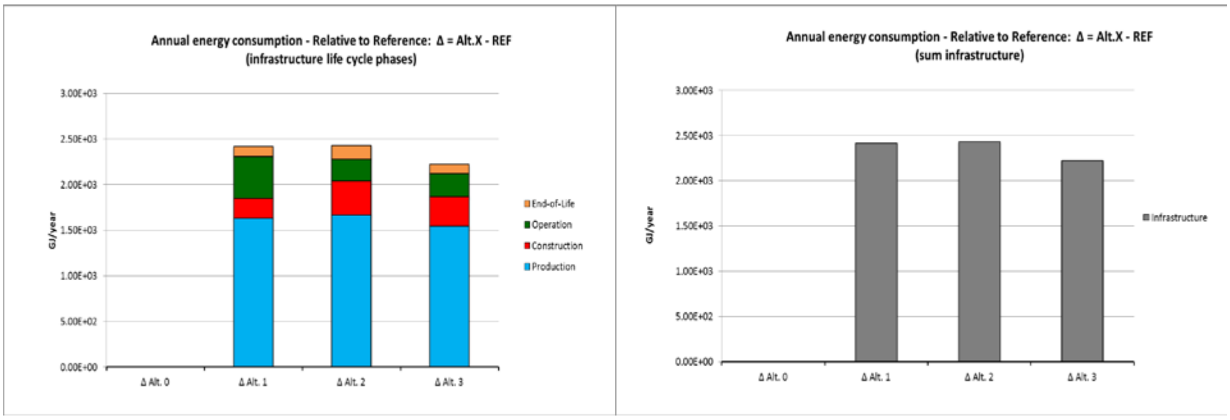


Figure 19: Annual life cycle energy use for infrastructure in 'Comparison' mode

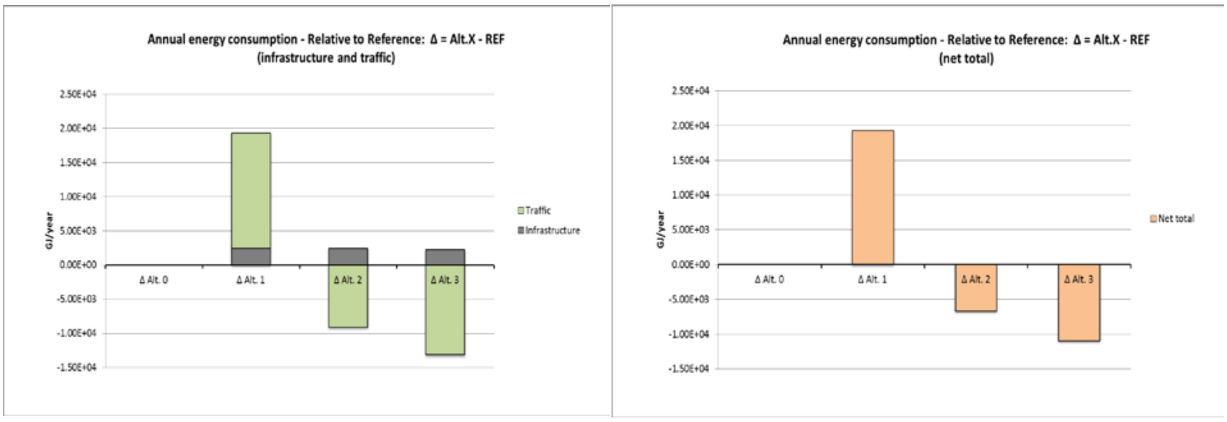


Figure 20: Annual life cycle energy use for infrastructure and traffic in 'Comparison' mode

The interpretation of results for annual life cycle energy use can be done in the same way as for annual GHG emissions in the previous section.

Table 9: Absolute annual energy use by material and traffic type

	Lifecycle energy consumption from infrastructure, by material type	(unit)	Alt. 0	Alt. 1	Alt. 2	Alt. 3
	Steel and Rebar	GJ/year	0.00E+00	4.30E+01	2.60E+01	5.84E+01
	Concrete Materials (excl. pavement)	GJ/year	0.00E+00	3.41E+01	1.11E+02	5.87E+00
	Pavement Layer Materials	GJ/year	7.63E+02	2.39E+03	2.06E+03	2.11E+03
	Subbase and Base Layer Materials	GJ/year	0.00E+00	2.91E+02	4.28E+02	3.43E+02
	Transport of Materials	GJ/year	2.42E+01	1.59E+02	2.10E+02	1.64E+02
	Other Direct Energy Use	GJ/year	1.66E+02	3.14E+02	2.01E+02	2.01E+02
	Earthworks and Explosives	GJ/year	1.09E+02	2.56E+02	4.56E+02	4.04E+02
	Other Materials	GJ/year	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Subtotal	GJ/year	1.06E+03	3.48E+03	3.50E+03	3.29E+03
	Lifecycle energy consumption from traffic, by fuel type	**(unit)**	**Alt. 0**	**Alt. 1**	**Alt. 2**	**Alt. 3**
Light Vehicles	Biofuel and Electricity	GJ/year	6.30E+04	7.14E+04	5.86E+04	5.66E+04
	Gas and Diesel	GJ/year	4.01E+04	4.54E+04	3.72E+04	3.60E+04
Trucks	Biofuel	GJ/year	2.38E+03	2.69E+03	2.21E+03	2.13E+03
	Gas and Diesel	GJ/year	2.21E+04	2.51E+04	2.06E+04	1.99E+04
	Subtotal	GJ/year	1.28E+05	1.45E+05	1.19E+05	1.15E+05
	Total	**GJ/year**	**1.29E+05**	**1.48E+05**	**1.22E+05**	**1.18E+05**

Table 9 refers to the absolute energy use related to material type and traffic type for each of the alternatives. These results provide the user with more detailed information about a project without the need to aggregate information from the calculations tab. All material results here are considered for the entire life cycle while traffic is considered in the operation phase (from well-to-wheel). The results of this table are in Figure 21.

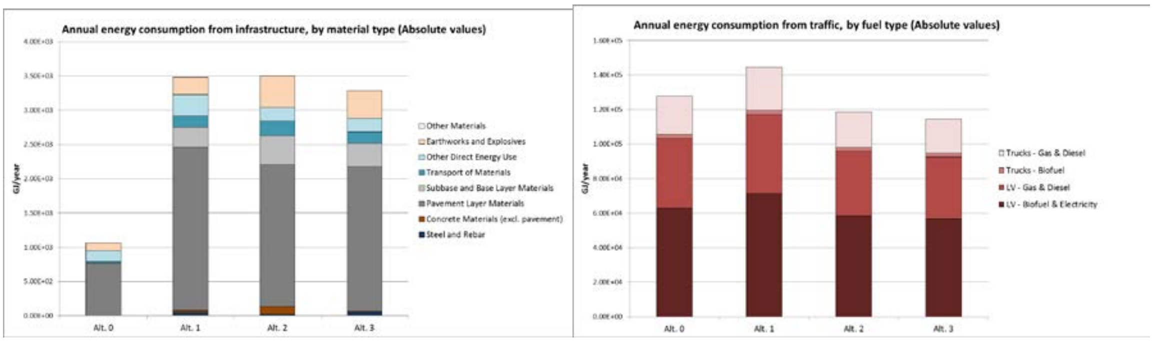


Figure 21: Energy consumption by material and traffic type

As pointed out in the end of section 5.3, if the user wants to examine more in details what are the causes of results, there are detailed information available in the 'Calculations' tab of the model, where values for the consumption of input materials and energy carriers in every part of the system (life cycle stages and road elements) are reported, as well as their corresponding energy use and GHG emissions values. These tables offer opportunities for a complete in-depth analysis of why model results become as they do, and understanding what parts of the system turn out to be the most important ones.

5.5 Results from 'Adding-Up' mode analysis

The 'Adding-Up' tab gives the results from the analysis of separate new road sections that in-series constitute a new road corridor alternative. For model structure technical reasons the sections are also labelled as alternatives, however, they do not represent independent new road corridor alternatives but sections within the same (one) new road corridor alternative. The results in the 'Adding-Up' tab are expressed relative to the reference alternative. Please note that these results *should be used only* when you want to analyse a specific road corridor alternative that consists of a sum of new road *in-series sections* (1+2+3, i.e. all three successively following each other) on the way between "A" and "B". So together they constitute one complete new road corridor alternative that can be compared with the reference alternative (0).

The advantage of this analysis mode option of the model is increased flexibility, because now a selected road corridor alternative can be analysed in more detail along its way between "A" and "B". For instance, given road element types within each of the sections of interest (for instance, tunnels within sections 1, 2 and 3) can have different road geometry, such as number and width of lanes and depth of layers. The 'Adding-Up' mode can deal with the situations where such increased flexibility is needed, while in the 'Comparison' mode these things have to be defined constant all the way between "A" and "B". Figure 22 gives the overview information of such an analysis.

