EMISSIONS OF BARGE TRANSPORT IN FLANDERS: A LIFE-CYCLE ASSESSMENT APPROACH

Tom van Lier, Vrije Universiteit Brussel, tom.van.lier@vub.ac.be

Cathy Macharis, Vrije Universiteit Brussel, cathy.macharis@vub.ac.be

ABSTRACT

European transport policy as advocated by the European Commission aims to increase the sustainability of the overall transport system, proposing an internalisation of external costs in order to achieve more socially optimal transport decisions by stakeholders. By internalizing the negative externalities, the Commission intends to initiate a shift from less to more sustainable transport services. However, with regards to the environmental component of the external costs of transport modes, the focus is primarily directed towards vehicle travel related emissions, while emissions related to well-to-tank operations, vehicle fleet and transport infrastructure receive less or no consideration.

In order to assess the environmental sustainability of transport services, a life-cycle assessment (LCA) based framework is recommended. This allows to map the environmental emissions for the different transport components in much greater detail and enables to determine their relative importance.

This paper analyses in detail the environmental emissions (both air polluting and greenhouse gas emissions), for one particular transport mode, namely barge traffic, for one particular geographical region, namely Flanders (in Belgium), applying such a LCA approach. The analysis focuses on CO_2, CO, NO_x, SO_2, NH_3, N_2O, CH_4, VOC, NMVOC, TSP and PM, and divides emissions in three distinct categories: emissions directly related to vehicle operation (both "tank-to-wheel" and "well-to-tank" emissions), emissions related to the barge fleet (building and maintenance of barges) and emissions related to the transport infrastructure (construction, operation and maintenance of waterway infrastructure). The relative share of the different components in the total emissions is compared in order to assess their importance.

Keywords: barge transport, emissions, life-cycle assessment

1. INTRODUCTION

Next to large economic and social benefits, transport services also cause significant, mostly negative, external costs, defined by Bickel and Friedrich (2005) as:

> "*An external cost arises, when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group.*"

A rather impressive list of external costs is associated with transport activities, caused by transport related emissions (climate change effects and air pollution), accidents, noise, soil contamination, interference in the ecological system, damage to infrastructure, visual nuisance, congestion and effects during so-called up and downstream processes, such as extracting, refining and transporting fuels used in transport modes (pre-combustion processes), as well as externalities associated with construction, maintenance and scraping of transport vehicles and infrastructure (Maibach et al., 2008). The existence of these external costs causes transport market prices to not fully reflect the societal cost of transport services, resulting in transport activity levels that are generally above the social optimum.

This failure of the market mechanism to achieve the social optimum can provide a rationale for government intervention (Schmidtchen et al., 2009). European transport policy as advocated by the European Commission proposes an internalisation of external costs in order to achieve more socially optimal transport decisions by stakeholders. By internalizing the negative externalities, the Commission intends to initiate a shift from less to more sustainable transport services (European Commission, 2011).

In this paper, focus will be on one particular type of transport externalities namely transport related air emissions. These emissions can be divided in two broad categories. On the one hand the emission of air pollutants such as particulates (particulate matter $PM_{2,5}$ and PM_{10}), nitrogen oxide (NO_x), sulphur dioxide (SO_2), heavy metals and volatile organic compounds (VOCs). Air pollution related external costs include impacts on human health, impacts on materials and buildings, damages to agricultural crops and costs for further damage to ecosystems (biosphere, soil, water, forests). Health costs (mainly caused by particulates, emission of exhaust gases or transformation of other pollutants) are by far the most important air pollution external cost category (Maibach et al, 2008). On the other hand there are the emissions of greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrogen oxide (N_2O) and methane (CH_4). Social costs of climate change are described in literature as rising sea levels, modified energy use (changes in the need of heating), agricultural impact, need of drinking water, health impact, ecosystems and biodiversity, external winter situations and an increase of so-called "major events" (such as a change in the Gulf current, the collapse of the Amazon forest, methane explosions, alteration of the monsoon season, etc.). The estimation of climate change costs is characterized by a high complexity rate when predicting long term effects on a global scale and risk patterns which are hard to anticipate (Maibach et al, 2008).

With regards to the environmental emissions of transport modes, scientific literature and policy makers are still largely focussing on vehicle travel related emissions. However, in order to effectively mitigate environmental impacts from transportation modes, life-cycle environmental performance should be considered including both the direct and indirect processes and services required to operate the vehicle, taking into account raw materials extraction, manufacturing, construction, operation, maintenance, and end of life of vehicles, infrastructure, and fuels (Chester and Horvath, 2009).

In order to assess the full environmental sustainability of a transport service with regards to emissions, a life-cycle assessment (LCA) based methodology is recommended (Spielmann et al, 2007; Chester and Horvath, 2009; Pettersen, 2011). This allows to map the environmental air emissions for the different transport service components in much greater detail and to determine their relative importance.

The structure of the paper comprises two main parts. First, as a starting point, a literature study is performed to identify the current academic knowledge on transport related LCA's. Based on the literature study, a LCA-based framework is proposed to map transport related emissions. Secondly, the proposed methodology is applied to barge transport in Flanders, in order to derive specific emission factors for the different GHG and air pollutants, differentiated by barge type and per waterway class, and this for the different transport service components (vehicle operation, vehicle fleet and transport infrastructure). This allows determining the relative importance of the different components in a variety of cases (for different pollutants, for different barge types, for different waterway classes). In this way, the environmental impact of barge transport related emissions is assessed in much greater detail. To finish, conclusions and further research goals are formulated.

2. TRANSPORT RELATED LIFE-CYCLE ASSESSMENTS

This section consists of three parts. First, the background and theoretical concept of life-cycle assessment is shortly described. Secondly, scientific literature with regards to transport related life-cycle assessments is summarized. Thirdly, the findings from literature that are relevant for applying a LCA-based framework to map emissions of transport services are identified and a framework to map the emissions of a transport service is discussed.

2.1. Life-cycle assessment: background and theoretical concept

Frischknecht (1998) defines Life Cycle Assessment (LCA) as a method for the analysis and assessment of potential environmental impacts along the life cycle of a good or a service. An LCA is, according to Frischknecht (1998)

> *[...] applicable on products, processes or firms, to document their environmental performance, to identify potentials for environmental improvements, to compare alternative options as well as to substantiate ecolabelling criteria.*

LCA takes into account a product's full life cycle from the extraction of resources, through production, use and recycling, up to the disposal of remaining waste. Essentially, LCA studies help to avoid an unwanted shifting of burdens by reducing the environmental impact at one point in the life cycle, only to increase it in another (Institute for Environment and Sustainability, 2010). Life Cycle Assessment is therefore considered to be a vital and powerful decision support tool, complementing other methods, which are equally necessary

to help effectively and efficiently make consumption and production more sustainable (Institute for Environment and Sustainability, 2010).
In order to create a methodological framework for the practical application of LCA's and to ensure that all requirements of the methodologies are met, the International Standardization Organization (ISO) has published two standards, namely, the ISO 14040 (European Committee for Standardization, 2006a) and the ISO 14044 (European Committee for Standardization, 2006b).
According to ISO standards, an LCA study consists of four phases: goal and scope definition phase, inventory analysis phase, impact assessment phase and interpretation phase (European Committee for Standardization, 2006a). A clear initial goal definition is essential for a correct later interpretation of the results. During the scope definition phase the object of the LCA study is identified and defined in detail. The main part of this phase is to derive the requirements on methodology, quality, reporting and review in accordance with the goal of the study (Institute for Environment and Sustainability, 2010). During the life cycle inventory (LCI) phase the actual data collection and modelling of the system is carried out, in line with the goal definition and requirements set in the scope phase. Life Cycle Impact Assessment (LCIA) is the phase where inputs and outputs of elementary flows that were collected and reported in the LCI phase are translated into impact indicator results related to human health, natural environment, and resource depletion. In the interpretation phase, results of the LCIA are appraised in order to answer questions posed in the goal definition and to develop recommendations (Institute for Environment and Sustainability, 2010).

2.2. Transport related LCA's: literature review

With regard to transport services, an LCA takes into account not only emissions directly associated with the vehicle operation, but also emissions related with all the other aspects required to facilitate the transport service, making it a valuable approach to analyse exactly how transport modes perform environmentally. Therefore, LCA methodology has already been applied in a variety of cases in the field of transport. Below, scientific literature related to LCA's will be discussed for, first, passenger transport, and, secondly, freight transport.

Passenger transport

Chester and Horvath (2009) state that several studies and models analyse a single mode (mostly automobiles, less for buses, rail and air), particular externalities, or specific phases, but a complete LCA of multiple passenger transport modes was lacking in the US. Therefore, Chester and Horvath (2009) presented results of a comprehensive life-cycle energy, GHG emissions, and air pollutant emissions inventory for automobiles, buses, trains, and airplanes in the US, including vehicles, infrastructure, fuel production, and supply chains. Using a methodology of hybrid LCA in combination with an Input/Output-analysis, total life-cycle energy inputs and GHG emissions were found to contribute an additional 63% for road, 155% for rail, and 31% for air systems over vehicle tailpipe operation. For air pollutants, vehicle non-operational components were found to often dominate total emissions, with life-cycle air pollutant emissions between 1.1 and 800 times larger than vehicle operation. The relative performance of modes was found to be highly sensitive to ranges of passenger occupancy.

