LCA IN TRANSPORTATION

LCA of land-based freight transportation: facilitating practical application and including accidents in LCIA

Nikolaus Fries · Stefanie Hellweg

Abstract

Purpose A major task concerning the greening of freight transportation is to influence the process of choosing an appropriate transport solution for a shipment. This paper presents the results of a detailed environmental benchmark study of freight transport chains recorded during a shipper survey administered in Switzerland in 2008.

Materials and methods For the environmental evaluation, life cycle assessment was applied and enhanced with a new method for integrating damage to human health caused by traffic accidents based on the disability adjusted life year concept.

Results and discussion The results show that in land-based transport, road generally has a lower environmental performance compared to intermodal and rail-only transport. Exceptions exist, e.g. for long pre- and post-haulage distances in intermodal transport or for very low train-load factors. The most relevant environmental interventions to pay attention to are, according to the methods applied, emissions of CO_2, NO_x and particulates as well as accident damages.

Conclusions Rail transport is often, but not always, environmentally preferable than truck transport. Accident damages to human health should be included in each benchmark study. For practical application, a simplified benchmark methodology is proposed requiring a reduced level of detail for the input data.

Keywords Accidents · Freight transport · Intermodal · Rail · Truck transport

N. Fries (✉)
ETH Zurich, Institute for Transport Planning and Systems (IVT), Wolfgang-Pauli-Strasse 15, 8093 Zurich, Switzerland
e-mail: nfries@web.de

S. Hellweg
ETH Zurich, Institute of Environmental Engineering (IfU), Schafmattstr. 32, 8093 Zürich, Switzerland

N. Fries
ETH Zurich, Institute for Transport Planning and Systems (IVT), Karl-Marx-Str. 33, 68199 Mannheim, Germany

1 Introduction

The transport sector accounts for 32 % of today's total energy consumption in the EU and has become the second largest emitter of greenhouse gases (in 2009 responsible for 19 % of the EU's total annual volume). While all other sectors decreased their GHG emissions since 1990, emissions of the transportation sector grew by almost 30 % until today (European Commission 2009). Freight transport has been shown to contribute to more than 10 % of the greenhouse gas emissions in life cycle assessment (LCA) studies on goods consumption (Hawkins and Dente (2010). Therefore, the transport sector deserves special efforts to reduce overall greenhouse gas emissions and environmental impact.

Recent work in the field of freight transport LCA was published, e.g. by Facanha and Horvath (2006), focussing on environmental performance of different transport modes and the share of emissions from vehicle operation relative to system-wide emissions. In several countries including Switzerland, comprehensive models were developed for calculating external costs of transportation induced by different impact categories including, e.g. GHG emissions, noise and traffic accidents (Federal Office for Spatial Development ARE 2008; INFRAS 2007). Furthermore, software tools exist as a reference for freight transport environmental impacts, such as the free online tool

"EcoTransIT World" (IFEU Heidelberg 2011). Early work on comprehensive life-cycle inventories for various modes includes Frischknecht et al. (1996) and Maibach et al. (1999). Since then, data sources and methodology have been extended, updated and harmonised within the ecoinvent framework (Spielmann et al. 2007). A drawback of the latter data sources are rather simple modelling approaches; in road transport, for example, no difference is made between road categories (such as motorway, inter-urban, and inner-urban roads), although emission factors vary significantly depending on average speed and degree of congestion. For both rail and road transport, ecoinvent does not account for differences in topography between countries (e.g. flat, hilly or mountainous), although this has a considerable impact on energy consumption for train operation (Umweltforschung Heidelberg GmbH 2003). Such factors have been considered in studies about the fuel efficiency of freight transportation, but these either refer to a selection of corridors in a given region (Barth and Tadi 1996), or they focus on fuel use and do not account for environmental impacts from emissions of particles and NOx, for example (ICF 2009). Furthermore, while accidents have been shown to be relevant in the assessment of external costs of transportation (Federal Office for Spatial Development ARE 2008), they were not included in LCAs of freight transport so far.