INFORMATION ABOUT THE ANALYSIS:		
Name of project:	Road 55, Yxtatorpet to Malmkoping. LICCER Case Study.	
Name of analyst:	Ola Norman	
Analysis No:	1	Adding-Up mode
Date:	31.12.2013	
New alternatives:	Alt. 1	New section 1
	Section 1	
	Alt. 2	New section 2
	Section 2	
	Alt. 3	New section 3
	Section 3	
Reference:	NO REF	No reference used, but Alt. 0 can be included in the analysis

Figure 22: Analysis overview of 'Adding-Up' mode

This 'Adding-Up' situation of analysis in our hypothetic example assumes that one new road corridor alternative ('Road corridor X') is to be compared with the reference alternative, and that this new alternative is divided into three in-series sections ('Section 1', 'Section 2' and 'Section 3'). Please notice that the data in Chapter 5.5 here also represent a hypothetical case. Each section includes the similar types of road elements (road, tunnel, bridge, etc.) as were used in the previous 'Comparison' mode example (see Chapter 5.4 above). However, we now have adjusted the input values of road lengths of Alt.1 ('Section 1'), Alt.2 ('Section 2') and Alt.3 ('Section 3'), so that their sum is in the same order of magnitude of the reference alternative towards which the sum of new road sections must be compared.

Alt. 0 is 7574 metres long; Alt. 1 is 8574 metres, Alt.2 is 7034 metres, and Alt.3 is 6794 metres. The sum length of Alt.1 + Alt 2 + Alt.3 is 22.402 km.

5.5.1 Greenhouse gas emission results

Table 10 and Figure 23 and Figure 24 show how results are reported for annual GHG emissions in the 'Adding-Up' mode. The last three columns in the table show the different resulting values depending on what is chosen as a reference and which results are used in the figures. When Alt.0 is chosen as reference, the resulting values represent sum of the three new sections (1+2+3) minus the reference (0). Alternatively, if the existing road is included as one of the sections in a new route, the resulting values represent the sum of all four sections (0+1+2+3). In this example Table 10 shows that results are calculated relative to a reference (0), and these are the results also used in the following figures.

Table 10: Annual GHG emissions in 'Adding-Up' mode

						When REF = Alt.0	When NO REF	RESULTS USED
PHASE	(unit)	Alt. 0	Alt. 1	Alt. 2	Alt. 3	Alt. (1+2+3) - Alt. 0	Alt.(0+1+2+3)	Alt. (1+2+3) - Alt. 0
Production	ton CO2-e/year	0.00E+00	4.00E+01	5.04E+01	3.77E+01	1.28E+02	N.A.	1.28E+02
Construction	ton CO2-e/year	0.00E+00	1.05E+01	2.46E+01	2.15E+01	5.67E+01	N.A.	5.67E+01
Operation	ton CO2-e/year	1.68E+01	2.47E+01	2.17E+01	2.13E+01	5.10E+01	N.A.	5.10E+01
End-of-Life	ton CO2-e/year	7.51E+00	1.50E+01	1.77E+01	1.44E+01	3.96E+01	N.A.	3.96E+01
Infrastructure	ton CO2-e/year	2.43E+01	9.03E+01	1.14E+02	9.49E+01	2.75E+02	N.A.	2.75E+02
Traffic	ton CO2-e/year	4.96E+03	5.61E+03	4.60E+03	4.45E+03	9.70E+03	N.A.	9.70E+03
Net total	ton CO2-e/year	4.98E+03	5.70E+03	4.72E+03	4.54E+03	9.98E+03	N.A.	9.98E+03
Production	% of Infrastructure	0.0	44.3	44.0	39.7	46.5	N.A.	46.5
Construction	% of Infrastructure	0.0	11.7	21.5	22.7	20.6	N.A.	20.6
Operation	% of Infrastructure	69.1	27.4	19.0	22.4	18.5	N.A.	18.5
End-of-Life	% of Infrastructure	30.9	16.6	15.5	15.1	14.4	N.A.	14.4
Infrastructure	% of Net total	0.5	1.6	2.4	2.1	2.8	N.A.	2.8
Traffic	% of Net total	99.5	98.4	97.6	97.9	97.2	N.A.	97.2
Net total	% of Net total	100.0	100.0	100.0	100.0	100.0	N.A.	100.0

The results in Table 10 show that for infrastructure there is a positive difference between the sum of new infrastructure in the new alternatives and the reference alternative. There is also a positive difference for traffic and the Net total. This means that the sum of three new sections gives more GHG emissions in total (including traffic) than the reference.

Figure 23 shows that the dominant life cycle stages of infrastructure are Production, as expected.

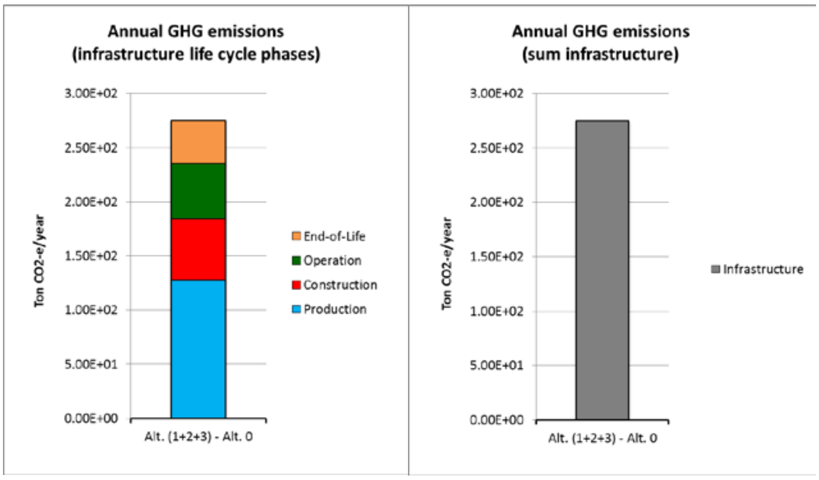


Figure 23: Annual GHG emissions from infrastructure in 'Adding-Up' mode

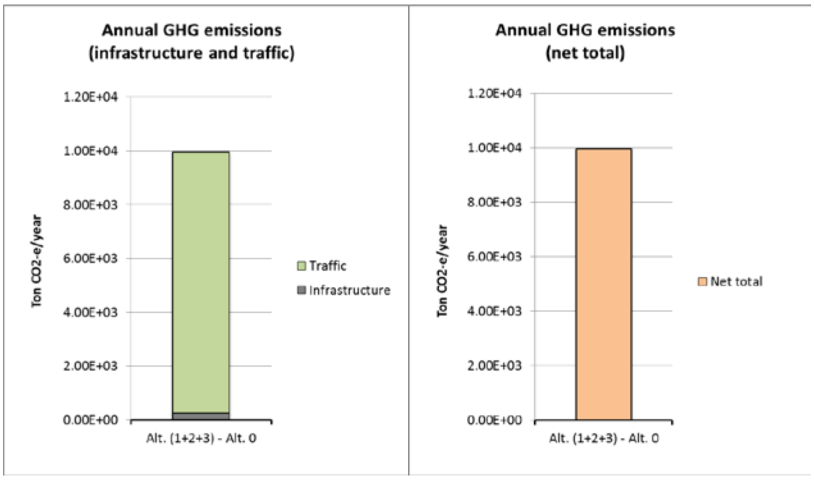


Figure 24: Annual GHG emissions from infrastructure and traffic in 'Adding-Up' mode

Figure 23 shows, in the left chart, that the emissions from infrastructure for Alt.1+Alt.2+Alt.3 are more than the emissions in Alt.0. In the right hand side chart of Figure 24 it is clear that the net total emissions difference is positive, meaning that the new route alternative with three road sections (Alt.1, Alt.2 and Alt.3) has greater total emissions including traffic than the reference alternative. Please note that if 'No Reference' is chosen, these values will be absolute values, with the contributions from Alt.0 included in the sum.

The absolute GHG emissions by material type and traffic type are also included in the 'Adding-Up' mode tab. They are structured identically to those on the 'Comparison' mode tab. For reference on these figures, please refer to explanations given for Figure 18**.**

5.5.2 Life cycle energy use results

As for GHG emissions, the model results for life cycle energy use in our example where the added-up sum of Alt.1, Alt.2 and Alt.3 compared to the reference alternative are given in Table 11 and Figure 25 and Figure 26 below.