In 2010, Chester and Horvath added an LCA for high-speed rail in California, again stressing the importance of the assumed level of ridership when comparing modes (Chester and Horvath, 2010). Also other papers have focused on high-speed rail LCA. Rozycki, Koeser and Schwarz (2003) developed an ecology profile for the German high-speed rail passenger transport system. Tuchschmid (2009) developed a methodology to account for the infrastructure of European high-speed passenger traffic (e.g. TGV-lines in France or AVE-network in Spain) in carbon footprint calculation, taking into account the components of operation, rolling stock and track system. Rail infrastructure was assessed in more than 40 modules with a strong focus on the rail track system: tunnel, viaducts, bridges, the track itself with ballast, energy & signalization equipment, etc. Applying the methodology showed that the infrastructure share in the carbon footprint of high-speed rail is not negligible, ranging for different situations of the average European network between 31% and 85%, depending on the electricity mix, the traffic on the rail network and the share of bridges & tunnels (Tuchschmid, 2009). Pettersen et al. (2011) performed life cycle management projects with regards to infrastructure development and operation of high-speed rail in Norway. Their results also confirm the importance of infrastructure, in most cases representing half or more of total GHG emissions. In addition, Pettersen et al. state that the importance of infrastructure is very different for rail compared to alternative transport systems, such as private car or air transport, both for greenhouse gas emissions and life-cycle energy use.

In the ‘Clean Vehicle Research: LCA and policy measures’ (CLEVER) project, an extensive LCA was performed of the complete Belgian passenger car fleet. The environmental impacts of vehicles with conventional and alternative fuels and drive trains were analysed in a Belgian context. All stages of the life cycle of a vehicle were included in the analyses: raw material extraction, transport, distribution, manufacturing of components, assembly, vehicle use (Well-to-Wheel basis), maintenance and end-of-life treatment. The ecoinvent database (discussed in detail below) has been used to calculate LCI data for materials, manufacturing processes, energy production, fuel production and distribution involved in the life cycles of both conventional and alternative vehicles. (Van Mierlo, J. et al., 2011).

Hawkins et al. (2012) developed a life cycle inventory of conventional and electric vehicles in order to assess environmental sustainability over a range of impact categories. The results are mixed, with electric vehicles powered by present European electricity mix offering a 10% to 24% decrease in global warming potential relative to conventional diesel or gasoline vehicles, but showing the potential for significant increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion impacts, largely originating from the vehicle supply chain. Results were demonstrated to be sensitive to a number of assumptions such as vehicle lifetime.

Freight transport

Eriksson, Blinge and Lövrgren (1996) studied the road transport sector with a life-cycle perspective by collecting detailed data on the environmental burdens caused by different transportation activities such as fuel production, fuel combustion at driving, maintenance of the vehicle and production and after use treatment of the vehicle. Production, maintenance and after use treatment of vehicles were found to contribute significantly to the total environmental impact of road transportation, measured per vehicle kilometre. Infrastructure related emissions were not considered.

Spielmann and Scholz (2005) indicate that comprehensive LCIs of various modes of transport are available from Frischknecht (1996) and Maibach (1999). Frischknecht et al. (2004) updated and harmonised these LCI's within the framework of the ecoinvent 2000 project. The ecoinvent database was created by the Swiss Centre for Life Cycle Inventories and is a reference work for life cycle inventory data covering the areas of energy, building materials, metals, chemicals, paper and cardboard, forestry, agriculture, detergents, transport services and waste treatment (Frischknecht et al., 2005). The goal was to generate a set of generic uniform and consistent LCI data of high quality for the different areas, valid for Swiss and other European conditions. The general modelling principles and structure of the ecoinvent-datasets are well documented, and for each of the 4000 covered processes, detailed background information can be found in a set of reports (Frischknecht et al., 2007). Transport services receive particular attention within ecoinvent, since:

> *Freight transport occurs between nearly any two process steps of a product system and is often of major importance for a product life cycle [...] (*Spielmann and Scholz, 2005)

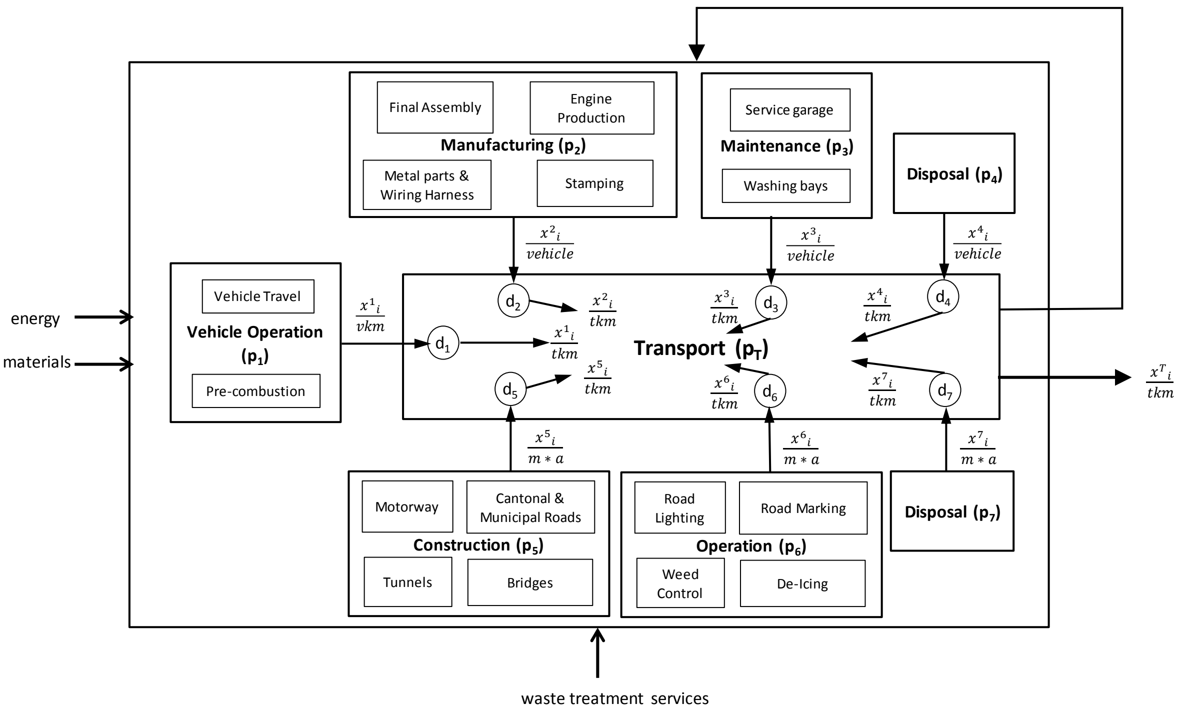

Figure 1 – Life Cycle Inventory of transport service (Spielmann and Scholz, 2005)

In order to account for cumulative exchanges due to the transportation occurring between two process steps of a product system, generic background data representing average transport conditions in Switzerland and Europe is generated for four modes of transport (air, rail, road and water transport) (Spielmann & Scholz, 2005). Environmental exchanges are related to the reference unit of one tonne kilometre, in order to quantify environmental exchanges of transport services and to relate transport datasets to other product life cycles (Spielmann & Scholz, 2005). The general model structure is shown in Figure 1 using the example of road transport.

In ecoinvent, each mode of transport is further separated into sub-groups, referred to as transport services, using several criteria such as geographical operation (e.g. rail transport), vehicle size (e.g. road transport) and transported goods (e.g. water transport). Vehicle operation accounts for both direct environmental interventions due to vehicle travel (predominately airborne emissions) and precombustion of fuels. Three components cover environmental interventions related to vehicle fleet: manufacturing, maintenance and disposal of a vehicle. Three components are included for transport infrastructure modelling: construction, operation and disposal of transport infrastructure (Spielmann and Scholz, 2005).

Based on average operation and infrastructure characteristics, Spielmann and Scholz (2005) conclude that for gaseous emissions, freight transport by inland waterway and rail show 65% to 92% lower cumulative emissions than road transport. They also stress that, although vehicle travel remains the most important category for a number of pollutants, the picture is much more mixed for others such as NMVOCs, PM and heavy metals, with important relative emission shares for precombustion and infrastructure processes.

2.3. LCA-based framework for barge transport

Since the general modelling principles and structure of the ecoinvent-datasets are considered to be scientifically sound and transparent (Tuchschmid, 2009), the modelling of barge transport in this paper will be based on the ecoinvent transport service framework. The framework presented in Figure 1 is therefore applied to barge transport (Figure 2).

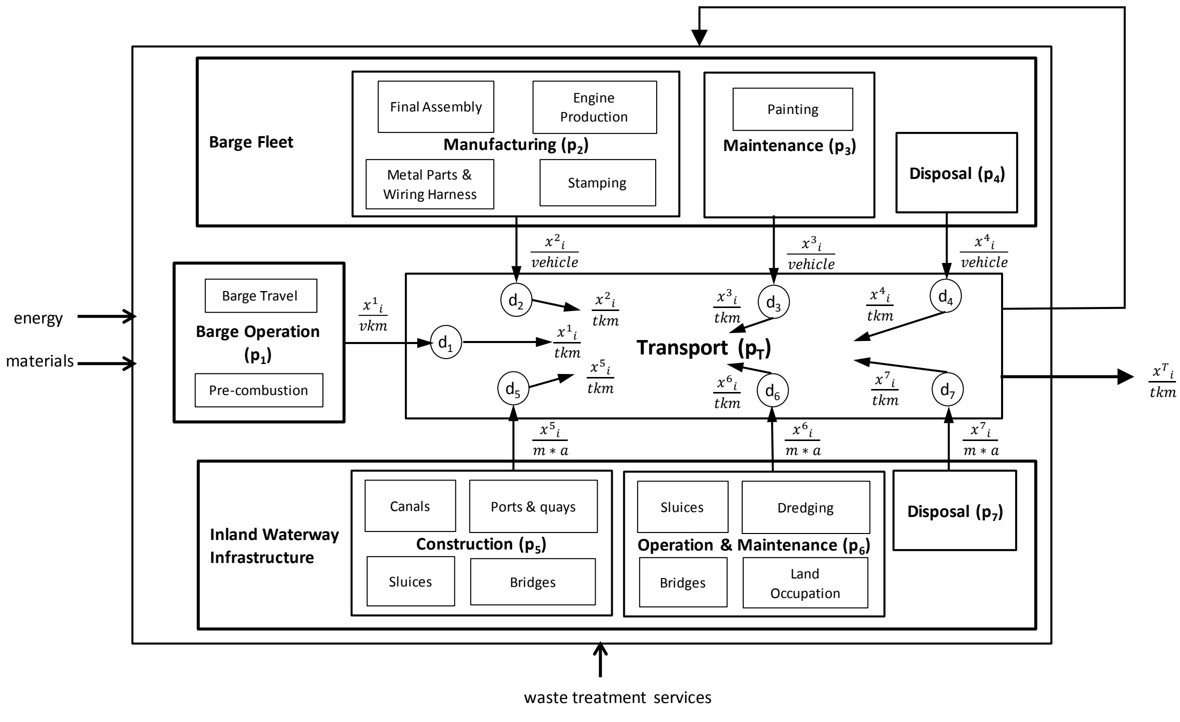

Figure 2 – Life Cycle Inventory of barge transport (Own setup based on Spielmann and Scholz, 2013)

