VTI rapport 736A
Published 2011

www.vti.se/publications

Life cycle assessment of roads and pavements

Studies made in Europe

Annelie Carlson

FINDING A BETTER WAY

Publisher:

SE-581 95 Linköping Sweden

Publication:
VTI rapport 736A

Published:	**Project code:**	**Dnr:**
2011	60959	2009/0701-29

Project:
MIRIAM

Author:
Annelie Carlson

Sponsor:
The Swedish Transport Administration

Title:
Life cycle assessment of roads and pavements – Studies made in Europe

Abstract (background, aim, method, result) max 200 words:

This is a report in sub-project 3 (SP3) in MIRIAM. The main aim in MIRIAM is to provide sustainable and environmentally friendly road infrastructure by reducing rolling resistance. In SP3 the importance of rolling resistance regarding energy use is studied as well as if maintenance measures can be viable options to reduce total energy use.

In this publication there is a compilation and short description of a number of scientific studies made in Europe that use the life cycle assessment methodology to study roads and pavements. One conclusion is that the results of these studies are not directly comparable since the underlying prerequisites differ considerably. A common understanding in the studies is that all roads are unique and have their own specific conditions, which means that a flexible method is needed that can be adjusted to suite the road you want to study. Also, it is concluded that the energy used for construction, operation and maintenance of the road infrastructure only amounts to a small part of the energy use due to traffic.

Keywords:
LCA, pavement characteristics, traffic energy use, maintenance, energy use

ISSN:	**Language:**	**No. of pages:**
0347-6030	English	22

Utgivare:	Publikation:		
vti 581 95 Linköping	VTI rapport 736A		
	Utgivningsår: 2011	Projektnummer: 60959	Dnr: 2009/0701-29
	Projektnamn: MIRIAM		
Författare: Annelie Carlson	Uppdragsgivare: Trafikverket		

Titel:
Livscykelanalyser av vägar och vägbeläggningar – studier genomförda i Europa

Referat (bakgrund, syfte, metod, resultat) max 200 ord:

Rapporten om livscykelanalyser av vägar och vägbeläggningar är en rapport i delprojekt 3 (SP3) i projektet MIRIAM. Det övergripande syftet i MIRIAM är att ta fram kunskap som ska ge en mer hållbar och miljövänlig väginfrastruktur genom ett minskat rullmotstånd. I SP3 är syftet att undersöka rullmotståndets betydelse i den totala energianvändningen på grund av vägtrafik och underhållsåtgärder samt vilka möjligheter det finns att via olika åtgärder för underhåll kunna minska den totala energianvändningen.

I denna sammanställning beskrivs en del av de vetenskapliga studier genomförda i Europa, som med livscykelanalysmetoden beskrivit miljöpåverkan, energiåtgång och resursanvändning för vägar och vägbeläggningar. En slutsats av översikten är att resultaten från dessa studier inte är jämförbara eftersom de bakomliggande förutsättningarna och även syftet och fokus skiljer sig markant åt. Det gör att resultaten i studierna inte är jämförbara. Det som är gemensamt är att man ser att vägar är unika objekt och varje vägsträckning har sina specifika förutsättningar. Det innebär att man behöver en metod som kan anpassas till just de förutsättningar som gäller för den sektion av väg som man vill utvärdera. Vidare konstateras att den energi som behövs för konstruktion och underhåll av väginfrastrukturen är endast en liten del av den energianvändning som trafiken medför.

Nyckelord:
LCA, beläggning, livscykelanalys, energianvändning, rullmotstånd, miljö, väg

ISSN:	Språk:	Antal sidor:
0347-6030	Engelska	22

Preface

The survey of life cycle assessment studies of roads and pavements made in Europe is a report in sub-project 3 (SP3) in MIRIAM. MIRIAM is an acronym for "Models for rolling resistance In Road Infrastructure Asset Management systems" and involves twelve partners from Europe and USA. The managing partner is the Danish Road Institute. The overall purpose of MIRIAM is to provide information useful for achieving a sustainable and environmentally friendly road infrastructure. In the project, the focus is on reducing the energy use due to the tyre/road interaction, by selection of pavements with lower rolling resistance – and hence lowering CO_2 emissions and increasing energy efficiency. In SP3 the objective is to investigate the importance of rolling resistance to total energy use as well as if maintenance measures can be viable options to reduce total energy use.

Linköping november 2011

Gunilla Franzén *Annelie Carlson*

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Quality review

Internal peer review was performed on 28 November 2011 by Ulf Hammarström and Robert Karlsson. Annelie Carlson has made alterations to the final manuscript of the report. The research director of the writer, Maud Göthe-Lundgren, VTI, examined and approved the report for publication on 2 December 2011.