Table 11: Annual life cycle energy use in 'Adding-Up' mode

						When REF = Alt.0	When NO REF	RESULTS USED
PHASE	(unit)	Alt. 0	Alt. 1	Alt. 2	Alt. 3	Alt. (1+2+3) - Alt. 0	Alt.(0+1+2+3)	Alt. (1+2+3) - Alt. 0
Production	GJ/year	0.00E+00	1.63E+03	1.67E+03	1.55E+03	4.85E+03	N.A.	4.85E+03
Construction	GJ/year	0.00E+00	2.17E+02	3.76E+02	3.27E+02	9.20E+02	N.A.	9.20E+02
Operation	GJ/year	9.52E+02	1.41E+03	1.19E+03	1.20E+03	2.85E+03	N.A.	2.85E+03
End-of-Life	GJ/year	1.11E+02	2.22E+02	2.62E+02	2.13E+02	5.85E+02	N.A.	5.85E+02
Infrastructure	GJ/year	1.06E+03	3.48E+03	3.50E+03	3.29E+03	9.20E+03	N.A.	9.20E+03
Traffic	GJ/year	1.28E+05	1.45E+05	1.19E+05	1.15E+05	2.50E+05	N.A.	2.50E+05
Net total	GJ/year	1.29E+05	1.48E+05	1.22E+05	1.18E+05	2.59E+05	N.A.	2.59E+05
Production	% of Infrastructure	0.0	46.9	47.7	47.0	52.7	N.A.	52.7
Construction	% of Infrastructure	0.0	6.2	10.7	10.0	10.0	N.A.	10.0
Operation	% of Infrastructure	89.6	40.5	34.0	36.5	31.0	N.A.	31.0
End-of-Life	% of Infrastructure	10.4	6.4	7.5	6.5	6.4	N.A.	6.4
Infrastructure	% of Net total	0.8	2.4	2.9	2.8	3.6	N.A.	3.6
Traffic	% of Net total	99.2	97.6	97.1	97.2	96.4	N.A.	96.4
Net total	% of Net total	100.0	100.0	100.0	100.0	100.0	N.A.	100.0

Table 11 shows for life cycle energy use, as Table 10 showed for GHG emissions. This table is summarized shown graphically in Figure 25, where we see that for energy use as it is now in our hypothetic example, the Production stage gives the largest contributions for energy use from Infrastructure. In Figure 26, energy use from traffic is shown to dominate the infrastructure in aggregated energy use.

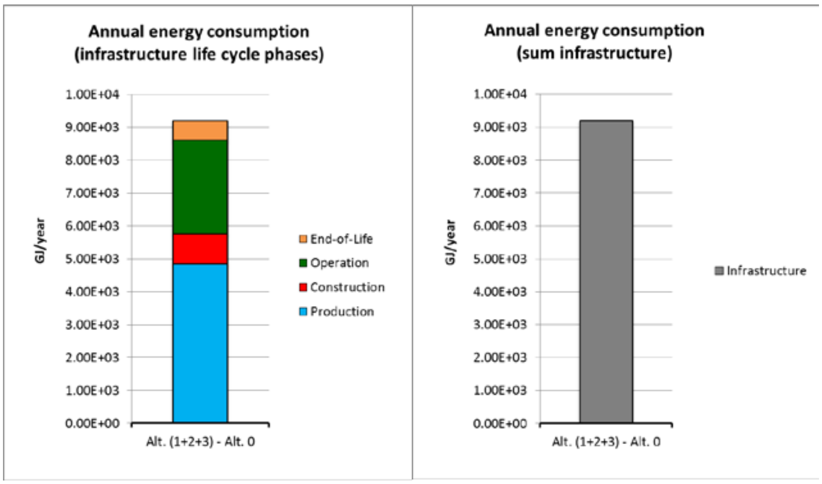


Figure 25: Annual life cycle energy use for infrastructure in 'Adding-Up' mode

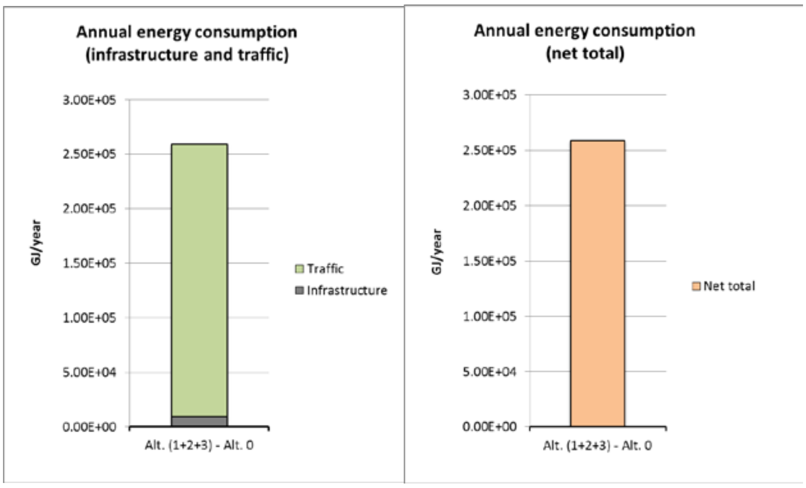


Figure 26: Annual life cycle energy use for infrastructure and traffic in 'Adding-Up' mode

The absolute energy use by material type and traffic type are also included in the 'Adding-Up' mode tab. They are structured identically to those on the 'Comparison' mode tab. For reference on these figures, please refer to explanations given for Figure 21**.**

As pointed out in the end of Chapter 5.3 and Chapter 5.4, if the user wants to examine more in details what are the causes of results, there are detailed information available in the 'Calculations' tab of the model, where values for the consumption of input materials and energy carriers in every part of the system (life cycle stage and road elements) are reported, as well as their corresponding life cycle energy use and GHG emissions values. These tables offer opportunities for a complete in-depth analysis of why model results become as they do, and understanding what parts of the system turn out to be the most important ones.

6 Discussion and conclusion about LICCER-model, and its parameters and default values

The LICCER model presents a comprehensive basic set of data and algorithm for calculating GHG and energy use in road projects, but there are ways that can improve the precision and results for a specific project. Additionally, certain parameters are more critical to the calculation procedure than others and should be considered accordingly.

6.1 Importance of parameters

When doing an LCA of road projects there is a multitude of parameters to consider. Some of them can be considered ‘project data parameters’, and are related to the length and composition of elements (e.g. road, tunnels, bridges) of the road project, the presence of any crossing structures, and the cross-section geometry of the road. These are included in the RoadDesign sheet of the LICCER model, and will have values that are unique for a given road project. Hence, it is important to provide as accurate input values as possible for these parameters.

Other parameters in the LICCER model are considered more generic, for which default values, serving as background data, according to national practice and conditions are provided. These are included in the ModelValues sheet of the LICCER model, and default values are provided for Norway and Sweden, and may in future be inserted for other countries. The user can run the model without any project-specific values inserted, i.e. only relying on the default values. Otherwise, the user may provide project-specific values for as few or as many parameters as needed, depending on the context of the analysis and the local conditions (e.g. service life, transport distances, tunnel geometry, specific material consumption, energy coefficients and GHG emission coefficients).

Not all parameters are equally important, with respect to how their value (or the uncertainty of their value) may influence the model results. The two sections below give a brief presentation of the relative importance of project data parameters and background data (with default values) parameters.

6.1.1 Project data parameters of importance

The project data parameters are the parameters that are inputted directly by the user into the LICCER model in the ‘RoadDesign’ tab. Empirical case study data, and general results given from the model, indicate that some input parameters are highly important to include in any analysis performed by the LICCER model.

The following project parameters are considered essential to include in any analysis undertaken

- ***Length, width and depth of road layers***, especially the pavement layers but also the other layers
- ***Earthworks***, either by indicating total diesel fuel usage or by using the expanded earthworks section in order to input soil and rock volumes
- ***Concrete use***, by selecting a tunnel lining type for different tunnel types, or by inputting extra concrete use in auquaducts, underpasses, road below groundwater, or crossing structures. If the project has additional concrete included that do fit within the parameters, please place concrete use in the *Crossing elements* section.

- ***Total soil stabilized and stabilization type*** (if applicable; might be important in road projects with long lengths of soil that requires stabilization)
- ***Share length of road lighting***, especially in tunnels where lighting occurs 24 hours a day

Other variables that have an influence on results are the parameters included in the uppermost section of the 'RoadDesign' sheet, specifically AADT and ATH. It is always best to include as much data as possible.

6.1.2 Background data parameters of importance

While the LICCER model assumptions are aligned with road authorities' assumptions, there are always differences between national averages used in the model and the project specific values. The most important parameters to consider within the background data are highlighted within the 'ModelValues' sheet as white cells. Figure 27 is a collapsed and Figure 28 is an expanded version of the 'ModelValues' sheet, where Figure 28 shows an example in the 'ModelValues' tab of where the important variables are highlighted in white (note that all parameters in Figure 27 are considered important).