The ecoinvent modelling of the "water transport" process is divided in three components (Spielmann et al., 2007):

1. Vessel operation: all processes directly connected with the operation of the barge, distinguishing between exchanges linked to vessel travel and exchanges related with upstream pre-combustion processes. Two types of inland waterways transport vessels are distinguished: barge and barge tankers. Ecoinvent assumes exclusive use of diesel for propelling. Exhaust emissions are assumed to be characterized by similar emission profiles as diesel engines of heavy duty vehicles (i.e. PM and heavy metal emissions). Distinction is further made between fuel content dependent emissions (SO_2) and combustion process dependent emissions (NO_x, CO, HC,N_20). All exchanges and interventions are referred to a transport performance of one tonne kilometre (tkm).
2. Vessel fleet: all processes describing the vessel life cycle (excluding the operation), such as construction, maintenance and disposal of the vessels. All exchanges and interventions are referred to one vehicle (unit). So in order to relate these interventions to the functional unit of 1 tkm, ecoinvent uses average kilometric performance and transport performance figures for barge and barge tanker (Spielmann et al, 2007). For exchanges of barge and barge tanker manufacturing, ecoinvent assumes an average barge capacity of 1.000 t/vessel and barge tanker capacity of 1.200 t/vessel.
3. Port infrastructure: all processes comprising the port infrastructure life cycle, including port construction, operation and maintenance as well as disposal. For inland shipping, artificial waterways construction and operation are modelled. All exchanges are expressed in one metre and year (ma) for line infrastructure (canal), for point infrastructure (port) the reference unit is m^2a. Since port infrastructure data is based on seaports and thus applicable for maritime water transport, only artificial waterway construction and operation datasets in ecoinvent are relevant for barge transport. A specific canal demand of 2,33E-04(m*a)/tkm is assumed in ecoinvent (Spielmann et al., 2007). For canal construction, data is based on the Main-Donau Canal in Germany, characterised by a width of 42m and an average depth of 4m. Life span is assumed to be 118 years. Canal operation exchanges are mainly related to electricity consumption for the operation of sluices. The canal bed area is estimated to be $42m^2$/m canal, with an additional 10 meters at each edge modelled as road traffic area (Spielmann et al., 2007)

Transport datasets provided in ecoinvent are however primarily designed to provide background data for straightforward application in a variety of life cycle studies, and are therefore mainly intended to allow for a preliminary screening of the importance of transport processes within a product life cycle (Spielmann and Scholz, 2005). The objective of water transport-LCA modelling in ecoinvent is indeed to supply sets of highly aggregated environmental interventions due to water transport. Spielmann et al. (2007) therefore state that:

> *For transport-focused LCA the presented generic datasets may have to be replaced with more specific data. In either case, whether transport processes are identified as sensitive for the overall outcome of a certain*

> *product life cycle or for transport specific comparisons, the modular model structure and transparent documentation of demand factors allows for an easy and transparent integration of more case-specific data for the selected transport components.*

This integration of more case-specific data for barge transport in Flanders within the ecoinvent transport service framework will be the focus of the next section and forms the core of this paper. Since the main goal is to map the environmental air emissions for barge transport in detail for the different components and to determine their relative importance, focus will be on the inventory analysis phase of LCA and thus the construction of barge related life cycle inventory (LCI).

3. LCI FOR BARGE TRANSPORT RELATED EMISSIONS IN FLANDERS

In this section, focus is on analysing in detail the environmental emissions (both air polluting and GHG emissions), for one particular transport mode, namely barge traffic, for one particular geographical region, namely Flanders (in Belgium), by integrating case-specific, regional data for barge transport in Flanders within the ecoinvent transport service framework. The analysis includes CO_2, CO, NO_x, SO_2, NH_3, N_2O, CH_4, VOC, NMVOC, TSP, $PM_{2,5}$ and PM_{10}. Structure in this section is based on the three components described in the ecoinvent modelling of the “water transport” process, namely barge operation, barge fleet and inland waterway infrastructure. First however, a literature study was performed to identify the available case-specific regional emission data related to barge transport in Flanders to be applied in the framework.

3.1. Literature study: barge related emissions for Flanders

Scientific literature with regards to barge related emission data was screened. Goal was to identify the emission factors published in literature, together with the applied hypothesis, that were relevant and applicable for barge transport in Flanders. Following studies and models were analyzed: TREMOVE (De Ceuster et al., 2007), VITO (De Vlieger et al., 2004), STREAM (den Boer, Otten and van Essen, 2011), Royal Haskoning (Schilperoord, 2004), Environ (Lindhjem, 2004), INFRAS (Schreyer et al., 2004), ADEME (2006), EcoTransIT (Knörr et al., 2010), EMMOSS (Vanherle, Van Zeebroeck and Hulskotte, 2007), EMS (Ministerie van Verkeer en Waterstaat, 2003) and Arcadis (Franckx, Vanhove and Schoukens, 2011).
Relevance of studies was determined based on following criteria: explicit inclusion of barge transport, explicit inclusion of emission factors, publication data and geographical focus (preferably Flanders or Belgium oriented). Most recent studies are EcoTransIT, TREMOVE and STREAM. However, EcoTransIT has a worldwide focus, TREMOVE a European focus and STREAM is mostly based on Dutch data, all three applying general assumptions with regards to fuel consumption, load rate and share of empty trips without country specific differentiation, making them less applicable for direct application in a Flemish context. The

EMMOSS model (Vanherle, Van Zeebroeck and Hulskotte, 2007), developed by Transport & Mobility Leuven (TML) for the Flemish Environmental Agency (VMM), has a solid scientific basis and uses a detailed bottom-up approach to determine operational tank-to-wheel rail and ship (both barge and maritime) related emissions in a Flemish context, giving it the right geographical scope. A wide variety of pollutants are included in EMMOSS. A first group of emissions including CO, PM, VOC and NO_x are expressed in function of their energy consumption (g/kWh) and classified per ship engine age, while a second group of emissions including i.e. CO_2, CH_4, SO_2, N_2O, NH_3, Cd and Cr are expressed in function of fuel consumption (g/kg fuel). A third category of emissions including Polycyclic Aromatic Hydrocarbons (PAHs) and VOC components are linked to VOC and expressed in g/kg VOC (Vanherle, Van Zeebroeck and Hulskotte, 2007).

EMMOSS differentiates between 30 different barge types, taking into account engine age structure of barges using a Weibull distribution, and identifies 9 waterway types, including 6 CEMT classes and 3 river classes, taking into account maximum speed per barge type per waterway. Operational energy usage by barges in EMMOSS thus takes into account ship characteristics (length, width, hull shape), waterway characteristics (width, depth, current) and transported volume (load rate, empty trips). This makes EMMOSS particularly interesting as a source of operational emission factors.

EMOSS, however, was built to map the overall total direct emissions of rail and water transport in Flanders and thus emission factors expressed in tonkilometers are not direct outputs of the model. Based on outputs of the model provided by VMM, together with the underlying assumptions for load factors, engine age and canal characteristics, recalculations were nevertheless possible to derive emission factors in tonkilometer for the different pollutants, differentiated per ship type and per waterway class. These emission factors will be used to model the barge travel related operational emissions in the LCA framework. Focus in this paper will be on M-type barges as classified in EMMOSS (Table I).

With regards to barge fleet or infrastructure related emission data, useful and/or directly applicable data was lacking in all the studies consulted in the literature review, confirming the need for an LCA based approach to map total emissions of barge transport.

Next, emission factors for the different components will be discussed in detail.