Kvalitetsgranskning

Intern peer review har genomförts 2011-11-28 av Ulf Hammarström och Robert Karlsson. Annelie Carlson har genomfört justeringar av slutligt rapportmanus. Författarens närmaste chef Maud Göthe-Lundgren, VTI, har därefter granskat och godkänt publikationen för publicering 2011-12-02.

Table of contents

Life cycle assessment of roads and pavements – studies made in Europe

by Annelie Carlson
VTI (Swedish National Road and Transport Research Institute)
SE-581 95 Linköping Sweden

Summary

The energy use due to transport is considerable, around 30% of the total energy use in Europe. Road transport is responsible for a large part, more than 80%, and since it is mainly fossil fuel that is used, the emission of greenhouse gases is substantial. Added to this is the energy used for building, operating and maintaining the infrastructure such as roads, railways etc. The infrastructure of roads is also an important factor, not only because of the environmental impact and resource use due to building and maintenance but also because of the effect it has on the fuel consumption of the vehicles due to road alignment and rolling resistance.

In this report a number of scientific studies using the life cycle assessment methodology to study roads and pavements are described shortly. The report is limited to European studies that can be considered the most relevant and that have been performed since the mid-1990s.

One conclusion of the compilation is that the results of these studies are not directly comparable since the underlying prerequisites differ. For instance they include different stages in the life cycle and also different aspects of the environmental impacts. Other differences are the design of road construction and the number of years for which the environmental impact is estimated. Another important difference is the focus of the studies. For example, some make comparisons of asphalt and concrete pavements, whereas other compare the alternatives either to deposit the waste materials, for example slag, or to use them in road construction.

A common result is the conclusion that all roads are unique and have their own specific conditions, which means that a flexible method is needed that can be adjusted to suite the road you want to study. Also, the studies that have in some way estimated the energy use due to traffic have concluded that the energy used for construction, operation and maintenance of the infrastructure only amounts to a small part of the energy use for traffic. A conclusion of this is that if the purpose is to make road transports more energy efficient it can be better to accept higher energy use for the infrastructure if it leads to lower fuel use of vehicles, since it can result in lower total energy use.

Livscykelanalyser av vägar och vägbeläggningar – studier genomförda i Europa

av Annelie Carlson
VTI
581 95 Linköping

Sammanfattning

Transporters direkta energianvändning utgör en betydande andel, ca 30 %, av den totala energianvändningen i Europa och det är vägtransporter som står för merparten av denna andel, drygt 80 %. Då vägtransporter främst förbrukar fossila bränslen är också utsläppen av CO_2 betydande. På senare tid har det uppmärksammats att även infrastrukturen behöver relativt mycket energi och råmaterial för konstruktion, drift och underhåll. Dessutom är infrastrukturen för vägar och dess utformning med linjeföring, beläggningars rullmotstånd etc. en viktig faktor i vägtransporters energianvändning eftersom bränsleförbrukning i hög grad påverkas av detta.

I denna sammanställning beskrivs en del av de vetenskapliga studier som med livscykelanalysmetoden beskrivit miljöpåverkan, energiåtgång och resursanvändning från vaggan till graven för vägar och vägbeläggningar. Sammanställningen är avgränsad till de studier som genomförts i Europa sedan mitten av 1990-talet.

En slutsats av översikten är att resultaten från dessa studier inte är jämförbara eftersom de bakomliggande förutsättningarna och även syftet skiljer sig markant åt. Det gäller till exempel vilka steg i livscykeln som är inkluderade, hur vägavsnittet är utformat, studerade miljöeffekter och antalet år som studierna sträcker sig över. En annan viktig skillnad är vilket fokus studien har där vissa gör jämförelser mellan asfalt- och betongbeläggningar medan andra syftar till att göra jämförelser mellan alternativet att deponera restprodukter, som exempelvis slagg, istället för att använda dem i vägkonstruktioner. Det som är gemensamt är att man är överens om att vägar är unika objekt och varje vägsträckning har sina specifika förutsättningar. Det innebär att man behöver en metod som kan anpassas till just de förutsättningar som gäller för den sektion av väg som man vill utvärdera. En annan gemensam nämnare är att man i de studier som inkluderat energianvändning från trafiken konstaterat att den energi som behövs för infrastrukturen är endast en liten del av den energiåtgång som trafiken medför. Det ger som följd att det i syfte att energieffektivisera kan vara värt att acceptera en högre energiförbrukning för att bygga och underhålla vägar om de leder till en lägre bränsleförbrukning hos fordonen eftersom det i det stora hela kan ge en total lägre energiförbrukning.