Expand
Collapse

Transport distance of materials (truck on road only)		Default value	Project value	National default values (km)			
Materials from outside suppliers		(km)	(km)	Norway	Sweden	Denmark	Netherlands
Sand/soil, all usage	TD-SAND	20		20	20	N/A	N/A
Concrete, pavement	TD-CON-PV	150		150	150	N/A	N/A
Concrete, tunnel portals	TD-CON-TP	150		150	150	N/A	N/A
Concrete, tunnel wall elements	TD-CON-TWE	150		150	150	N/A	N/A
Concrete, tunnel lining (cast on site)	TD-CON-TL	150		150	150	N/A	N/A
Concrete, other	TD-CON-OTH	300		300	300	N/A	N/A
Concrete, guardrails	TD-CON-GR	150		150	150	N/A	N/A
Rebar, bridges	TD-RE-BR	500		500	500	N/A	N/A
Rebar, tunnel wall elements	TD-RE-TWE	500		500	500	N/A	N/A
Rebar, tunnel portals	TD-RE-TP	500		500	500	N/A	N/A
Rebar, tunnel lining	TD-RE-TL	500		500	500	N/A	N/A
Rebar, other	TD-RE-OTH	500		500	500	N/A	N/A
Shortcrete, tunnel lining	TD-SHO-TL	150		150	150	N/A	N/A
Steel, steel bridges	TD-ST-SBR	500		500	500	N/A	N/A
Transport distance of materials (truck on road only)		Default value	Project value	National default values (km)			
Internal transportation of masses		(km)	(km)	Norway	Sweden	Denmark	Netherlands
Internal transportation masses from earthwork	TD-EARTH	0.5		1.5	0.5	N/A	N/A
Internal transportation rock masses from tunneling	TD-ROT	2.5		2.5	2.5	N/A	N/A

Figure 27: Collapsed transport distances in the 'ModelValues' tab

Expand
Collapse

Transport distance of materials (truck on road only)		Default value	Project value	National default values (km)			
Materials from outside suppliers		(km)	(km)	Norway	Sweden	Denmark	Netherlands
Aggregate/gravel, all usage except pavement asphalt	TD-AGG	20		20	20	N/A	N/A
Asphalt membrane	TD-AM	500		150	500	N/A	N/A
Asphalt, pavement (incl. bitumen and aggregate)	TD-AST-PV	30		30	30	N/A	N/A
Sand/soil, all usage	TD-SAND	20		20	20	N/A	N/A
Concrete, pavement	TD-CON-PV	150		150	150	N/A	N/A
Concrete, bridges	TD-CON-BR	150		150	150	N/A	N/A
Concrete, tunnel portals	TD-CON-TP	150		150	150	N/A	N/A
Concrete, tunnel wall elements	TD-CON-TWE	150		150	150	N/A	N/A
Concrete, tunnel lining (cast on site)	TD-CON-TL	150		150	150	N/A	N/A
Concrete, other	TD-CON-OTH	300		300	300	N/A	N/A
Concrete, guardrails	TD-CON-GR	150		150	150	N/A	N/A
Cement, soil stabilization	TD-CEM-SS	300		300	300	N/A	N/A
Lime from lime pillars, soil stabilization	TD-LIMEP-SS	300		300	300	N/A	N/A
Explosives	TD-EXP	100		150	100	N/A	N/A
PE-foam, tunnel lining	TD-PEF-TL	500		300	500	N/A	N/A
Rebar, bridges	TD-RE-BR	500		500	500	N/A	N/A
Rebar, tunnel wall elements	TD-RE-TWE	500		500	500	N/A	N/A
Rebar, tunnel portals	TD-RE-TP	500		500	500	N/A	N/A
Rebar, tunnel lining	TD-RE-TL	500		500	500	N/A	N/A
Rebar, other	TD-RE-OTH	500		500	500	N/A	N/A
Shortcrete, tunnel lining	TD-SHO-TL	150		150	150	N/A	N/A
Steel, guardrails	TD-ST-GR	500		500	500	N/A	N/A
Steel, tunnel securing bolts	TD-ST-TSB	500		500	500	N/A	N/A
Steel, steel bridges	TD-ST-SBR	500		500	500	N/A	N/A

Figure 28: Expanded transport distance in the 'ModelValues' tab

The "Expand" and "Collapse" buttons on the 'ModelValues' tab show the more important variables in white and the ones that are, in general, less important in grey. Despite the classification between important and less-important within the model, it is highly recommended that all data project specific data available be included in the 'ModelValues' tab.

The following background parameters are considered essential parameters to include in any analysis undertaken:

- ***All service life of road infrastructure variables***
- Most ***transport of materials used in larger quantities***, such as concrete, and sand/soil
- Most ***transport of materials that come from a long distance***, such as steel
- ***All fuel consumption from traffic variables***
- ***Pavement material mixture (if available)***
- ***Tunnel cross-section variables for tunnels***
- ***Material consumption variable for superstructures,*** such as concrete use in steel and concrete bridges
- ***Diesel fuel consumption by machinery***

The importance of these variable do not underscore the importance of populating the 'ModelValues' sheet with as much data as is available in a project.

6.2 Default values and assumptions

The default values or background data used in the LICCER model will be publicly available and can be used without restriction by the LICCER users. Coordinating and collecting this data to be region dependent for the countries included in LICCER model proved to be a challenge and inherently involves numerous assumptions. These assumptions are primarily on technology choices and average national values for consumption variables, while some assumptions come from calculations by the LICCER team itself or by road authorities.

A certain familiarity with life cycle analysis and road engineering is required to use the LICCER model. This also applies for the data used in the LICCER model that is recommended to be adjusted according to project-specific needs where relevant and available. The LICCER model offers national default values for most background model-parameters, which will automatically be used if no project-specific values are provided by the model-user. Such project-specific values may provide data input that is more accurate or relevant for a given road project, and therefor might improve the accuracy of the model analysis. The inclusion of default values in the LICCER model is meant to ensure that coverage of all unknown variables in a project could be included. This also offers possibility of carrying out calculations even if no project-specific data are available or in situations when a rough analysis is wanted without spending time on data collection for project-specific data. A good example of including important background data comes from the handling of traffic in the LICCER model.

The focus in the LICCER model has been primarily on infrastructure, since this is specified in the project contract. Traffic has nevertheless been included in the LICCER model, though largely simplified, as traffic calculations were actually not part of the contract. Traffic data and traffic calculations implemented in the LICCER model present a roughly representative picture of traffic emissions, which is suitable for the early planning process. It cannot by itself describe, however, e.g. the differences in vehicle fuel consumption according the topographical conditions of a specific project. This is because vehicle fuel consumption background data collected in the LICCER model comes from national average data sources, and may vary a lot from different local road project situations.

On the other hand, the model-user may provide project-specific values for fuel consumption per vehicle type. Differences in vehicle fuel consumption may in specific projects be relevant to include in comparing road corridor alternatives. For example, given two road project that span the same length, a flat road will have lower fuel consumption variables then a mountain road with large vertical gradients. It is therefore recommended to input fuel consumption values in the ’ModelValues’ tab when available. Large differences may also occur in the local vehicle fleet mix.

Technology choices are fixed within the basic background data and represent present day or average recent technology, from different sources, which will not necessarily hold in future. A good example of this would be road lighting, which will more than certainly be constituted of newer technologies in the future, such as LED energy saving light bulbs being in used in place of today’s lighting systems. It is again recommended, when relevant, that any information available in a project be inputted into the ‘ModelValues’ sheet so that the most precise results are presented in the model.

The ‘DataSources’ tab within the LICCER model shows where the default data values in the model comes from and the reference list included in this report gives the expanded reference information if required. The ‘DataSources’ tab has all of the background information included. To view the data, simply click the Expand buttons for the sections indicated. There is also the ability to Expand and Collapse different country datasets. Figure 29 shows where the specific GHG emissions of materials come from and their default values. The ‘ModelValues’ tab references these default values.