Table I – Barge type characteristics applied in EMMOSS (Vanherle et al, 2007)

Ship type	Name	Distribution (engine age)	Length (m)	Width (m)	Unloaded draft (m)	Loaded draft (m)	Power class [indicative] (kW)	Load capacity (ton)
M0	small motorship	L	35	4,5	0,4	2,2	70	<=250
M1	Spits - Péniche	L	38,5	5,05	0,5	2,5	250	251-400
M2	Kempenaar - Campinois	L	55	6,6	0,6	2,5	250	401-650
M3	Dutch barge - Hagenaar	L	67	7,2	0,7	2,5	1000	651-800
M4	D.E.K. (Dortmund-Ems Canal)	M	67	8,2	0,7	2,7	1000	801-1050
M5	Extended D.E.K.	M	80	8,2	0,7	2,7	1000	1051-1250
M6	R.H.K. (Rhine-Herne-Canal)	S	85	9,5	0,8	2,9	1000	1251-1750
M7	Extended R.H.K.	S	105	9,5	0,8	3,0	1000	1751-2050
M8	Big Rhine barge	S	110	11,4	0,8	3,5	1300	>2050

3.2. Barge operation

Barge travel

This component comprises the fuel combustion related emissions that occur during the operational barge travel, the so-called tank-to-wheel emissions. As explained above, EMMOSS output values expressed in ton pollutant for specific waterways are used as a basis for recalculating emission factors expressed per tonkilometer per barge type per waterway class. A selection was made of waterways that were considered to be representative for the most common canal and river types in Flanders: Albert canal (CEMT 6), Brussels-Scheldt canal (CEMT 6), upper Scheldt river (CEMT 5), Roeselare-Leie canal (CEMT 5) Ghent-Bruges canal (CEMT 4) and Leuven-Dijle canal (CEMT 2). Transport performance figures per individual waterway expressed in tonkilometer required for the recalculation were provided by Waterwegen en Zeekanaal NV. Average load rates of barges on the selected canals were provided by EMMOSS.
As an example, Table II shows specific emission factors for barge travel with a loaded M4 type barge with a load rate of 68% on the canal Brussels-Scheldt (CEMT6) for 2010, expressed in grammes per tonkilometer.

Table II – 2010 emission factors for barge travel in g/tkm: loaded M4 type barge on canal Brussels-Scheldt (Own calculations based on EMMOSS data provided by VMM & TML, 2012)

barge type	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC	N_2O	PM2,5	PM10
M4	1,18E-04	2,36E-02	3,69E+01	1,02E-01	5,26E-01	8,73E-04	1,83E-02	2,18E-02	2,09E-02	9,43E-04	1,65E-02	1,74E-02

Calculations for other barge types revealed that, not surprisingly, larger ships are generally more environmentally friendly during travel due to scale effects, however between consecutive classes differences can be small or even more favourable for the smaller barge type (e.g. between M3 and M4). This might be due to the assumed age distribution of engines per barge type, the fuel efficiency differences between barges and/or the use of an average loading rate per waterway which might not reflect existing differences in loading rates between barge types.

Pre-combustion

This component comprises emissions that are indirectly linked to the operational use of barges, namely the emissions that occur during the exploration, refining, transporting and storage of fuels that are eventually used during barge travel, the so-called well-to-tank emissions. Scientific literature provides less data and no directly applicable emission factors for precombustion, therefore data from ecoinvent processes “diesel, at refinery” and “diesel, at regional storage” are used. Exploration related emissions are not included, due to uncertainty regarding fuel origin. Ecoinvent process “diesel at refinery” includes all processes on the refinery site excluding the emissions from combustion facilities, including waste water treatment, process emissions and direct discharges to rivers, while ecoinvent process “diesel, at regional storage” includes transportation of product from the refinery to the end user, operation of storage tanks and petrol stations and emissions from evaporation and treatment of effluents.

Ecoinvent datasets provide the resources used for the refining and storing of 1 kg of diesel (e.g. 0,0146 kg water, various chemicals, different variants of crude oil as well as energy and transport demand for refining 1kg of diesel). The resulting emissions associated with these processes are calculated from ecoinvent databases and shown in Table III, e.g. 0,441kg CO_2 will be emitted during the refining of 1 kg diesel.

Table III – Related emissions for selected ecoinvent processes (Own calculations, based on ecoinvent v2.2, 2012))

Name	Unit	diesel, at refinery	diesel, at regional storage	barge	barge tanker	maintenance, barge	canal	maintenance, operation, canal
Unit		kg	kg	unit	*unit*	*unit*	*ma*	*ma*
GHGs								
Carbon dioxide (CO2)	kg	4,41E-1	4,67E-1	7,88E+05	9,45E+05	1,23E+05	5,62E+01	1,82E+00
Dinitrogen monoxide (N2O)	kg	8,02E-06	8,80E-06	1,42E+01	1,70E+01	3,12E+01	3,49E-04	5,40E-05
Methane (CH4)	kg	1,85E-03	1,88E-03	1,61E+03	1,94E+03	3,55E+02	7,38E-02	3,06E-03
Ammonia (NH3)	kg	5,82E-06	8,75E-06	3,21E+01	3,85E+01	2,40E+01	2,18E-03	2,48E-05
Sulfur Dioxide (SO2)	kg	4,22E-03	4,33E-03	3,07E+03	3,68E+03	5,51E+02	5,51E-02	5,83E-03
Cadmium (Cd)	kg	4,52E-08	4,60E-08	2,62E-01	3,15E-01	7,70E-03	1,35E-06	3,49E-08
Chromium (Cr)	kg	1,00E-07	1,15E-07	3,51E+00	4,21E+00	2,02E-01	2,11E-05	3,31E-07
Copper (Cu)	kg	1,29E-07	1,48E-07	1,82E+00	2,18E+00	1,09E-01	2,06E-05	5,41E-07
Nickel (Ni)	kg	6,72E-07	7,02E-07	3,44E+00	4,12E+00	1,49E-01	1,65E-05	9,35E-07
Lead (Pb)	kg	1,42E-07	1,58E-07	2,47E+00	2,96E+00	7,50E-02	4,27E-05	5,43E-07
Zinc (Zn)	kg	2,18E-07	2,76E-07	4,32E+00	5,18E+00	1,55E-01	1,08E-04	7,63E-07
particulates <2,5um (PM2,5)	kg	1,63E-04	1,72E-04	4,54E+02	5,45E+02	2,41E+01	1,30E-02	4,43E-04
particulates >2,5um and <10um	kg	4,73E-05	5,46E-05	8,03E+02	9,63E+02	6,09E+01	2,59E-02	1,10E-04
particulates >10um	kg	1,27E-04	1,44E-04	1,32E+03	1,58E+03	3,89E+01	4,68E-02	1,14E-03
particulates <10um (PM10)	kg	2,10E-04	2,27E-04	1,26E+03	1,51E+03	8,50E+01	3,88E-02	5,54E-04
total particulates (TSP)	kg	3,37E-04	3,70E-04	2,58E+03	3,09E+03	1,24E+02	8,56E-02	1,69E-03
Carbon monoxide (CO)	kg	6,79E-04	7,34E-04	6,68E+03	8,02E+03	1,75E+02	2,36E-01	5,64E-04
Nitrogen Oxides (Nox)	kg	1,65E-03	1,78E-03	1,58E+03	1,89E+03	3,41E+02	1,23E-01	2,99E-03
NMVOC (via ecoinvent)	kg	1,18E-03	1,19E-03	1,27E+03	1,52E+03	1,60E+04	1,89E-02	2,28E-04

Barge travel fuel consumption per barge type can be deducted directly from CO_2-emissions generated in EMMOSS, since a conversion factor of 3.100 g CO_2 per 1 kg diesel is assumed. When combining the resulting fuel consumption with the ecoinvent pre-combustion emissions of Table III, the emission factors related to precombustion can be calculated for the selected waterways. Table IV shows the resulting emission factors for precombustion processes for barge travel with a loaded M4 type barge (again with a load rate of 68%) on the canal Brussels-Scheldt for 2010, expressed in grammes per tonkilometer.

Table IV – 2010 emission factors for precombustion in g/tkm: loaded M4 type barge on canal Brussels-Scheldt (Own calculations based on ecoinvent data, 2012 and EMMOSS data provided by VMM & TML, 2012)

barge type	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC	N_2O	PM2,5	PM10
M4	1,73E-04	1,02E-01	1,08E+01	1,68E-02	4,09E-02	4,44E-02	8,42E-03	2,93E-02	2,82E-02	2,00E-04	3,99E-03	5,20E-03

Also for other barge types, calculations were made. When comparing different barge types, the same conclusions apply here as for barge travel: larger ships are generally more environmentally friendly during travel due to scale effects, but differences can be small between consecutive barge classes or in some cases even more favourable for the smaller barge type.

3.3. Barge fleet

Barge manufacturing

This component comprises the emissions associated with the construction of barges. Two approaches can be proposed: a more straightforward approach starting from the processes “barge” and “barge tanker” available in the ecoinvent database and applying the emission factors proportionally depending on the dimensions of the different barge types, or a more refined approach using specific data related to materials, transport and energy used in the construction of different barge types and applying the emission factors of the relevant ecoinvent subprocesses (for i.e. “reinforcing steel, at plant”, “chromium steel 18/8, at plant”, “synthetic rubber at plant”, “alkyd paint, white, 60% in solvent, at plant”, “glued laminated timber, for outdoor use, at plant”, “transport, lorry >16t, fleet average”, etc.) in order to make a detailed calculation. However, barge construction data differentiated per barge type is currently lacking, so the first approach was applied. The second approach however is more accurate and advisable for specific case studies.
For exchanges related to the processes “barge” and “barge tanker” manufacturing, ecoinvent assumes an average barge capacity of 1.000 t/vessel and barge tanker capacity of 1.200 t/vessel, which corresponds to an M4 barge (D.E.K. barge).
The resulting emissions associated with the processes “barge” and “barge tanker” are shown in Table III, where the related emissions for selected ecoinvent processes are listed. For example, 788.000 kg CO_2 and 454 kg $PM_{2.5}$ will be emitted during construction of one barge with a load capacity of 1.000 tonnes.
In order to calculate average emissions for an M4 barge type, a proportional division of 81% barges versus 19% barge tankers was assumed for the Belgian inland waterway fleet (based on 2011 data from the Institute for Transport along Inland Waterways), resulting in average emissions for an M4 barge as presented in Table V.