1 LCA studies of roads and pavements in Europe

The energy use due to transportation is considerable, around 30% of the final energy use in Europe (European Commission, 2010). Roads are responsible for a large part, more than 80%, and since it is mainly fossil fuels that are used, the emission of greenhouse gases (GHG) is substantial. Furthermore, when most of the sectors in the economy have a decreasing or stabilizing trend there is an increasing trend in energy use as well as emissions of GHG within the transport sector (European Commission, 2010). Therefore, transport is a sector where measures need to be taken in order to reduce the energy demand and environmental impact. So far, a lot of attention has been put on developing renewable fuels and more fuel efficient engines. However, it has become evident that other aspects of the road infrastructure, such as construction and maintenance, also use a considerable amount of energy and that there can be large energy savings by choosing road alignment and road surface characteristics that can lower the fuel use of vehicles (ECRPD 2010).

To describe the net environmental performance of a road and its' different phases one can use the life cycle assessment methodology (ISO, 2006a; ISO, 2006b). Some European studies using this approach have been performed since the mid 90ties. In this report some of the more interesting scientific studies performed in Europe will be shortly described. Only papers and reports published in English are included, however there are studies published in other languages that could be of interest[1]. Table 1 lists the studies that are described and the life cycle stages they consider. The end-of-life of a road is not included in the table since a road, once it is constructed, can be considered to not have an end-of-life. Table 2 describes the environmental aspects measured in respective study and in table 3 there is a summary of analysis period, functional unit and width of the studied road section.

[1] Lundström (1998) Influence des chaussées en béton et asphalte sur le milieu, 8th International Symposium on Concrete Road, 13–16 Septembre 1998, Lisbon-Portugal. Theme V: Safety and Environment, pp. 195–202.
Pereira A, Blanc I, Coste JF. (1997) La consommation énergétique globale des infrastructures autoroutières. Contribution à l'analyse de cycle de vie, vol. 210 (4137). Bull. Laboratoires Ponts Chaussées; 1997. pp. 95–104.
Peuportier, B. (2003) Analyse de vie d'un kilomètre de route et comparaison de six variants. Rapport de Centre d'Energétique de l'Ecole de Mines de Paris pour CIM béton. 48p.

Table 1 Stages included in European life cycle assessment studies of roads and pavements.

References	Life cycle stage of roads			
	Construction		Maintenance	Use
	Earth works	Pavement		Traffic
Häkkinen & Mäkele (1996)		X	X	X
Mroueh et al. (2001)	X	X	X	X
Stripple (2001)	X	X	X	X
Chappat & Bilal (2003)		X	X	X
Hoang et al. (2005)		X	X	
Olsson et al. (2006)	X			
Birgisdottir et al. (2007)	X	X		
Huang et al. (2009)		X		
Sayagh et al. (2010)		X	X	
ECRPD (2010)		X	X	

Table 2 Environmental aspects considered in European life cycle assessment studies of roads and pavements.

References	Environmental aspect								
	Process energy	CO_2	NO_x	SO_x	CO	VOC	PM	Other	Impact
Häkkinen & Mäkele (1996)	X	X	X	X	X	X	X	X[1]	X
Mroueh et al. (2001)	X	X	X	X	X	X	X	X[2]	
Stripple (2001)	X	X	X	X					
Chappat & Bilal (2003)	X	X						X[3]	
Hoang et al. (2005)	X	X						X[4]	
Olsson et al. (2006)	X	X	X	X	X	X	X	X[5]	
Birgisdottir et al. (2007)	X	X						X[6]	X
Huang et al. (2009)	X	X	X		X	X		X[7]	
Sayagh et al. (2010)	X	X	X	X		X	X	X[8]	X
ECRPD (2010)	X	X	X	X	X		X	X[9]	

[1] Heavy metals, waste generation, water releases.

[2] Heavy metals, resource demand, leaching into land, land use, noise and dust.

[3] CH_4, N_2O

[4] Natural aggregates and bitumen.

[5] HC, CH_4, N_20, emissions to water, natural aggregates

[6] Leaching to the ground

[7] Aggregates, bitumen, solid waste

[8] NMGOC, CH_4, HCl, HF, COD, metals

[9] HC, CH_4, N_2O

Table 3 Analysis period, functional unit and width of the road for European life cycle assessment studies of roads and pavements.

References	Analysis period	Functional unit	Width
Häkkinen & Mäkele (1996)	50 yr	1 km pavement, motorway	8,5 m
Mroueh et al (2001)	50 yr	1 km motorway	12 m
Stripple (2001)	40 yr	1 km road	13 m
Chappat & Bilal (2003)	30 yr	1 m^2 pavement	1 m
Hoang et al. (2005)	30 yr	1 km pavement, highway	10 m
Olsson et al. (2006)	-	1 km road	-
Birgisdottir et al. (2007)	100 yr	4 400 tonnes ash (1 km road)	17.25 m
Huang et al. (2009)	-	30 000 m^2 asphalt surface	-
Sayagh et al. (2010)	30 yr	1 km pavement	3.5 m
ECRPD (2010)	25 yr	1 km pavement, 4 roads	9.5; 11.5; 25.5; 27.5m

1.1 Häkkinen and Mäkele (1996)

Häkkinen and Mäkele (1996) studied the environmental impact of concrete and asphalt road pavements. The life cycle assessment is based on the expected service life of the road and the environmental burdens due to production, use and disposal of the material. Furthermore the study takes into account the energy use of traffic which is assumed to be 20,000 vehicles per day, not making any difference between heavy and light duty vehicles or that different surface textures have an influence on fuel use. Also noise, requirements of lighting, dust formation, concrete carbonation and traffic disturbances during maintenance is considered while the end-of-life phase is not. The analysis period is 50 years and the functional unit is 1 kilometre of pavement on a motorway in Tampere, Finland. Besides the energy use, 18 more environmental aspects are included such as emissions of CO_2, SO_2, NO_x, CO, particulates and heavy metals.