			Norway	
Specific greenhouse gas emissions of materials	Abbreviation	Unit (CO2-e)	*Value*	*Source*
Aggregate	AGG	kg/ton	2.39	EFFEKT (Norwegian electricity mix)
Bitumen	BIT	kg/ton	430.00	Idemat 2012
Asphalt membrane	AM	kg/ton	206.00	EFFEKT (Norwegian electricity mix)
Aggregate/Gravel in reasphaltation	ASR-AGG	kg/ton	2.39	EFFEKT (Norwegian electricity mix)
Bitumen in reasphaltation	ASR-BIT	kg/ton	430.00	Idemat 2012
Asphalt mixing	AS-MIX	kg/ton	79.95	Zapata 2005 (Norwegian electricity mix)
Sand / Soil	SAND	kg/ton	2.39	EFFEKT (Norwegian electricity mix)
Concrete	CON	kg/m3	236.00	EFFEKT (Norwegian electricity mix)
Diesel	DIE	kg/m3	3190.00	EFFEKT (Norwegian electricity mix)
Biofuel	BIO	kg/m3	691.00	Østfoldforskning 2009 (99% Ethanol, Norwegian electricity mix)
Electricity	EL	kg/kWh	0.21	EFFEKT (Norwegian electricity mix)
Explosives	EXP	kg/ton	2380.00	EFFEKT (Norwegian electricity mix)
Gasoline	GAS	kg/m3	2750.00	EFFEKT (Norwegian electricity mix)
Gravel	GR	kg/ton	2.39	EFFEKT (Norwegian electricity mix)
PE-foam	PEF	kg/ton	2470.00	EFFEKT (Norwegian electricity mix)
Rebar (reinforcement steel)	RE	kg/ton	754.79	EFFEKT (Norwegian electricity mix)
Rockfill	RF	kg/ton	1.80	EFFEKT (Norwegian electricity mix)
Shotcrete	SHO	kg/m3	200.00	Østfoldforskning 2013
Steel	ST	kg/ton	1610.00	EFFEKT (Norwegian electricity mix)
Lime, soil stabilization	LIME-STAB	kg/ton	780.00	Hammond, Jones (2011)
Cement	CEM	kg/ton	748.00	NORCEM EPD 2012, Standard cement
Transport work	TRAN	kg/tkm	0.13	EFFEKT (Norwegian electricity mix)

Figure 29: Typical presentation of sources in the ‘DataSources’ tab

Figure 29 shows the sources for the specific GHG emissions of materials and their default values. The ‘ModelValues’ tab references these default values in the calculations. These values are fixed and cannot be changed in the ‘DataSources’ tab. All project specific changes must be added in the ‘ModelValues’ tab.

In general, the LICCER model is developed under the principle that national default values should represent a set of values that are approved by, and will be used by, the National Road Administrations. For Norway this would at present be values that are already approved and used in EFFEKT, while for Sweden this would be values that are approved and used in Klimatkalkyl. For some parameters that are not covered by EFFEKT or Klimatkalkyl, one will have to rely on data from other sources. Over time, as the LICCER model is more extensively tested and used for many road project cases, the idea is that the National Road Administrations should update and improve the quality of the dataset relevant for their respective country.

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Appendix 1: Common variables and input parameters

This section contains information and explanation on the variables, parameters and equations used in the calculations in the LICCER model.

Common variables

Road infrastructure element types (i) along the road corridor

$EXR = existing\ road\ (i.e.\ road\ serving\ current\ traffic)$
$NR = new\ road\ (i.e.\ new\ plain\ road)$
$ER = extended\ road$
$RBG = road\ below\ groundwater$
$AD = aquaduct$
$UP = underpass$
$T = tunnel$
$DT = dual\ tunnel$
$UWT = underwater\ tunnel$
$UWDT = underwater\ dual\ tunnel$
$BR = bridges, general$
$SBR = steel\ bridge/steel\ \ overpass$
$CBR = concrete\ bridge/concrete\ overpass$
$OR_i = off\ road\ crossing\ structures\ by\ type\ i, where\ i\ can\ be\ denoted\ as:$
$SBR = steel\ bridge/steel\ overpass$
$CBR = concrete\ bridge/concrete\ overpass$
$UP = underpass$
$LI = large\ intersection$

Road lane types (j)

$DL = driving\ lanes$
$HS = hard\ shoulders$
$CR = central\ reserve\ including\ guardrail$
$CPL = cycling/pedestrian\ lane$
$SS = soft\ shoulders\ including\ guardrail$
$RD = road\ ditch$

Life cycle stage variables (p)

$PROD$	Production stage
$CONS$	Construction stage
$OPER$	Operation stage
EOL	End of life stage
$TRAF$	Traffic during operation stage

Countries

$NORW$	Norway
$SWED$	Sweden
$DANK$	Denmark
$NETH$	Netherlands
$EURO$	European other or average

’RoadDesign’ parameters

The parameters in this section relate to the ’RoadDesign’ sheet of the LICCER model. These parameters all rely on input values provided by the user. For each alternative such input is provided within three sections of the input tables:

i) Elements along this road corridor alternative
ii) Elements crossing this road corridor alternative
iii) Cross-section geometry of the road corridor

The input parameters included in each of these sections are listed and explained below.

Elements along the road corridor alternative

$SHL_{LG,i} = share\ of\ length\ road\ with\ lighting\ in\ corridor\ on\ road\ type\ i, \%$
$SHL_{SG,m,i} = share\ of\ length\ road\ with\ side\ guardrails\ in\ material\ m, on\ road\ type\ i, \%$
$SHL_{CG,m,i} = share\ of\ length\ road\ with\ centre\ guardrails\ in\ material\ m, on\ road\ type\ i, \%$
$SHL_{ES,i} = share\ of\ length\ with\ simple\ excavated\ soil\ ofnroad\ type\ i, \%$
$SHL_{ERS,i} = share\ of\ length\ with\ excavated\ soil\ requiring\ ripping\ on\ road\ type\ i, \%$
$SHL_{BLR,i} = share\ of\ length\ with\ blasted\ rock\ on\ road\ type\ i, \%$
$Q_{DIE-EARTH} = quantity\ of\ diesel\ fuel\ used\ in\ earthworks, in\ m^3$
$Q_{DIE-TEUD} = quantity\ of\ diesel\ fuel\ used\ in\ earthworks, user\ defined, in\ m^3$
$Q_{ES} = quantity\ of\ excavated\ soil\ in\ earthworks, in\ m^3$
$Q_{ERS} = quantity\ of\ excavated\ ripped\ soil\ in\ earthworks, in\ m^3$
$Q_{BLR} = quantity\ of\ blasted\ rock\ in\ earthworks, in\ m^3$
$Q_{SOIL-STAB} = total\ quantity\ of\ soil\ stabilized, in\ m^3$
$Q_{CON-OTH} = quantity\ of\ reinforcing\ concrete\ used, in\ m^3$

Elements crossing the road corridor alternative

$A_{PV,i} = Area\ of\ paved\ section\ in\ road\ crossing\ i, in\ m2$
$Q_{CON-OTH} = quantity\ of\ reinforcing\ concrete\ used\ in\ road\ crossing\ i, in\ m^3$
$Q_{ST-\mathrm{SBR},i} = quantity\ of\ construction\ steel\ used, in\ tons$
$Q_{DIE-TEUD,i} = quantity\ of\ diesel\ used\ in\ earthworks\ in\ road\ crossing\ i, user\ defined, in\ m^3$

Cross-section geometry of the road corridor

$L_i = length\ of\ road\ type\ i, in\ metres$
$L_{TOT} = length\ of\ route\ for\ all\ \ road\ types\ combined, in\ metres$
$L_{OUTS} = length\ of\ route\ serving\ outside\ traffic, in\ metres$
$L_{ARCH,CONS} = arch\ length\ of\ tunnel\ at\ construction, in\ metres$
$L_{ARCH,OPER} = arch\ length\ of\ tunnel\ during\ operation, in\ metres$
$W_{i,j} = width\ of\ road\ type\ i\ for\ road\ element\ j, in\ metres$
$N_n = number\ of\ lanes$
$W_{TOT} = width\ of\ road\ for\ all\ road\ types\ combined, in\ metres$
$H_{SBL,m} = height\ of\ sub\ base\ layer\ by\ material\ m, in\ metres$
$H_{BL,m} = height\ of\ base\ layer\ by\ material\ m, in\ metres$
$H_{PVRS,m} = height\ of\ pavement\ resurfacing\ layer\ by\ material\ m, in\ metres$
$H_{PV,m} = height\ of\ pavement\ layer\ by\ material\ m, in\ metres$
$H_{TOT} = height\ of\ of\ all\ road\ layers\ combined, in\ metres$
$N_{E,i,j}\ = Number\ of\ elements\ (in\ series\ of\ in\ parallel)$
$N_{n,i,j}\ = Number\ of\ lanes$

'ModelValues' parameters

The parameters in this section do not necessarily rely on user input, as the model calculations will work by using predefined default values that are given for all parameters. However, these default values can be replaced by input of *'project-specific values'* whenever the user chooses to do so in order to feed the calculations with input values that are more accurate for a given road project than what default values may provide.