Table V – Emissions related to barge construction for M4 barge type in kg (Own calculations based on ecoinvent data, 2012)

barge type	NH_3	SO_2	CO_2	CO	Nox	Methaan	TSP	VOC	NMVOC	N_2O	PM2,5	PM10
M4	3,33E+01	3,18E+03	8,17E+05	6,94E+03	1,63E+03	1,68E+03	2,67E+03	1,37E+03	1,32E+03	1,47E+01	4,72E+02	1,30E+03

For other barge types, the resources listed in ecoinvent can be recalculated proportionally based on the dimensions presented in Table I, since the product of length, width and loaded draft can be used as a proxy for the volume of a barge type. Resources are than assumed to be used in proportion to the volume of the ship, with M4 serving as the base type. As a result, construction of a larger barge type will result in larger overall emissions compared to a smaller barge type, and this in proportion to their dimensions. However, to calculate emission factors per tonkilometer, data is needed on the transport performance over the life-time of a barge, expressed in tonkilometers. This data is provided in ecoinvent for the modelled M4 barge (738.644.684 tkm for barge and 881.119.408 tkm for barge tanker), but similar data for other barge types is lacking in literature. Therefore, the same emission factors in tonkilometer are applied for all different barge types, under the assumption that the larger absolute emissions for larger barge types are exactly compensated by relatively higher tonkilometers over their life-time due to scale effects. However, one might expect that scale effects overcompensate the absolute larger emissions in case of the larger barge types, but current lack of specific transport performance data per barge type does not allow to incorporate this effect into the calculations. Further research and data collection would be needed to resolve this issue. For the time being, emission factors per tonkilometer related to the construction of a M4 barge, as presented in Table VI, are applied to the other barge types

Table VI – Emission factors for barge construction in g/tkm for M4 barge (based on ecoinvent data, 2012)

barge type	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC	N_2O	PM2,5	PM10
M4	3,94E-05	3,76E-03	9,67E-01	8,21E-03	1,93E-03	1,98E-03	3,16E-03	1,62E-03	1,56E-03	1,74E-05	5,58E-04	1,54E-03

Barge maintenance

This component comprises emissions that are linked to the maintenance of barges. Again, two approaches similar to the ones described for barge manufacturing can be applied, namely a straightforward calculation based on the ecoinvent process “barge maintenance”, or a more refined calculation based on specific data regarding the materials, transport and energy used in the maintenance of different barge types, and using the appropriate ecoinvent subprocesses. Again, a lack of specific data related to the barge maintenance of different barge classes obliges to apply the more straightforward approach.
The ecoinvent process “barge maintenance” assumes that a barge is painted 10 times during a life-time of 40 years. The use of lubricates is assumed to be included in the fuel consumption for vessel operation. So next to some road and rail transport, the main resource consumed during the maintenance of one unit “barge” modelled in ecoinvent is 43.600 kg alkyd white paint (with 60% solvent). The resulting emissions associated with barge maintenance are shown in Table III. For example, 123.000 kg CO_2 will be emitted during maintenance of one barge with a load capacity of 1.000 tonnes. Notable is the high amount of NMVOC, namely 16.000 kg.
Recalculation for other barge types can be done in a similar way as for barge construction, namely proportionally based on the dimensions presented in Table I. Again however, lack of transport performance data over life-time per barge type prohibits a differentiated recalculation per tonkilometer, so also here emission factors per tonkilometer related to the maintenance of a M4 barge are applied to the other barge types (Table VII).

Table VII – Emission factors for barge maintenance in g/tkm for M4 barge (based on ecoinvent data, 2012)

barge type	NH_3	SO_2	CO_2	CO	NO_x	Methaan	TSP	VOC	NMVOC	N_2O	PM2,5	PM10
M4	2,72E-05	6,25E-04	1,39E-01	1,99E-04	3,87E-04	4,03E-04	1,41E-04	1,89E-02	1,81E-02	3,54E-05	2,73E-05	9,64E-05

3.4. Inland waterway infrastructure

Inland waterway construction

Distinction should be made between artificial waterways (canals) and natural waterways (rivers and lakes). Only the first category is relevant. Similarly as above, two approaches are possible: a straightforward approach starting from the process "canal" and applying the emission factors proportionally depending on the dimensions of the different canals, or a more refined approach using specific data related to materials, transport and energy used in the construction of specific canals and applying the emission factors of the relevant ecoinvent subprocesses (such as "excavation, skid-steer loader", "concrete, exacting, at plant", "reinforcing steel, at plant", etc). The first approach focuses solely on canal construction; the second approach allows to incorporate other elements (building of bridges, locks, etc.). Specific canal construction data was only available for one M2 type canal, allowing a detailed calculation. Due to the lack of construction data for other canals however, the first approach was applied for the other canals.

Data for the ecoinvent process "canal" is derived from the Main-Donau canal in Germany, having a width of 42 meter and average depth of 4 meter. Bridges and locks are not included in the modelling, resulting in an underestimation of canal construction related emissions with this approach. Ecoinvent assumes that 4,03m^3 of ground has to be excavated and 0,31m^3 of concrete, 8,68kg of reinforced steel and 0,0087kg of bitumen are required for the construction of 1 meter*year (ma) of canal. Lifetime of canals is considered to be 118 years (Spielmann et al, 2007). However, in many cases, this seems to be an underestimation.

Emissions related to the construction of one meter*year of canal of the above dimensions are presented in Table III. To derive total canal construction emissions for a specific canal, these values have to be multiplied with 118 years and the total length of the selected canal.

For other canals, the used resources for the Main-Donau canal are recalculated proportionally based on the canal dimensions for the selected canals, presented in Table VIII.

Table VIII – Waterway dimensions for selected waterways (MOSI-T based on several sources, 2012)

	Waterway dimensions		
Waterway	Length (m)	Average width (m)	Average depth (m)
Upper Scheldt	50.014	5,3	2,5
Canal Ghent- Bruges	39.739	46,0	4,1
Canal Leuven - Dijle	30.034	28,0	2,7
Canal Roeselare - Leie	16.512	55,0	5,3
Canal Brussels - Scheldt*	27.000	55,0	6,0
Albert canal	129.577	86,0	5,0
Main-Donau canal	171.000	42,0	4,0

Emissions expressed in kg per meter*year for selected waterways are shown in Table IX. Ecoinvent models emissions that would have been emitted if canals would have been built with current technology and assuming a lifetime of 118 years. Some of these canals however have been excavated centuries ago before the industrialization age, and amply surpass a lifetime of 118 years. Therefore, only canal construction emissions for more recently excavated or enlarged canals are relevant and presented in Table IX.

Table IX – Emissions related to canal construction per selected waterway in kg per meter*year (Own calculations based on ecoinvent data, 2012)

Waterway	NH3	SO2	CO2	CO	NOx	Methaan	TSP	VOC	NMVOC (kg/ma)	N2O	PM2,5	PM10
Ecoinvent (Main-Donau)	2,18E-03	5,51E-02	5,62E+01	2,36E-01	1,23E-01	7,38E-02	8,56E-02	1,97E-02	1,89E-02	3,49E-04	1,30E-02	3,88E-02
Canal Brussels - Scheldt*	4,29E-03	1,08E-01	1,10E+02	4,64E-01	2,42E-01	1,45E-01	1,68E-01	3,87E-02	3,72E-02	6,85E-04	2,54E-02	7,63E-02
Albert canal	5,59E-03	1,41E-01	1,44E+02	6,05E-01	3,16E-01	1,89E-01	2,19E-01	5,05E-02	4,84E-02	8,93E-04	3,32E-02	9,94E-02

In order to recalculate emissions on a tonkilometer base, data with regard to the specific transport demand per waterway is needed, expressed in ((m*a)/tkm). Ecoinvent assumes a specific canal demand of 2,33E-04(m*a)/tkm for the Main-Donau canal. Specific canal demand data for the selected Flemish waterways was derived based on statistics from inland waterway administrating bodies Waterwegen en Zeekanaal NV and NV Scheepvaart (1,23E-04 canal Brussels-Scheldt and 4,79E-05 for Albert canal).

Since waterways provide other functions in addition to enabling and promoting barge transport, such as functions related to recreation, water management, environment and energy, only a portion of the canal construction emissions should be assigned to barge transport. Financial data from Waterwegen en Zeekanaal NV indicate that almost 45% of the expenses related to waterway management in Flanders are barge transport related.

Table X shows emission factors per tonkilometer for canal construction for the relevant canals.

Table X – 2010 emission factors for canal construction in g/tkm on selected waterways (Own calculations based on EMMOSS data provided by VMM & TML, 2012)

Waterway	NH3	SO2	CO2	CO	NOx	Methaan	TSP	VOC	NMVOC (kg/ma)	N2O	PM2,5	PM10
Ecoinvent (Main-Donau)	5,07E-04	1,28E-02	1,31E+01	5,50E-02	2,87E-02	1,72E-02	1,99E-02	4,58E-03	4,40E-03	8,11E-05	3,01E-03	9,03E-03
Canal Brussels - Scheldt	2,36E-04	5,96E-03	6,07E+00	2,55E-02	1,33E-02	7,98E-03	9,25E-03	2,13E-03	2,04E-03	3,77E-05	1,40E-03	4,20E-03
Albert canal	1,20E-04	3,03E-03	3,09E+00	1,30E-02	6,78E-03	4,06E-03	4,70E-03	1,08E-03	1,04E-03	1,92E-05	7,12E-04	2,14E-03

Waterway infrastructure maintenance and operation

This component comprises emissions linked to the maintenance and operation of waterway infrastructure. These emissions occur both on natural and artificial waterways. Again, two approaches can be proposed: starting from the ecoinvent process “maintenance, operation, canal” or linking specific data related to materials, transport and energy used in maintenance and operation of specific canals to relevant ecoinvent subprocesses (such as “gravel, unspecified, at mine”, “brick, at plant”, “roundwood, azobe (SFM)”, “electricity mix”, etc). Specific waterway maintenance and operation data was only available for one M2 type canal, allowing a detailed calculation. Due to the lack of such data for other waterways however, the first approach was applied to the other waterways.