The main contribution to environmental burden was the cement content for concrete pavements and for asphalt is was the content of bitumen, the manufacturing and the presumed maintenance operations. However, the environmental impact due to pavement materials, paving, maintenance and lighting is relatively low compared to the energy use and environmental impact caused by traffic during the analysis period. Mäkele and Häkkinen calculated that the traffic emission during the analysis period amounted to a magnitude of 2 orders compared to all of the other stages in the life cycle.

A number of different valuation methods for the environmental impacts were used in the study and it was shown that the estimated environmental impact due to asphalt and concrete pavements differed depending on the valuation method used. With some there were no significant differences between the two pavements, some valuation methods showed that concrete had higher environmental burdens, while others showed that asphalt had a higher environmental impact.

1.2 Mroueh et al. (2001)

Mroueh et al. (2001) made a life cycle study of alternative road and earthwork construction, with an aim of creating an inventory analysis program that could be used to calculate and compare the life cycle impacts of the most common road construction and foundation engineering methods. A database was compiled of environmental burdens of the most significant construction materials. Case studies were made of using different industrial by-products, such as coal ash, crushed concrete waste and granulated blast-furnace slag, in road and earth constructions. These were compared to using natural aggregates. The analysis included all significant stages identified by the authors, covering the production and transportation of materials, their placement in and use of the construction. However, the life cycle stages that were considered to have no significant impact when comparing the alternatives were excluded, such as site clearance, lane markings, lights, traffic signs, and regular and seasonal maintenance. Also emissions due to traffic were excluded with the argument that this is only meaningful to include if it is possible to determine the effect on fuel use due to different materials. Though for comparison, traffic emissions were estimated for 7,000 vehicles a day of which 1,000 was heavy duty vehicles.

The results show that by using by-products such as blast-furnace slag and crushed concrete instead of natural aggregates the environmental impacts can be reduced for some categories. Furthermore, the most significant burdens were generated by the production and transportation of materials used in road construction. The energy conversion is responsible for a large part of the atmospheric emissions and the most energy consuming parts of the LCA was production of bitumen and cement and crushing of materials. The energy use and CO_2 emissions of the studied life cycle stages for each road construction alternative were very small in comparison with traffic, 0.1–0.2% for energy and 0.8–1.8% for CO_2.

1.3 Stripple (2001)

Stripple developed and used a method where construction, maintenance and operation of a road are broken down into small process units. This approach results in a dynamic model that makes it possible to vary the process conditions. The study compared the life cycle phases of two asphalt pavements and one concrete pavement. Included in the inventory analysis were the entire roadway and also the effects of road markings, signs, vegetation etc. The main energy consuming life cycle stage is, according to Stripple (2001), the operation of the road where electricity use due to street lighting and traffic lights are the major energy consumer. However, since most of the electricity is produced with nuclear and hydro power in Sweden this life cycle stage does not have a significant share of the emissions. Regarding emissions of CO_2, NO_x and SO_2, it is the construction of the road that is the major contributor.

In the study the energy use of a traffic volume of 5,000 vehicles per day was estimated in order to relate the energy use of the other life cycle stages of the road. The comparison showed that the calculated energy use of construction, operation and maintenance was between 9.9–11.8% of the estimated traffic energy.

1.4 Chapat and Bilal (2003)

The LCA study performed by Chapat and Bilal (2003) described the contribution made by 20 different road construction techniques regarding pavement, on energy use and greenhouse gas emission. Different traffic classes describing the number of light and heavy duty vehicles per day was assumed and analysed in regards to the effect on energy use. A heavier traffic load requires a better bearing capacity and there will also be an increased need for maintenance operations. The traffic intensity will also have an effect on the GHG emissions, where there will be more emissions with a heavier traffic load.

It is shown that there is a benefit of using bitumen emulsion and high modulus mixes due to that these techniques makes it possible to manage and optimise energy use and also to reduce greenhouse gases. Another result is that recycling material may save both natural aggregates and transport. The pavement leading to the highest energy use and emission of GHG was continuous reinforced cement concrete pavement followed by undowelled cement concrete pavement. Two types of pavements with special hydraulic binder and cold mix asphalt pavement were the tree alternatives leading to the lowest energy use and GHG emissions.