Service life

$SL_R = Superstructure\ road\ components\ service\ life, in\ years$
$SL_{AU} = Superstructure\ aquaducts/underpasses\ components\ service\ life, in\ years$
$SL_{TUWT} = Superstructure\ tunnels\ components\ service\ life, in\ years$
$SL_{BR} = Superstructure\ bridges\ components\ service\ life, in\ years$
$SL_{PV} = Pavement\ resurfacing\ frequency, in\ years$

Transport distance of materials

TD_m	*Transport distance of material m, from outside suppliers, in km*
TD_{EARTH}	*Transport distance internal transportation of masses from earthworks, in km*
TD_{ROT}	*Transport distance of internal rock masses from tunneling, in km*
TD_{SRSS}	*Transport of soil replaced in soil stabilisation, in km*
$TD_{m\text{-}DEP}$	*Transport of material m to depot at End-of-Life*

Fuel consumption from traffic in use stage

DIE_{TRnT}	*Diesel consumption in traffic during use stage, trucks without trailer, in liter/10km*
DIE_{TRwT}	*Diesel consumption in traffic during use stage, trucks with trailer, in liter/10km*
DIE_{LVT}	*Diesel consumption in traffic during use stage, light vehicles, in liter/10km*
GAS_{LVT}	*Gasoline consumption in traffic during use stage, light vehicles, in liter/10km*
$ELEC_{LVT}$	*Electricity consumption in traffic during use stage, light vehicles, in MJ/10km*
$SHL_{T\text{-}TRnT}$	*Share of truck traffic in use stage, trucks without trailers, in % of AADT*
$SHL_{T\text{-}TRwT}$	*Share of truck traffic in use stage, trucks with trailers, in % of AADT*
$SHL_{T\text{-}LVT}$	*Share of light vehicle traffic in use stage, in % of AADT*
$SHL_{T\text{-}DIE\text{-}LVT}$	*Share of light vehicle traffic in use stage, vehicles on diesel fuel, in % of light vehicles*
$ELEC_{T\text{-}BIO}$	*Share of biofuel in diesel/gasoline fuel, in % of total fuel use*
$ELEC_{T\text{-}ELEC}$	*Share of electric cars in light vehicles, in % of light vehicle stock*

Base materials and pavement mixtures

$\mathrm{PV1} = Pavement\ layer, default\ mix$
$\mathrm{PV2} = Pavement\ layer, user\ defined\ mix$
$\mathrm{SB1} = Subbase\ layer, 100\%\ aggregate$
$\mathrm{SB2} = Subbase\ layer, 100\%\ sand$
$\mathrm{SB3} = Subbase\ layer, user\ defined\ mix$
$\mathrm{B0} = Base\ layer, default\ mix$
$\mathrm{B1} = Base\ layer, 100\%\ aggregate$
$\mathrm{B2} = Base\ layer, 100\%\ sand$
$\mathrm{B3} = Base\ layer, user\ defined\ mix$

Tunnel cross section variables

$CSA_{T-CONS} = Tunnel\ cross\ section\ area\ at\ construction, in\ m2$
$CSA_{T-OPER} = Tunnel\ cross\ section\ area\ at\ operation, in\ m2$
$AL_{T-CONS} = Arch\ length\ of\ tunnel\ at\ construction, in\ metres$

AL_{T-OPER} = *Arch length of tunnel during operation, in metres*
$CSA_{DT-CONS}$ = *Dual tunnel cross section area at construction, in m2*
$CSA_{DT-OPER}$ = *Dual tunnel cross section area at operation, in m2*
$AL_{DT-CONS}$ = *Arch length of dual tunnel at construction, in metres*
$AL_{DT-OPER}$ = *Arch length of dual tunnel during operation, in metres*
$CSA_{UWT-CONS}$ = *Underwater tunnel cross section area at construction, in m2*
$CSA_{UWT-OPER}$ = *Underwater tunnel cross section area at operation, in m2*
$AL_{UWT-CONS}$ = *Arch length of underwater tunnel at construction, in metres*
$AL_{UWT-OPER}$ = *Arch length of underwater tunnel during operation, in metres*
$CSA_{UWDT-CONS}$ = *Underwater dual tunnel cross section area at construction, in m2*
$CSA_{UWDT-OPER}$ = *Underwater dual tunnel cross section area at operation, in m2*
$AL_{UWDT-CONS}$ = *Arch length of underwater dual tunnel at construction, in metres*
$AL_{UWDT-OPER}$ = *Arch length of underwater dual tunnel during operation, in metres*

Material and energy types consumed, by unit *(m)*

PV	*Top pavement, layer, in tons*
AGG-B	*Aggregate/Gravel in base layer, in tons*
AGG-SB	*Aggregate/Gravel in sub-base layer, in tons*
AGG-PV	*Aggregate/Gravel in asphalt layer, in tons*
AGG-PVRS	*Aggregate/Gravel in pavement resurfaced layer, in tons*
AM	*Asphalt membrane on bridges, in tons*
AS-MIX	*Asphalt mixing*
SAND-B	*Sand in base layer, in tons*
SAND-SB	*Sand in sub-base layer, in tons*
SAND-PV	*Sand in asphalt layer, in tons*
SAND-PVRS	*Sand in pavement resurfaced layer, in tons*
BIT-B	*Bitumen in base layer, in tons*
BIT-PV	*Bitumen in asphalt layer, in tons*
BIT-PVRS	*Bitumen in pavement resurfaced layer, in tons*
BIT-OTH	*Bitumen in other road crossings, in tons*
CON-B	*Concrete in base layer, in tons*
CON-PV	*Concrete in asphalt layer, in tons*
CON-PVRS	*Concrete in pavement resurfaced layers, in tons*
CON-CB	*Concrete, concrete bridges, in tons*
CON-SB	*Concrete, steel bridges, in tons*
CON-TP	*Concrete, tunnel portals, in tons*
CON-TWE	*Concrete, tunnel wall elements, in tons*
CON-TL	*Concrete, tunnel lining, in tons*
CON-OTH	*Concrete, other, in tons*
CON-GR	*Concrete, guardrails, in tons*
LIME-SS	*Lime used in soil stabilization, in tons*
LIMEP-SS	*Lime, lime-cement pillars in soil stabilization, in tons*
CEM-ISSS	*Cement, used in in-situ soil stabilization, in tons*
CEM-MSSS	*Cement, used in mass stabilizing soil stabilization, in tons*
CEMP-SS	*Cement, Lime-Cement pillars in soil stabilization, in tons*
EXP	*Explosives, in tons*
PEF-TL	*PE-foam, tunnel lining, in tons*
RE-BR	*Rebar, bridges, in tons*
RE-TWE	*Rebar, concrete tunnel wall elements tunnel, in tons*
RE-TP	*Rebar, tunnel portals, in tons*
RE-TL	*Rebar, tunnel lining, in tons*
RE-OTH	*Rebar, other, in tons*
SHO-TL	*Shotcrete, tunnel lining, in m3*

ST-GR	*Steel, guardrails, in tons*
ST-TSB	*Steel, securing bolts tunnel, in tons*
ST-SBR	*Steel, steel bridges, in tons*
DIE-UPTR	*Diesel, uploading blasted tunnel rock, in m3*
DIE-EURO	*Diesel, moving blasted rock (not in tunnels), in m3*
DIE-EUSS	*Diesel, used in simple soil excavation, in m3*
DIE-EURS	*Diesel, used in moving and ripping soil, in m3*
DIE-EUSR	*Diesel, used in soil replacement, in m3*
DIE-TRME	*Diesel, transportation of masses in earthworks, in m3*
DIE-MA	*Diesel, machinery in construction, in m3*
$DIE\text{-}EOL_m$	*Diesel, machinery in end of life stage, by material, in m3*
BIO	*Biofuel, in m3*
EL-LRB	*Electricity, used in lighting roads and bridges, in kWh*
EL-LT	*Electricity, used in lighting tunnels, in kWh*
EL-VT	*Electricity, used in ventilating tunnel, in kWh*
EL-WPUT	*Electricity, used in water pumps of tunnels, in kWh*
EL-LVT	*Electricity, used by electric vehicles, in kWh*

General coefficients

$x_{m,j,i} = consumption\ coefficient\ of\ material\ m\ for\ a\ given\ section\ of\ road\ j\ in\ road\ type\ i, \%$
$E_{m,p,i,j} = energy\ use\ for\ material\ m\ in\ phase\ p\ of\ road\ type\ i\ in\ road\ element\ j, in\ MJ\ per\ year$
$E_m = energy\ requirement\ in\ production\ of\ one\ unit\ o\ material\ m\ , in\ MJ\ per\ unit\ produced$
$E_{TOT,p,i} = total\ annual\ energy\ requirement\ in\ phase\ p\ of\ road\ type\ i, in\ MJ\ per\ year$
$E_{OPER} = average\ annual\ energy\ use\ in\ operation\ phase\ p, in\ kWh\ per\ year$
$GHG_m = greenhouse\ gas\ emissions\ from\ production\ of\ one\ unit\ material\ m\ , in\ kg\ CO2\ equivalents$
$GHG_{TOT,p} = total\ annual\ greenhouse\ gas\ emissions\ by\ phase\ p, in\ kg\ or\ ton\ CO2\ equivalents\ per\ year$
$\rho_m = density\ conversion\ of\ material\ m$