The ecoinvent process “maintenance, operation, canal” inventory is again based on values for the Main-Donau canal and includes the electricity consumption due to the operation of watergates. Also land occupation and transformation are taken into account. The main resource consumed is electricity (3,42 kWh per meter*year). Emissions linked to the maintenance and operation of one meter*year of canal are presented in Table III. Total maintenance emissions for a specific canal on a yearly basis require multiplying with canal length.

Applying the same approach as with canal construction, using specific waterway demand on the selected waterways and assigning 45% of emissions to barge transport, emissions per tonkilometer can be calculated for waterway maintenance and operation (Table XI). Since operation and maintenance is required on all canals, the related emissions are relevant for all selected canals, including the older ones.

Table XI – 2010 emission factors for waterway maintenance and operation in g/tkm on selected waterways (Own calculations based on EMMOSS data provided by VMM & TML, 2012)

Waterway	NH3	SO2	CO2	CO	NOx	Methaan	TSP	VOC	NMVOC (kg/ma)	N2O	PM2,5	PM10
Ecoinvent (Main-Donau)	5,77E-06	1,35E-03	4,24E-01	1,31E-04	6,96E-04	7,12E-04	3,93E-04	5,52E-05	5,30E-05	1,26E-05	1,03E-04	1,29E-04
Canal Ghent- Bruges	1,08E-07	2,52E-05	7,90E-03	2,44E-06	1,30E-05	1,33E-05	7,32E-06	1,03E-06	9,86E-07	2,34E-07	1,92E-06	2,40E-06
Canal Leuven - Dijle	4,65E-06	1,09E-03	3,42E-01	1,06E-04	5,61E-04	5,74E-04	3,17E-04	4,45E-05	4,27E-05	1,01E-05	8,31E-05	1,04E-04
Canal Roeselare - Leie	2,11E-05	4,96E-03	1,55E+00	4,80E-04	2,55E-03	2,60E-03	1,44E-03	2,02E-04	1,94E-04	4,59E-05	3,77E-04	4,71E-04
Canal Brussels - Scheldt	8,26E-06	1,94E-03	6,07E-01	1,88E-04	9,97E-04	1,02E-03	5,62E-04	7,90E-05	7,58E-05	1,80E-05	1,48E-04	1,84E-04
Albert canal	2,68E-06	6,29E-04	1,97E-01	6,09E-05	3,24E-04	3,31E-04	1,82E-04	2,56E-05	2,46E-05	5,83E-06	4,79E-05	5,98E-05

3.5. Synthesis

Based on the above calculations, the relative importance of the different transport service components can be analysed for the different pollutants, per barge type and per waterway. This provides a much more detailed understanding of the importance of the different pollutants in the case of barge transport, and also allows to demonstrate the weight of each of the components for the different pollutants. Also the impact of barge type and waterway size on the resulting emissions over the different components can be examined in this approach.
Below, three cases are presented to illustrate the main conclusions.

Comparison between pollutants

This type of comparison is based on the calculated data in Table XII and illustrated by Figure 3, showing the relative importance of the different transport service components for a number of pollutants based on a loaded M4 type barge on the canal Brussels-Scheldt (CEMT 6) on a tonkilometer basis.

Table XII – Emission factors for different components in g/tkm for M4 barge on CEMT 6 canal Brussels-Scheldt (Own calculations, 2012)

	Barge operation		Barge fleet		Transport infrastructure		
	Barge travel	Precombustion	Barge manufacturing	Barge maintenance	Canal Construction	Infrastructure operation & maintenance	Total emission (g/tkm)
NH3	1,18E-04	1,73E-04	3,94E-05	2,72E-05	2,36E-04	2,68E-06	5,96E-04
SO2	2,36E-02	1,02E-01	3,76E-03	6,25E-04	5,96E-03	6,29E-04	1,36E-01
CO2	3,69E+01	1,08E+01	9,67E-01	1,39E-01	6,07E+00	1,97E-01	5,51E+01
CO	1,02E-01	1,68E-02	8,21E-03	1,99E-04	2,55E-02	6,09E-05	1,53E-01
NOx	5,26E-01	4,09E-02	1,93E-03	3,87E-04	1,33E-02	3,24E-04	5,83E-01
CH4	8,73E-04	4,44E-02	1,98E-03	4,03E-04	7,98E-03	3,31E-04	5,60E-02
NMVOS	2,09E-02	2,82E-02	1,56E-03	1,81E-02	2,04E-03	2,46E-05	7,09E-02
PM2,5	1,65E-02	3,99E-03	5,58E-04	2,73E-05	1,40E-03	4,79E-05	2,25E-02
PM10	1,74E-02	5,20E-03	1,54E-03	9,64E-05	4,20E-03	5,98E-05	2,85E-02

The share of barge travel related emissions for this case varies between 1,56% for CH_4 to 90,2% for NO_x. While barge travel remains by far the most important category for CO_2, CO, NO_x, $PM_{2,5}$ and PM_{10}, it is relatively less important for NMVOS, NH_3, SO_2 and CH_4. Next to barge transport, also emissions related to other categories are often not negligible. E.g, for CO_2, the share of non-barge travel related emissions is responsible for more than 30% of emissions, with precombustion and canal construction taking up the largest parts. Precombustion related emissions are also very significant for CH_4, SO_2 and NMVOC, where this component is even more important than barge travel related emissions. Also for NH_3 and PM precombustion related emissions are important and non-negligible. Barge manufacturing and maintenance related emissions are generally relatively small, except for NMVOC. Canal construction is particularly important for NH_3 emissions. Also for CO, CH_4 and PM_{10} the effect of emissions related to canal construction is relevant and non-negligible. Share of infrastructure operation and maintenance related emissions is relatively very small for all pollutants, ranging from almost zero (0,03% for NMVOC) to 0,59% (for CH_4).

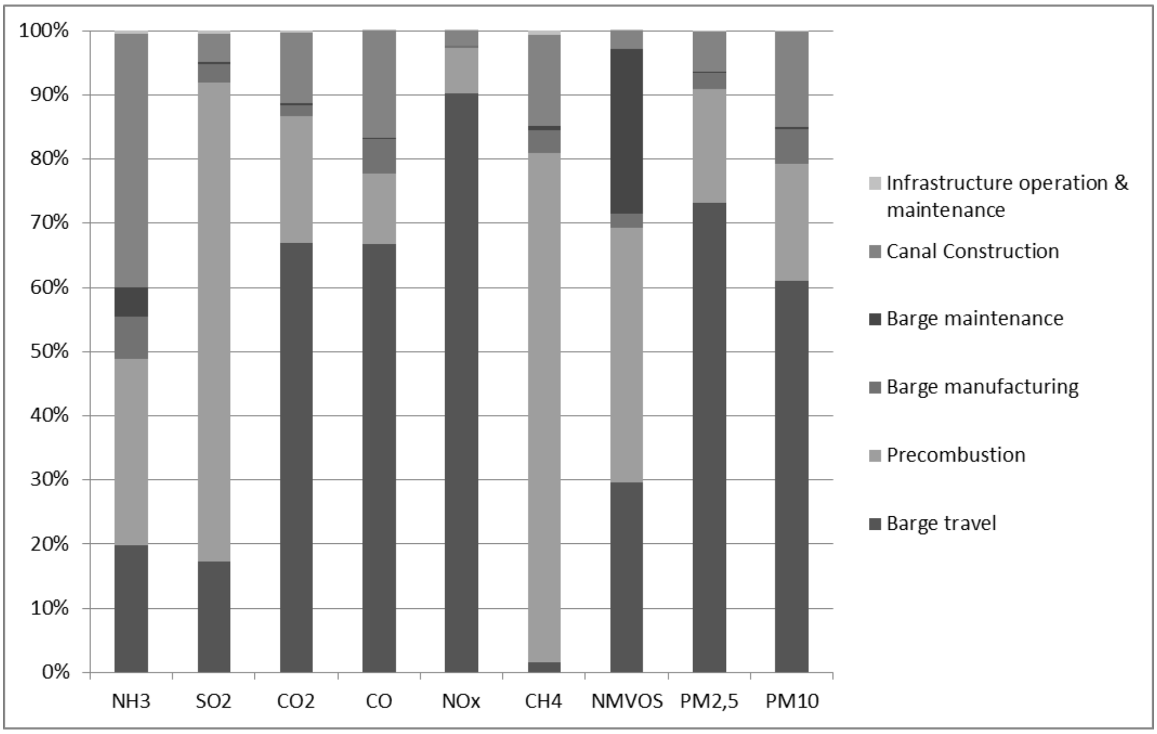

Figure 3 – Relative importance of transport service components for different pollutants: M4 barge on CEMT6 type canal (tonkilometer basis)

Comparison between barge types

In addition to the above comparison between pollutants, it is also interesting to look at how the relative share of the different components varies per barge type for a particular pollutant on a specific waterway. To illustrate this type of comparison, Figure 4 shows the relative importance of the different components per loaded barge type on the canal Brussels-Scheldt for CO_2 emissions on a tonkilometer basis.