In the study, the direct traffic energy was estimated for the different classes. One main result is that the energy use and GHG emissions of traffic by far exceeds the energy needed for pavement construction and maintenance, between 10 and 345 times over a 30 year period depending on whether it is light or heavy traffic.

1.5 Hoang et al. (2005a)

Hoang et al. (2005) made case studies of two different highway sections in France, one with asphalt concrete (AC) and the other with reinforced concrete (CRC). In the paper, only energy use, emissions of CO_2 and use of natural aggregates and bitumen is presented. However, it is possible to calculate the use of other material and also emissions of several other substances (Hoang, 2005b). The result of the comparison shows that during a 30 year period the CRC alternative uses more energy than AC, about 40% more. CRC also leads to more emissions of CO_2, almost 3 times more, than AC. The energy use for construction and maintenance work was estimated to 7,780 GJ for CRC and 5,500 GJ for AC. The CO_2 emissions for the two alternatives were estimated to 1,050 tonnes for CRC and 310 tonnes for AC. The differences are mainly due to the construction phase, whereas the contribution from the maintenance phase is approximately the same regardless of pavement. The two main contributors to both energy use and CO_2 emissions for CRC are the production of cement and steel work and for AC they are hot mix production and materials transportation.

1.6 Olsson et al. (2006)

In Olsson et al. (2006) an environmental systems analysis (ESA) was made on using bottom ash from incineration of municipal solid waste (MSW) for road construction as material in the sub-base layer. ESA is a method to describe environmental impact from a holistic point of view and it is built on the framework of life cycle assessment. Two cases were studied in the analysis, one where only natural aggregates were used and one where bottom ash was used in the sub base of the road. The life-cycle stages for the base course and sub-base layers regarding production and transportation of materials, their location in the road structure and the use of the road was included. The parts of the system that were similar between the two cases were excluded and thus only the differences in environmental impact are described. The conclusion was that the use of reused or recycled material leads to less energy use and energy-derived emissions. However, in the example with MSW bottom ash the leaching of certain metals from the road was found to be larger. According to Olsson et al. (2006) the major energy use is due to production of materials and the disposal stage, while the metals leach during the use stage of a roads life cycle.

1.7 Birgisdottir et al. (2007)

In Birgisdottir et al. (2007) two different disposal methods for bottom ash from incineration of municipal solid waste were compared, one were the ash was placed in landfill and one where it was used as sub base layer in a road. The article is focussed on leakage to the soil and hence the results that are presented are mainly about this topic. But the analysis also included use of resources and energy concerning upgrading bottom ash, transport, landfilling processes, using bottom ash in road construction and replacement of natural gravel as road construction material. The environmental impacts of emissions to air, water and soil were divided into twelve categories, for example global warming, acidification, ecotoxicity etc. In the paper the results for the environmental impacts of the different categories were presented. According to the study there were no significant differences in environmental impacts for most of the impact categories between the two alternatives of disposal methods for bottom ash. However, for human toxicity in soil and environmental toxicity in water the alternative using bottom ash in road construction has a higher impact compared to the landfill alternative.

1.8 Huang et al. (2009)

Huang et al. (2009) made a case study of an asphalt paving project at London Heathrow Terminal-5. In the case study natural aggregates were replaced with waste glass, incinerator bottom ash and recycled asphalt pavements. The results of the life cycle for these alternatives were then compared to a case where only virgin material was used to produce a pavement of the same size and function. According to the results the production of hot mix asphalt and bitumen was the most energy intensive processes and was also responsible for most of the emissions. The main aim, however, was to test and calibrate an LCA model that was developed for data and conditions specific for the UK.

1.9 Sayagh et al. (2010)

Sayagh et al. (2010) described the problems involved when performing an environmental assessment of various pavement structures. In the analysis they used a tool developed by LCPC called ERM (elementary road modulus), which applies the life cycle assessment methodology to road structures. According to the authors ERM makes it possible to compare various construction techniques and materials. In this study they assessed three different pavement structures; two with classical material, bituminous and concrete, and one where blast furnace slag (BFS) was used. Stages included in the ERM are construction and structural maintenance of pavements. The energy use was lowest for asphalt pavement, where bitumen refining and asphalt concrete mixing are the main contributors. Two assumptions regarding allocation procedures of steel plant contribution were estimated for the alternatives cement and BFS pavement, one where BFS is considered as waste from steel production and one where it is considered as a by-product. For reinforced concrete the steel and cement plant were the main contributors to energy use and in the case with BFS it was the bitumen refining and steel production. The different allocation procedures just had a minor effect on the energy use for concrete pavement. For BFS it had a substantial effect where the ‘by-product’-allocation resulted in an energy use more than twice as high compared with the ‘waste’-allocation. Regarding the environmental impacts it is concrete pavement that has the highest impacts in the categories global warming, acidification and eutrophication. BFS and the ‘by-product’-allocation had the highest impact in photochemical and ecotoxicity, whereas asphalt pavement had the highest toxic potential.