Partition coefficients

$a_{OUTS} = partition\ attributed\ to\ traffic\ from\ outside$
$a_{LVT-DIE} = proportion\ of\ light\ vehicles\ using\ diesel\ fuel$
$a_{LVT-GAS} = proportion\ of\ light\ vehicles\ using\ gasoline$
$a_{LVT-BIO} = proportion\ of\ light\ vehicles\ using\ biofuel$
$a_{LVT-ELEC} = proportion\ of\ light\ vehicles\ which\ are\ electric$
$a_{TRnT-DIE} = proportion\ of\ trucks\ without\ trailers\ using\ diesel$
$a_{TRnT-BIO} = proportion\ of\ trucks\ without\ trailers\ using\ biofuel$
$a_{TRwT-DIE} = proportion\ of\ trucks\ withtrailers\ using\ diesel$
$a_{TRwT-BIO} = proportion\ of\ trucks\ withtrailers\ using\ biofuel$

Appendix 2: Calculation equations

The calculations will follow in this order:

1. *Common equations and calculations* used by all equations (such as adjusting for any traffic from outside along parts of the road corridor, and adjusting for service life of the road infrastructure)
2. *Material and energy requirement calculations* calculated first by order of lifecycle, then by order of road element, then by order of material followed by summation equations
3. *Annual cumulative energy consumption calculations* calculated first by order of lifecycle, then by order of road element, then by order of material followed by summation equations
4. *Annual GHG emissions calculations* calculated first by order of lifecycle, then by order of road element, then by order of material followed by summation equations

Common equations and calculations

If there on any part of an element in the alternative road corridor of our project is some traffic from outside ($AADT_{OUT,i}$), this has to be adjusted for as explained in section 4.1.7. If s, on the given share length ($L_{OUTS,i}$) of the total length (L_i) of the road element *i*, this traffic from outside comes in addition to the traffic within our project ($AADT_t$). Hence, the impact from the road infrastructure on this share length has to be allocated both to the traffic within our project and the traffic from outside. The LICCER model uses a calculation method for this allocation by multiplying each road infrastructure input, such as pavement materials, with a partitioning coefficient ($a_{OUTS,i}$) on a Vehicle Kilometer (VKM) basis, as shown in Equation 1:

$$(1)\ a_{OUTS,i} = \frac{VKM_{OUTS,i}}{VKM_i + VKM_{OUTS,i}} = \frac{L_{OUTS,i} * 0{,}5 * (AADT_{OUTS,t=0} + AADT_{OUTS,t=ATH})}{L_i * 0{,}5 * (AADT_{t=0} + AADT_{t=ATH}) + L_{OUTS,i} * 0{,}5 * (AADT_{OUTS,t=0} + AADT_{OUTS,t=ATH})}$$

Moreover, each road infrastructure input has to be adjusted for the corresponding service life, by multiplying with the inverse service life value, in order to give the input value on a yearly basis.

In general, we can use the notation $M_{m,p,i,j}$ where:

- M refers to the total material required, in specified units
- m refers to the material type
- p refers to the lifecycle stage of the project
- i refers to the road type
- j refers to the road element

This follows so that material requirements of each material can be organized within the model after project specifications have been entered. Each material requirement is organized according to national road construction standards and is embedded in the model as such. Additionally, each material requirement may have different calculating variables depending on how the regulations require the material to be used.

Material and energy requirement calculations

Below are given equations for calculation of the material and energy requirements within a road project.

Aggregate

$$(2)\ M_{AGG-B,p,i,j} = L_i * W_{i,j} * N_n * \left(H_{B,j} * x_{AGG-BL,i,j}\right) * \rho_{AGG} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(3)\ M_{AGG-SB,p,i,j} = L_i * W_{i,j} * N_n * (H_{SB,j} * x_{AGG-SB,i,j}) * \rho_{AGG} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(4)\ M_{AGG-PV,p,i,j} = L_i * W_{i,j} * N_n * (H_{PV,j} * x_{AGG-PV,i,j}) * \rho_{AGG} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(5)\ M_{AGG-PVRS,p,i,j} = L_i * W_{i,j} * N_n * \left(H_{PVRS,j} * x_{AGG-PV,i,j}\right) * \rho_{AGG} * (1 - a_{OUTS}) * \frac{1}{SL_{PV,i}}$$

Sand

$$(6)\ M_{SAND-B,p,i,j} = L_i * W_{i,j} * N_n * (H_{B,j} * x_{SAND-B,i,j}) * \rho_{SAND} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(7)\ M_{SAND-SB,p,i,j} = L_i * W_{i,j} * N_n * (H_{SB,j} * x_{SAND-SB,i,j}) * \rho_{SAND} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(8)\ M_{SAND-PV,p,i,j} = L_i * W_{i,j} * N_n * (H_{PV,j} * x_{SAND-PV,i,j}) * \rho_{SAND} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(9)\ M_{SAND-PVRS,p,i,j} = L_i * W_{i,j} * N_n * \left(H_{PVRS,j} * x_{SAND-PV,i,j}\right) * \rho_{SAND} * (1 - a_{OUTS}) * \frac{1}{SL_{PV,i}}$$

Bitumen

$$(10)\quad M_{BIT-B,p,i,j} = L_i * W_{i,j} * N_n * (H_{B,j} * x_{BIT-B,i,j}) * \rho_{BIT} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(11)\quad M_{BIT-PV,p,i,j} = L_i * W_{i,j} * N_n * (H_{PV,j} * x_{BIT-PV,i,j}) * \rho_{BIT} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(12)\quad M_{BIT-PVRS,p,i,j} = L_i * W_{i,j} * N_n * \left(H_{PVRS,j} * x_{BIT-PV,i,j}\right) * \rho_{BIT} * (1 - a_{OUTS}) * \frac{1}{SL_{PV,i}}$$

Concrete in road pavement

$$(13)\quad M_{CON-B,p,i,j} = L_i * W_{i,j} * N_n * (H_{B,j} * x_{CON-B,i,j}) * \rho_{CON} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(14)\quad M_{CON-PV,p,i,j} = L_i * W_{i,j} * N_n * (H_{PV,j} * x_{CON-PV,i,j}) * \rho_{CON} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(15)\quad M_{CON-PVRS,p,i,j} = L_i * W_{i,j} * N_n * \left(H_{PVRS,j} * x_{CON-PV,i,j}\right) * \rho_{CON} * (1 - a_{OUTS}) * \frac{1}{SL_{PV,i}}$$

Asphalt membrane

$$(16)\quad M_{AM,p,i,j} = L_i * W_{TOT,i,j} * \frac{x_{AM,i,j}}{1000} * \rho_{AM} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

Concrete

$$(17)\quad M_{CONCB,p,i,j} = L_i * W_{TOT,i,j} * x_{CONCB,i,j} * \rho_{CONCB} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(18)\quad M_{CONSB,p,i,j} = L_i * W_{TOT,i,j} * x_{CONSB,i,j} * \rho_{CONSB} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(19)\quad M_{CONTP,p,i,j} = N_{E,i,j} * x_{CONTP,i,j} * \rho_{CONTP,i,j} * AL_{T-CONS} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(20)\quad M_{CONTWE,p,i,j} = N_{E,i,j} * H_{CONTWE,i,j} * W_{CONTWE,i,j} * L_i * x_{CONTWE,i,j} * \rho_{CONTW} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(21)\quad M_{CONTL,p,i,j} = L_i * AL_{T-CONS} * x_{CONTL,i,j} * \rho_{CONTL} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(22)\quad M_{CONOTH,p,i,j} = Q_{CONOTH} * \rho_{CONOTH} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(23)\quad M_{CONGR,p,i,j} = L_i * (SHL_{CG} + SHL_{SG} * 2) * x_{CONGR,i,j} * \rho_{CONGR} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

Soil-stabilization material

$$(24)\quad M_{CEM-ISSS,p,i,j} = Q_{SOIL-STAB} * x_{CEM-ISSS,i,j} * \rho_{CEM-ISSS} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(25)\quad M_{CEM-MSSS,p,i,j} = Q_{SOIL-STAB} * x_{CEM-MSSS,i,j} * \rho_{CEM-MSSS} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(26)\quad M_{CEMP-SS,p,i,j} = Q_{SOIL-STAB} * x_{CEMP-SS,i,j} * \rho_{CEMP-SS} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(27)\quad M_{LIME-SS,p,i,j} = Q_{SOIL-STAB} * x_{LIME-SS,i,j} * \rho_{LIME-SS} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

$$(28)\quad M_{LIMEP-SS,p,i,j} = Q_{SOIL-STAB} * x_{LIMEp-SS,i,j} * \rho_{LIMEP-SS} * (1 - a_{OUTS}) * \frac{1}{SL_i}$$

Explosives

(29) $M_{EXP,p,i,j} = L_i * SHL_{RO,i} * x_{EXP,pi,j} * \rho_{EXP} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

Tunnel lining

(30) $M_{PEF,p,i,j} = L_i * x_{PEF,pi,j} * \rho_{PEF} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(31) $M_{SHO-TL,p,i,j} = L_i * AL_{T-CONS} * x_{SHO-TL,PROD,i.j} * \rho_{SHO-TL,i,j} * \rho_{SHO-TL} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