The figure indicates that (except for M1 and M2), the larger the barge type considered, the larger the relative share of emission related to vehicle fleet and waterway infrastructure becomes, and the lower the relative share of emissions related to vehicle operation. Indeed, comparing an M3 barge to an M8 barge, the share of barge travel is found to decrease from 67,2% to 55,4% and that of precombustion from 19,7% to 16,2%, while the share of barge

fleet related emissions increases from 2,0% to 4,3% and that of waterway infrastructure from 11,2% to 24,1%. However it should be stressed that these are changes in relative terms: over the range of barge types, the total emissions expressed in tonkilometer decrease significantly in absolute terms when the ship size increases: from 56,1 g CO_2/tkm for M3 barge to 26,0 g CO_2/tkm for M8 barge. due to the scale effects in barge operation.
It is important to stress that these results are sensitive to two important assumptions. First, the fact that the load rate is only differentiated per waterway, but considered constant for all barge types on that specific waterway. Secondly, the assumption that emission factors related to barge fleet (barge maintenance & barge manufacturing) expressed per tonkilometer are considered constant over the different barge types due to a lack of transport performance data over life-time per barge type, although one might expect that economies of scale would actually also play a role here in reality.
The same type of analysis can be applied to other pollutants and per different waterway class.

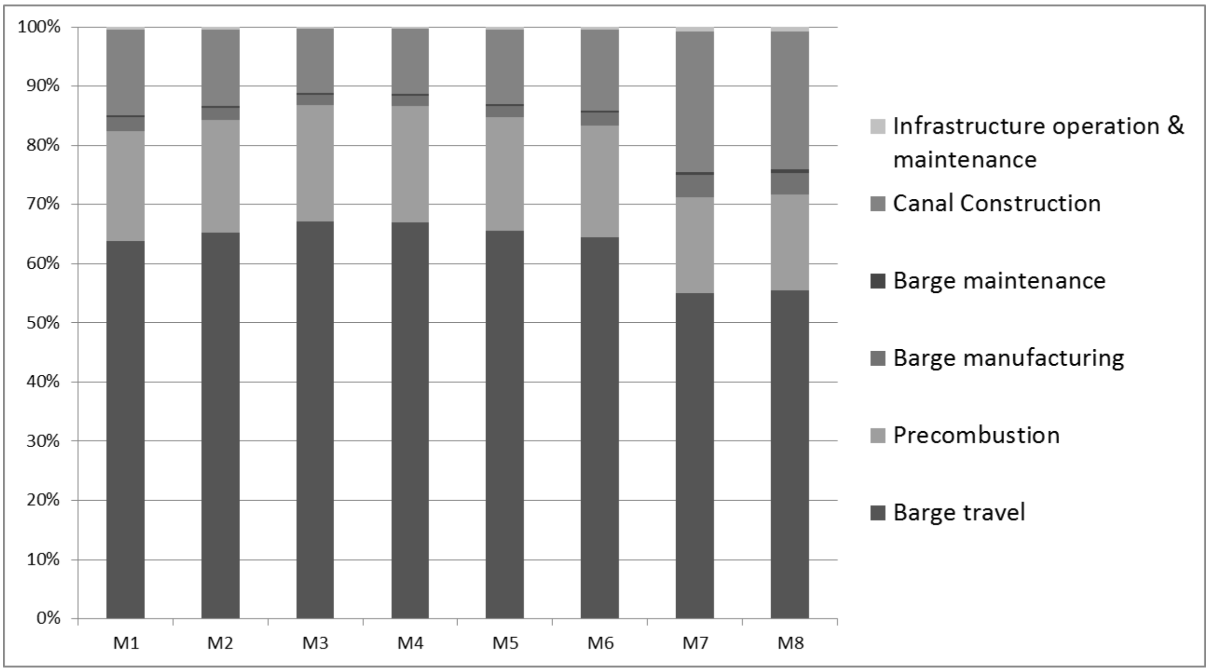

Figure 4 – Relative importance of transport service components per loaded barge type on CEMT6 type canal: CO_2 emissions (tonkilometer basis)

Comparison between waterways

This third type of analysis allows to assess how the relative share of the different components varies per waterway type for a particular pollutant and a particular barge type. Figure 5 illustrates a comparison of waterways, showing the relative importance of the different components for NH_3 on different waterways using a loaded M4 type barge (except for canal Leuven-Dijle where a M2 barge is considered, since larger types are not allowed on this waterway), on a tonkilometer basis.
The share of barge operation related NH_3 emissions (between 48,9% for canal Brussels-Scheldt and 79,3% for canal Bruges-Ghent) is relatively small compared to the share of barge operation related CO_2-emissions (see Figure 4), which means that other components

have a relatively large share in NH_3 emissions. For the smaller canals, emissions related to canal construction are assumed to be negligible due to the fact that these canals have been excavated centuries ago. For larger, more recent canals, the share of the NH_3 emissions is however significant, ranging between 28,1% for Albert canal and 39,5% for canal Brussels-Scheldt. On the other hand, emissions related to operation and maintenance of waterway infrastructure are relatively larger for smaller waterways, due to the limited economies of scale on these waterways and thus the higher specific canal demand. This last effect does not fully compensate the large canal construction related NH_3 emissions for the larger more recent canals, so that total NH_3 emissions are largest for canal Brussels-Scheldt (5,96E-04 gNH_3/tkm) and Albert canal (4,27E-04 gNH_3/tkm), and lower for the smaller canals (between 3,10E-04 gNH_3/tkm for canal Roeselare-Leie and 3,44E-04 gNH_3/tkm for canal Ghent-Bruges). Obviously, rivers have no canal construction related emissions and thus lower total values (2,11E-04 gNH_3/tkm for Upper Scheldt).

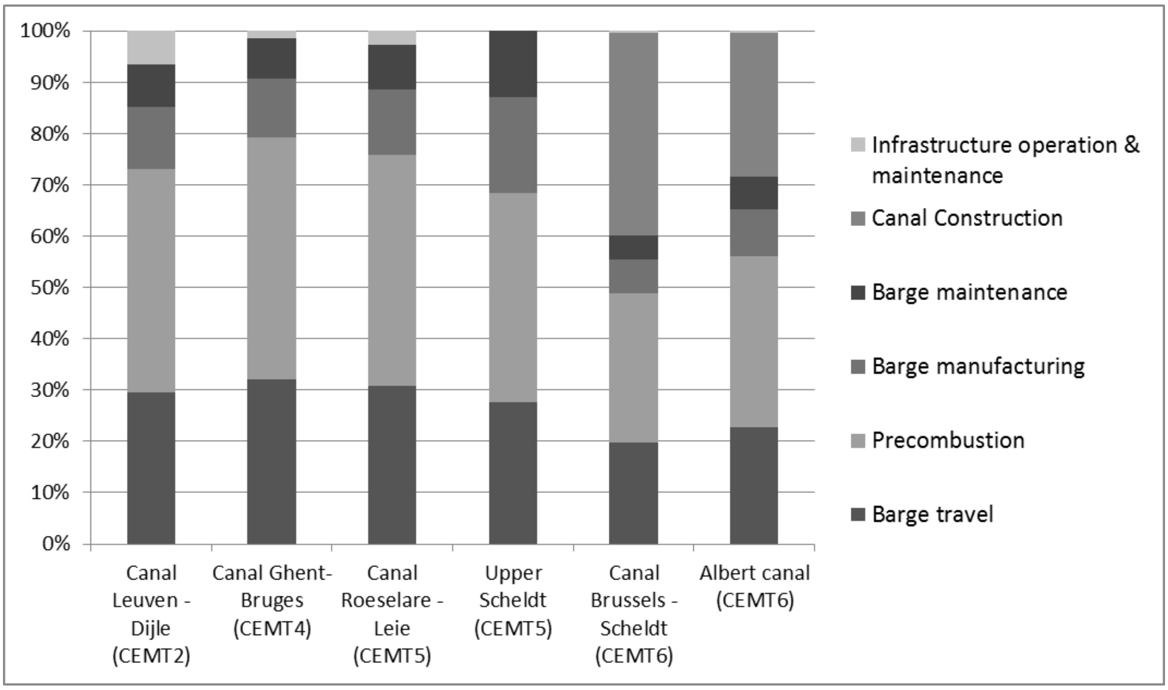

Figure 5 – Relative importance of transport service components for NH_3 on different waterways using loaded M4 type barge (tonkilometer basis)

Figure 6 repeats this comparison between waterways, but for CO_2. Similar conclusions can be drawn, but due to the larger share of barge operation related emissions, total emissions are comparable for the selected waterways and range between 4,03 gCO_2/tkm for canal Roeselare-Leie and 5,51 gCO_2/tkm for canal Brussels-Scheldt.