1.10 ECRPD (2010)

ECRPD is an EU project that was finalised in 2010 (ECRPD, 2010). The overall aim was to evaluate energy conservation in pavement manufacture and placement, i.e. low energy pavement materials and pavement maintenance on existing roads. In particular one looked at energy saving in road maintenance in order to save fuel use by vehicles. Within this project an LCA study was performed in 6 countries and for four different road sections; motorway, dual carriage way, wide single carriage way and single carriage way (ECRPD, 2009). Only the life cycle stages of road surfacing during construction and maintenance were included, whereas initial phases of road construction, like land preparation and foundation construction, were excluded. The starting point is extraction of raw material and the end is the rolling of the asphalt. Thereby end-of-life is not included. The LCA focuses on the energy use and emissions in extraction and processing of raw materials, production and handling of asphalt mixtures and their components. The main aim of the LCA-study was to compare the environmental impacts of asphalt road construction and maintenance during its life cycle. Another aim was to determine where and in which process the major environmental damage occurs.

Traffic is assumed to be 20,500 vehicles (41% heavy) per day on motorway, 18,500 (30% heavy) on dual carriageway, 15,500 (25% heavy) on wide single carriage way and 7,500 (12% heavy) on a single carriage way. However, the energy use due to traffic is not calculated.

The result shows that it is the production of asphalt mixtures and their components that are the most energy consuming stage, around 90% of all energy needed. For the emissions the result is the same where almost all is due to production. The exception is emissions of N_2O where operation is the main source.

1.11 Re-ROAD (2011)

Re-ROAD is an EU-project with the aim of developing knowledge and innovative technologies for enhanced end-of-life strategies for asphalt road infrastructure, mainly by evaluating strategies for recycling of asphalt. In the project they will use the LCA methodology in order to analyse the environmental impacts of different material strategies for recycled asphalt. The life cycle will include installation, maintenance, use and deconstruction of asphalt and the reference flow is one tonne of asphalt. The goal is to improve energy efficiency and reduce the environmental impact of the European transport system. One part of this project is to evaluate environmental criteria, such as assessment of risks and benefits to the environment with the use of recycled asphalt. Special attention will be to assess potentially harmful substances. The study will make use of comparative analysis, exploring different strategies for utilisation of recycled asphalt and to reach the required level of accuracy it will be necessary to generate some specific life cycle inventory data for recycled asphalt. The report on the LCA study will be made public at the project web site.

2 Example of LCA of interest for roads and pavements

Some life cycle studies have been concentrated to a well-defined part of a road. Such partial analysis can be useful for evaluating possible improvements in environmental behaviour and for developing more complete life cycles for specific products like, bridges, pavements etc. For example Josa et al. (2004) did a comparative analysis of different cement produced in Europe and Marinkovic et al. (2010) made a comparative environmental assessment of natural and recycled aggregate concrete. Vares and Häkkinen (2010) have developed a life cycle assessment tool of cement called LCA-CEMENT and is based on Excel and Visual Basic. The tool is meant to be used by manufacturers and as a help to consider environmental aspects in production development. The life cycle ends at the cement factory gate since it is considered to be part of another products life cycle.

In 2011 the organisation Eurobitume published an updated version of a life cycle inventory of production of bitumen (Eurobitume 2011). The study covers extraction of crude oil, transport (ship and pipeline), different manufacturing processes of bitumen and hot storage. The construction of production facilities was also studied. The process where the most energy was used and where the most emissions of CO_2 occurred was the crude oil extraction, almost 60% for both energy and CO_2. Crude oil extraction also leads to the highest emissions of CO, CH_4, NMVOC and particulates of the studied life cycle stages. Concerning emissions to waste and soil it was transport and refinery that were the most significant contributors.

Jullien et al. (2006) made an experimental study of road building and recycling of used pavement within the framework of LCA. They studied four equivalent asphalt concretes with different recycling rates where they determined and compared airborne emissions, pollutant release over time and odour related to asphalt laying between the various recycling rates; 0% (all new material), 10%, 20% and 30% recycled asphalt pavement. They made in situ measurements of airborne emissions using a gas-flux sensor and used a 600 meter road divided into four sections, each featuring different recycling rate and the functional unit was m^2 of asphalt. The study concerns part of one of the subsystems of a road, i.e. new pavement construction and asphalt laying and only VOC, PAH and odours were measured. The result showed that some gas emissions increase with the recycling rate while odours decrease.