Rebar

(32) $M_{RE-CB,CBR} = (L_i * W_{TOT,CB} * x_{RE-CB}) * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(33) $M_{RE-SB,SBR} = L_i * W_{TOT,SB} * x_{RE-SB} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(34) $M_{RE-TWE,p,i,j} = M_{CONTW,p,i,j} * x_{RE-CET} * \rho_{RE-CET} * \frac{1}{SL_i}$

(35) $M_{RE-TP,p,i,j} = N_{E,i,j} * 2 * x_{RE-TP,i,j} * \rho_{RE-TP} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(36) $M_{RE-TL,p,i,j} = L_i * AL_{T-CONS} * x_{RE-TL,p,i,j} * \rho_{RE-TL} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(37) $M_{RE-OTH,p,i,j} = Q_{CON-OTH,i} * x_{RE-OTH,p,i,j} * \rho_{RE-OTH} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

Steel

(38) $M_{ST-GR,p,i,j} = L_i * (SHL_{CG,i} + SHL_{SG,i} * 2)/100 * x_{ST-GR,i,j} * \rho_{ST-GR\ i,j} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(39) $M_{ST-CBR,p,i,j} = L_i * W_{TOT} * x_{ST-CBR,i} * \rho_{ST-CBR\ i,j} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(40) $M_{ST-SBR,p,i,j} = L_i * W_{TOT} * x_{ST-SBR,i,j} * \rho_{ST-SBR\ i,j} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

Diesel fuel in infrastructure

(41) $M_{DIE-TEUD,CONS,i,j} = Q_{DIE-TEUD,i} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(42) $M_{DIE-UPTR,CONS,i,j} = Q_{BLR,i} * x_{DIE-UPTR} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(43) $M_{DIE-EURO,CONS,i,j} = Q_{BLR,i} * x_{DIE-EURO} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(44) $M_{DIE-EUSS,CONS,i,j} = Q_{EUSS,i} * x_{DIE-EUSS} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(45) $M_{DIE-EURS,CONS,i,j} = Q_{EURS,i} * x_{DIE-EURS} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(46) $M_{DIE-EUSR,CONS,i,j} = Q_{SOIL-STAB,i} * x_{DIE-EUSR} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(47) $M_{DIE-TRME,CONS,i,j} = Q_{DIE-TRME,i} * x_{DIE-TRME} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(48) $M_{DIE-T_m,i,j} = T_{m,i} * x_{T_m,i,j} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(49) $M_{DIE-EOL-PV,EOL,i,j} = (M_{PV,i} + M_{PVRS,i}) * x_{DIE-EOL-PV} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(50) $M_{DIE-EOL-BSB,EOL,i,j} = (M_{SB,i} + M_{B,i}) * x_{DIE-EOL-BSB} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(51) $M_{DIE-EOL-CON,EOL,i,j} = (M_{CONOTH,i}) * x_{DIE-EOL-CONOTH} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(52) $M_{DIE-EOL-EW,EOL,i,j} = L_{i,j} * W_{i,j} * x_{DIE-EOL-EW} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

Electricity in infrastructure

(53) $Q_{EL-TV,CONS,i,j} = L_i * x_{EL-TV} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(54) $Q_{EL-LRB,OPER,i,j} = L_i * x_{EL-RB} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(55) $Q_{EL-LT,OPER,i,j} = L_i * x_{EL-LT} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(56) $Q_{EL-TV,OPER,i,j} = L_i * x_{EL-VT} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

(57) $Q_{EL-TV,OPER,i,j} = L_i * x_{EL-WPUT} * (1 - a_{OUTS}) * \frac{1}{SL_i}$

Road traffic during Operation stage

(58) $TRAF_{DIE-LVT,TOT} = L_{TOT} * a_{DIE-LVT} * x_{DIE-LVT} * \frac{1}{SL_i}$

(59) $TRAF_{GAS-LVT,TOT} = L_{TOT} * a_{GAS-LVT} * x_{GAS-LVT} * \frac{1}{SL_i}$

(60) $TRAF_{BIO-LVT,TOT} = L_{TOT} * a_{BIO-LVT} * x_{BIO-LVT} * \frac{1}{SL_i}$

(61) $Q_{EL-LVT,OPER,TOT} = L_{TOT} * a_{EL-LVT} * x_{EL-LVT} * \frac{1}{SL_i}$

(62) $TRAF_{DIE-TRnT,TOT} = L_{TOT} * a_{DIE} * x_{DIE-TRnT} * \frac{1}{SL_i}$

(63) $TRAF_{BIO-TRnT,TOT} = L_{TOT} * x_{BIO-TRnT} * \frac{1}{SL_i}$

(64) $TRAF_{DIE-TRwT,TOT} = L_{TOT} * x_{DIE-TRwT} * \frac{1}{SL_i}$

(65) $TRAF_{BIO-TRwT,TOT} = L_{TOT} * x_{BIO-TRwT} * \frac{1}{SL_i}$

Annual cumulative energy consumption calculations

The cumulative energy consumption calculations are for the basic for of production of each material, which is the same base equation regardless of road type. There will be more energy equations coming.

Each lifecycle stage will require separate energy equations but the general rule of thumb is that the energy equations follow this basic format

(66) $E_{M,p,i,j} = M_{M,p,i,j,} * E_m$

Where:

- E refers to the total energy required, in MJ
- M refers to the total material required, in specified units
- m refers to the material type
- p refers to the lifecycle stage of the project
- i refers to the road type
- j refers to the road element
- E_m refers to the energy required per unit to produce the material

Production stage

- All equations for energy use in the production stage follow the format in equation (66)

Construction stage

- All equations for energy use in the construction stage follow the format in equation (66)

Operation stage

The model has emissions equations from energy use on road elements such as lights in a tunnel from electricity consumption and from the production of replacement materials such as asphalt. There is also a section in the model on the energy use of vehicles on the road. This will include the production of the fuels. The following equations are a calculated by calculation total transportation (tkm) of vehicle traffic on the roads and multiplying by the energy consumption of each vehicle class (the average vehicle fuel efficiency). The resulting energy use calculations for road traffic are as follows.

(67) $E_{DIE-LVT,M} = TRAF_{DIE-LVT,TOT} * E_{DIE-LVT}$

(68) $E_{GAS-LVT,OPER} = TRAF_{GAS-LVT,TOT} * E_{GAS-LVT}$

(69) $E_{BIO-LVT,OPER} = TRAF_{BIO-LVT,TOT} * E_{BIO-LVT}$
(70) $E_{EL-LVT,OPER} = Q_{ELEC-LVT,TOT} * E_{ELEC-LVT}$
(71) $E_{DIE-TRnT,OPER} = TRAF_{DIE-TRnT,TOT} * E_{DIE-TRnT}$
(72) $E_{BIO-TRnT,OPER} = TRAF_{BIO-TRnT,TOT} * E_{BIO-TRnT}$
(73) $E_{DIE-TRwT,OPER} = TRAF_{DIE-TRwT,TOT} * E_{DIE-TRwT}$
(74) $E_{BIO-TRwT,OPER} = TRAF_{BIO-TRwT,TOT} * E_{BIO-TRwT}$

For all other energy use calculations in the operation stage follow the formula in equation (66)

Annual GHG emissions calculations

Each lifecycle stage will require separate GHG emissions equations but the general rule of thumb is that the GHG emissions equations follow this basic format for materials

(75) $GHG_{M,p,i,j} = M_{M,p,i,j,} * GHG_m$

Where:

- GHG refers to the total GHGs emitted, in $\mathrm{CO2-eq}$
- M refers to the total material required, in specified units
- m refers to the material type
- p refers to the lifecycle stage of the project
- i refers to the road type
- j refers to the road element
- GHG_m refers to the GHG emissions intensity to produce the material

The GHG emissions for energy use follow the basic format

(76) $GHG_{e,p,i,j} = E_{TOT,p,i,j,} * GHG_e$

Where:

- GHG refers to the total GHGs emitted, in $\mathrm{CO2-eq}$
- E_{TOT} refers to the total energy required, in MJ
- p refers to the lifecycle stage of the project
- i refers to the road type
- j refers to the road element
- GHG_e refers to the GHG emissions intensity from each unit of energy, by energy type e

The GHG emissions for traffic are calculated in similar ways to the energy use. This will include the production of the fuels. The following equations are a calculated by multiplying total transportation (tkm) of vehicle traffic on the roads by vehicle type and multiplying by the the average vehicle fuel efficiency emission per km

(77) $GHG_{V,p,i} = TRAF_{V,p,i} * GHG_V$

Where:

- $GHG_{V,p,i}$ refers to the total GHGs emitted, in $\mathrm{CO2-eq}$
- $TRAF_V$ refers to total traffic driven by transport type V, in tkm
- p refers to the lifecycle stage of the project
- i refers to the road type
- GHG_V refers to the GHG emissions intensity for each tkm driven, by transport type V