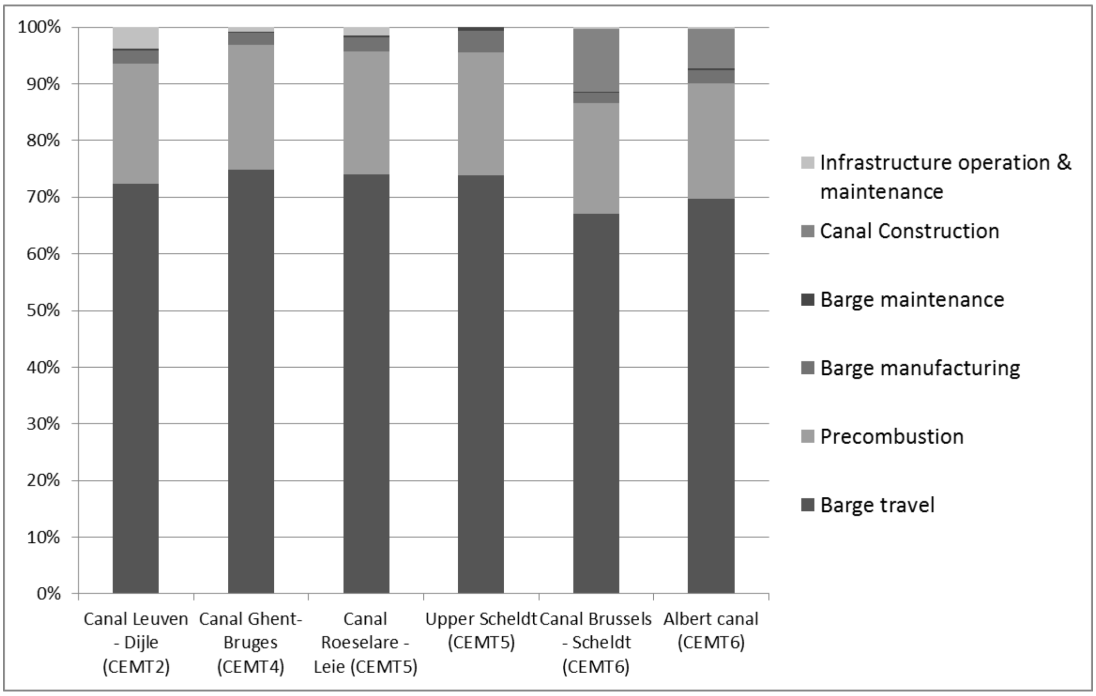

Figure 6 – Relative importance of transport service components for CO_2 on different waterways using loaded M4 type barge (tonkilometer basis)

6. CONCLUSIONS

This paper applied an LCA based methodology in order to determine the relative share of different transport service components (i.e. vehicle travel, precombustion, vehicle construction, vehicle maintenance, infrastructure construction and infrastructure maintenance) on total cumulative emissions for barge transport. Taking into account these different components allows assessing the environmental sustainability of a transport service with regards to emissions in much more detail.

In this paper emission factors recalculated from outputs of the EMMOSS model were combined with ecoinvent data for the relevant processes, in order to map barge related emissions in Flanders for a range of pollutants. For most pollutants, vehicle operation related emissions remain the most important category, however for some of these pollutants (e.g. SO_2 and CH_4) precombustion related emissions were found to be more important than vehicle travel related emissions. For some pollutants (NH_3, TSP, VOS en NMVOS), barge fleet and waterway infrastructure related emissions play a relatively large role in the cumulative emissions. For most pollutants however this share is relatively modest (between 10% and 20% for CO_2, CO and PM_{10}) or even relatively small (below 10% for SO_2, NO_X and $PM_{2,5}$) for average conditions. But the analysis also showed that on a particular waterway, the relative share of the different components in pollutant emissions can vary significantly with barge type. In addition, for a particular barge type relative shares can vary strongly depending on the waterway considered (e.g. emissions related to canal construction are only relevant for more recently built artificial waterways). Drawing generalised conclusions on the relative shares of the different components and on the total level of emissions is therefore not straightforward.

In a next phase, the methodology could be improved by employing a more refined approach using specific data related to materials, transport and energy used in barge fleet and waterway infrastructure construction and maintenance, and applying the emission factors of the relevant ecoinvent subprocesses. This requires filling data gaps with regards to both barge and waterway infrastructure and maintenance data, and this per barge and waterway type. Also data on transport performance of barges over their lifetime per barge type would allow further refinement in calculations. In order to allow a comparison of the environmental sustainability of different transport options in specific cases, the methodology should also be applied to other transport modes as well.
It should be stressed that such an LCA based approach will become even more important in the future, since improvements in engine technology and emission lowering technologies will further reduce the relative importance of direct vehicle-travel related emissions compared to vehicle and infrastructure related emissions.

ACKNOWLEDGEMENT

The authors would like to thank Waterwegen en Zeekanaal NV for funding this research and making valuable comments, as well as the Flemish Environmental Agency (Vlaamse Milieu Maatschappij) for providing the necessary outputs of the EMMOSS model. Also the feedback from reviewers in the review track of the 2013 WCTR conference in Rio was greatly appreciated.

REFERENCES

ADEME, Voies Navigables de France, T&L Associés (2006). Etude sur le niveau de consommation de carburant des unités fluviales françaises. Efficacités énergétiques et émissions unitaires de CO2 du transport fluvial de marchandises [rapport final]. France

Bickel, P. and R. Friedrich (2005). ExternE. Externalities of Energy. methodology 2005 Update, European Commission, Luxembourg, 270 p.

Chester, M.V. and A. Horvath (2009). Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. 4, 8 pp.

De Ceuster, G., van Herbruggen, B., Ivanova, O., Carlier, K. Martino, A. and D. Fiorello (2007). Service contract for the further development and application of the transport and environmental TREMOVE model Lot 1 (Improvement of the data set and model structure) [final report]. Leuven: Transport & Mobility Leuven.

den Boer L.C., Otten, M. and H. van Essen (2011). STREAM International Freight 2011. Comparison of various transport modes on a EU scale with the STREAM database. Delft, The Netherlands: CE Delft.

De Vlieger, I., Cornelis, E., Joul, H. and L. Int Panis (2004). Milieuprestaties van de binnenvaart in Vlaanderen [eindrapport]. Flanders: VITO.

Eriksson, E., Magnus, B. and G. Lövgren (1996). Life cycle assessment of the road transport sector. SCI. Total Environ. 189/190, 69-76

European Committee for Standardization (2006a). Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006). Brussels: European Committee for Standardization.

European Committee for Standardization (2006b). Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006). Brussels: European Committee for Standardization.

European Commission (2011). White Paper: Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. Brussels, Belgium

Franckx, L., Vanhove, F. and H. Schoukens (2011). Lokale maatregelen voor emissiereductie van binnenvaartemissies: Finaal rapport. Brussels.

Frischknecht, R. (1998). Life Cycle Inventory Analysis for Decision-Making. Scope-dependent inventory system models and context-specific joint product allocation. Dissertation ETH Nr. 12599, Basel, Switzerland.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G. and M. Spielmann (2005). The ecoinvent database: Overview and Methodological Framework. Int.J.LCA 10 (1), 3-9

Hawkins, T. R., Singh, B., Majeau-Bettez, G. and A. H. Strømman (2012). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J. Ind. Ecol. doi: 10.1111/j.1530-9290.2012.00532.x

Institute for Environment and Sustainability (2010). ILCD Handbook. General guide for Life Cycle Assessment – Detailed guidance. First edition. European Commission - Joint research Centre, Ispra, Italy.

Knörr, W., Seum, S., Schmied, M., Kutzner, F and R. Anthes (2010). EcoTransIT: Ecological transport information tool for worldwide transports. Environmental methodology and data. Duitsland: IFEU Heidelberg.

Lindhjem, C. E. (2004). LADCO nonroad emission inventory project for locomotive, commercial marine, and recreational marine emission sources. Novato, California: ENVIRON.

Maibach, M., Schreyer, C., Sutter D., Van Essen H.P., Boon, B.H.,Smokers, R., Schroten, A., Doll, C., Pawlowska, B. and M. Bak, 2008. Handbook on Estimation of External Cost in the Transport Sector. Internalisation Measures and Policies for All external Cost of Transport (IMPACT), Version 1.1., European Commission DG TREN, Delft, CE, The Netherlands.

Ministerie van Verkeer en Waterstaat (2003). Emissieregistratie en –Monitoring Scheepvaart (EMS), Deel I protocollen.

Pettersen J, Bergsdal H, Hung C and C. Solli (2011). Life cycle management in transport planning: infrastructure development and operation of high-speed rail in Norway. Paper presented at the 2011 LCM Conference in Berlin, Germany, 28-31 August.

Rozycki, C., H. Koeser, and H. Schwarz, Ecology Profile of the German High-speed Rail Passenger Transport System, ICE. *Int J Life Cycle Assess* 8, 2, 2003, 83-91.

Schilperoord, H. A. (2004). Binnenvaart voortdurend duurzaam [final report]. Royal Haskoning.

Schmidtchen, D., Koboldt, C., Helstroffer, J., Will, B., Haas, G. and S. Witte (2009). Transport, Welfare and Externalities. Replacing the Polluter Pays Principle with the Cheapest Cost Avoider Principle. Edward Elgar, Cheltenham, UK

Schreyer, C., Schneider C., Maibach, M., Rothengatter, W., Doll, C. and D. Schmedding (2004). External costs of transport. Update study [final report]. Zurich: INFRAS.

Spielmann, M. and R.W. Scholz (2004). Life cycle inventories of transport services. Zurich: Swiss Federal Institute of Technology Zurich.

Spielmann, M. and Scholz, R.W. (2005). Services - Life cycle inventories of transport services: background data for freight transport. Int. J. LCA, 10 (1), 85-94

Spielmann, M., Bauer, C., Dones, R., Scherrer, P., and M. Tuchshmid (2007). Transport Services. Ecoinvent report No. 14. Villigen/Uster: Swiss Centre for Life Cycle Inventories.

Tuchschmid, M. (2009). Carbon Footprint of High-Speed railway infrastructure (Pre-Study) - Methodology and application of High Speed railway operation of European Railways. Zurich: The International Union of Railways (UIC).

Van Mierlo, J., Boureima, F.-S., Messagie, M., Sergeant, N., Govaerts, L., Denys, T., Michiels, H., Vernaillen, S., Schrooten, L., Beckx, C., Macharis, C., Turcksin, L., Bernardini, A., Hecq, W., Klopfert, F., Englert, M., De Caevel, B. and M. De Vos (2011). Clean Vehicle Research: LCA and Policy measures (CLEVER), Final report of the project funded by the Belgian Science Policy

Vanherle, K., Van Zeebroeck, B. and J. Hulskotte (2007). Emissiemodel voor spoorverkeer en scheepvaart in Vlaanderen: EMMOS. Leuven: Transport & Mobility Leuven, Belgium