Eriksson et al. (1996) performed an LCA of the use of the road regarding transport activities and products used for road transportation, i.e. fuel combustion, production of fuel, production and end-of-life for vehicles, and production, use and end-of-life for tyres. The purpose of the project was to develop the LCA for transportation which could be used as input to LCA of goods like newspaper. A result of the analysis was that production, maintenance and after use treatment of vehicles contributes substantially to the total environmental impact of transportation measured per vehicle kilometres.

2.1 Databases and LCA tools

At the European Commission site for the Joint Research Center (JRC) there is a home-page dedicated to LCA. At this site there is a list of a several LCA tools and data bases with links to further information[2]. Some of them are free to download. Free access is

[2] http://lca.jrc.ec.europa.eu/lcainfohub/toolList.vm and http://lca.jrc.ec.europa.eu/lcainfohub/databaseList.vm, accessed 2011-05-26

also the case with the open source LCA database called SPINE@CPM database, where the data is transparent and quality reviewed[3].

No evaluation has been made on which one of these tools and databases that is suitable to use for LCA-studies of roads and pavements.

During recent years some tools have been developed specifically aimed at roads and/or pavements. Based on the result of their study, Mroueh et al. (2001) developed an Excel-based life cycle inventory analysis program for road construction. It covers the work stages from material production to road maintenance and the materials that are most commonly used in road construction. Though, at the time of the publishing of the article, the program was limited to calculating and comparing environmental loads from construction only. Another limitation is the estimation of environmental loading which includes those environmental factors that was considered the most important.

Stripple (2001) constructed a model, called Road Model, consisting of different processes that can be chosen and put together to give a more representative description of the studied road section. The model is developed using Excel and is built up by a number of work sheets for input and output data. The Road model includes construction, operation and maintenance and the inventory analysis includes resource use, energy parameters and the basic emissions CO_2, NO_x and SO_2. Also, the inherent energy in the asphalt layer, i.e. feedstock energy, is estimated. Other effects that can be considered of importance such as noise and severance effects are not included in the current design of the model. However, the Road model can be complemented with additional parameters as required.

The ROAD-RES model used by Birgisdottir (2007) is a life cycle assessment tool especially developed for road construction and disposal of residues from waste incineration. It is a software programme based on C++ and the Paradox database (Birgisdottir, 2005). The model calculates an inventory of environmental exchanges in the life cycle of a road and/or landfill and it also performs a life cycle impact assessment where the environmental exchanges are converted into contributions to impact categories and consumption of resources. For the road system it covers the stages of design, construction (earthworks, pavements, additional work), operation (maintenance, winter service, leaching) and demolition (removal of materials, area rehabilitation). For all the stages upstream activities are included such as extraction and upgrading of resources. In addition to the road system the alternative of landfilling of residues from waste incineration is included as a possible life cycle stage. The model can be used to evaluate the environmental impacts and resource consumption in life cycle stages of road construction and to evaluate and compare landfilling of incineration waste with using it in road construction. The default life cycle impact assessment method is EDIP97 which covers most of the emission-related impacts, resource use and working environment impacts.

The ERM/GRM[4] model used by Hoang et al. (2005) aims at calculating the consumption of raw materials, energy use and emissions of pollutant from the processes of initial construction of the road, exploitation and maintenance. The ERM is the inventory of environmental loads and GRM is the evaluation of environmental impacts. The different stages include manufacturing of raw material and transportation to the construction site. Also road works equipment used during pavement construction and maintenance is included. However the extraction of raw material and the end-of-life stage is not within

[3] www.cpm.chalmers.se, accessed 2011-05-26
[4] Elementary Road Modulus/Global Road Modulus

the system boundaries. The ERM is modular and can be composed for different kinds of road pavement layers or earthworks, and with various materials, and it can be adapted to several different case studies.

Huang et al. (2009) developed an LCA model based on spread sheet in Excel for estimating and presenting results of the inventory. It consists of 5 spreadsheets of which two represents parameters for processes and pavement that are specific for a project. The other three are: ‘unit inventory’ with calculating formulas and the life cycle inventory of unit processes; ‘project inventory’ where the inventory results are presented; and the ‘characterisation results’ where the characterisation models and factors can be found. The data in these spreadsheets are linked by calculation formulas.

In ECRPD and within the work package concerning LCA a spreadsheet model was produced that calculate energy use, resource use and the emissions for each work item that is required for manufacture and placement of current and new pavement materials (ECRPD, 2009). The model is developed in Excel and it is transparent, where the input data can easily be changed. The input to the spreadsheet model was made in consultation within the consortium regarding materials types and mixes, density of materials, construction plant, transport of material, placement practice, etc.

A recent developed tool for calculating carbon footprint of asphalt is asPECT, which is a collaborative research with the Highways Agency, Mineral Products Association, Refined Bitumen Association and TRL Limited in Great Britain. This model provides a methodology to calculate the life cycle GHG emissions of asphalt used in highways. Initially GHG emissions measurement was prioritised as the key sustainability issue. Therefore, the focus of the project was to develop a standardised method to measure the contribution to climate change of highway products and applications. The asPECT method facilitates measurement of the ‘whole life’ contribution of highway products to climate change and the life cycle steps included are raw material acquisition, transport and processing, transport of processed material, road component production, material transport to site, installation and scheme specific works. Maintenance and end of life are not included.

International Road Federation in Geneva has developed a GHG calculator called CHANGER (Calculator for Harmonised Assessment and Normalisation of Greenhouse gas Emissions for Roads) which is specifically tailored to road construction and rehabilitation projects[5]. It estimates the total amount of greenhouse gas emissions released in the course of a road construction project. It uses an input-output modelling approach where the calculation model is based on a set of equations that enable assessment of overall emissions that is generated by each identified and quantified source. It contains the modules pre-construction and pavement and a module for maintenance is under development. LAVOC[6] has analysed and validated the quality and reliability of the databases and the calculation procedures.

[5] http://www.irfghg.org

[6] Traffic Facilities Laboratory of the Swiss Federal Institute of Technology, EPFL (Ecole Polytechnique Fédérale de Lausanne)

3 Discussion

A common understanding in the studies presented in this compilation is that each road section is unique due to various reasons, like geotechnical conditions, traffic intensity etc. (Stripple, 2001; Mroueh et al., 2001; Hoang et al., 2005). In addition, according to Josa et al. (2004), the availability of reliable data is scarce. This makes it problematic to perform a representative life cycle inventory and hence also a life cycle assessment for a road. The uniqueness of roads means that calculations need to be done for each individual construction if one wants a representative result. It is difficult to use a static life cycle model and according to Stripple (2001) it is more appropriate to have a model based on processes in order to better describe the studied road section.

During recent years several studies using a life cycle assessment approach has been performed and a number of models have been developed which sometimes are using established databases of emissions, sometimes have gathered this information from manufacturers and contractors. But, as Huang et al. (2009) described, there are several reasons why these models are more or less suitable to use. The problems can be relevance, age and underlying assumptions of the data in the model. They can be limited to just some parts of a roads life cycle or of certain emissions, such as energy use, atmospheric emissions or leakage to the ground and they may not be accessible to use due to commercial restrictions.

A conclusion of this report is that it is impossible to perform straightforward comparisons of the results due to the differences in approach, functional units, analysis periods, system boundaries, regional differences, difference in input data etc. This is in accordance with a critical review made by Santero et al. (2010) of a number of LCA studies. In the review several of the studies presented in this compilation are included. Some differences are for example that the aim in Birgisdottirs et al. (2007) is to compare two different methods for disposal of bottom ash and the study include several environmental parameters, whereas Stripple (2001) makes a comparison between two asphalt pavements and a concrete pavement and limit the study to energy, CO_2, NO_x and SO_x. Also, the analysis period and functional unit in Birgisdottir et al. (2007) is 100 years and 4,400 tonnes of ash, equivalent to 1 km road with a width of 17.25 m. In Sayagh et al. (2010) the analysis period is 30 years and the functional unit is 1 km pavement that is 3.5 m wide. Regarding the input data there are also differences, where some have used different databases regarding the information needed (ECRPD used the Bousted and Gemis database) and some have gathered information from manufacturers and from other studies Huang (2009).

There is also a difference regarding the extent of the studies. Some of them make an inventory where resource use and emissions are calculated and presented, for example Stripple (2001) and ECRPD (2009). Others, such as Häkkinen and Mäkele (1996) and Birgisdottir et al. (2007) continue with the analysis and also present the resulting environmental impacts of the emissions and resource use. This difference can be of minor importance in the case where the main interest is the results derived in the inventory stage. However, if one is interested in the environmental impact it is of importance to know evaluation method used, since different valuation methods will have an effect on the result (Häkkinen, Mäkele, 1996).

Some of the presented studies have mentioned the importance of traffic energy and it has been calculated as a mean for comparison of the relative importance of other life cycle stages of a road (Häkkinen and Mäkele, 1998; Mroueh, 2001; Stripple, 2001; , 2009a). All of these studies have shown that the fuel use of traffic is the foremost contributor to energy use. Thus, a small change in the infrastructure, such as surface conditions that lower the fuel use, can have a large positive impact on an overall reduced energy use. However, none of the LCA studies has included the effect on traffic energy due to the surface characteristics, where increased rolling resistance due to road deterioration can be a significant reason for increased fuel consumption (ECRPD, 2010). Therefore, it is of importance to include and the interaction between the characteristics of the road and the fuel use of traffic when performing a LCA study. A further suggestion made by Santero et al. (2010) is that in order to have a "complete" picture of the LCA it is important to broaden the approach where more aspects are included, such as the effect of traffic delays. In the review they also conclude that there is a need for standardising functional units, improving data quality and reliability in order to quantify environmental impacts effects comprehensively and to be working as a guide for sustainability efforts.

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