Although the choice of an appropriate transport mode for a shipment of goods is rather important concerning the greening of freight transport, it is often not taken into account by decision makers. Interestingly, transport mode choice is not always based on logical decisions; often road transport is chosen because the manufacturing company (the "shipper") does not have the necessary information to compare with alternative modes (Barth and Tadi 1996). Therefore, innovative approaches must be applied to include environmental criteria in shippers' transport mode choice. One possibility is to provide shippers with standardised information on the environmental impact of their shipments. If such information were integrated in every offer for freight transport services, as for example promoted by the Green Freight Europe initiative (Green Freight Europe 2013), shippers would be able to evaluate them not only based on economic and quality criteria but also from an environmental perspective.

Three basic questions to answer in this context are as follows:

1. How large is the potential for environmental impact reduction when choosing an alternative transport mode?
2. Which environmental interventions are most relevant? In particular, is there a need to include traffic accidents in the assessments, which have so far been neglected in LCA studies?
3. What level of detail is needed in modelling and reporting information on environmental impact and reduction potential?

This paper focuses on these questions. It presents the setup and results of an environmental benchmark of real freight transport chains recorded during a shipper survey administered in Switzerland in 2008 (Fries et al. 2010). The goal of the benchmark was to evaluate the environmental performance of different transport modes on a given land transport connection. For the environmental assessment, the LCA approach was applied and enhanced with detailed data to avoid the abovementioned simplifications in the existing data sources. Furthermore, a new method was developed for integrating damage to human health caused by traffic accidents based on the disability adjusted life year (DALY) concept (Murray and Lopez 1996). The primary target users of the LCA results are logistics procurement managers of manufacturing companies, as they usually collect and compare offers from different service providers including also different transport mode alternatives (if appropriate from an economic and logistic process-related perspective). The background survey also included a willingness-to-pay study (Fries et al. 2010), which illustrated that in Switzerland decision makers have a general interest in good environmental performance of transport operations. In some cases, they are also willing to pay some additional (rather small) fee for it, if they can get access to quantitative environmental information. Further potential users are end-consumers as well as policy makers; the latter may provide regulatory frameworks and financial incentives to foster transport options with reduced environmental impact.

2 Methodology

2.1 Model description

The model employed for the environmental benchmark of freight transport chains bases on the principle of LCA. Transport chains are inventoried on the basis of unit processes. The transport modes relevant for land-based freight transport in Switzerland are road-only, rail-only wagonload and inter-modal transport road/rail.

Thirteen case studies from a shipper survey administered in the context of this project (Fries et al. 2010) were benchmarked. In the survey, a stated choice approach was followed with a total of 198 computer-assisted interviews. Only "transferable" transports were included in the survey, i.e. transport chains that realistically qualify for different transport modes considering for economic and logistic constraints. All realistic transport modes were put into direct comparison, since they are each specific in terms of price and service characteristics. In the current paper, we used a sub-selection of transport chains from this survey to analyse quantitatively the environmental impact of various transport options. The selection of case studies was based on the following criteria: (1) All relevant market sectors (domestic, import and export) should be represented, (2) if

possible, rail-only transport should also be a realistic alternative, (3) shipment sizes should be comparable (full truckload size due to the transferability requirement) and (4) the range of transport distances should be as wide as possible. The final selection embraced five transport chains within Switzerland and four each in import and export, respectively.

The calculations were based on the following basic assumptions:

- Road transport: 40 t lorry, emission class Euro 5
- Rail transport: 500 or 1,000 t train (depending on connection)
- Intermodal transport: assumptions same as for road and rail transport, respectively

The routing for each transport mode was made based on different data sources as follows: for road transport, the online routing planner "ViaMichelin" was used; the main haulage connection for intermodal transport was determined using the "SPIN-ALP Planner" (ETH Zurich 2009), while for rail-only transport, no dedicated routing tool exists. Instead, assumptions about train routing are based on standard operation processes of the national and international "hub-and-spoke" systems of rail wagonload transport (Wichser 2010).

"ViaMichelin" is a free online routing planner comparable to "Google Maps" and provides a routing algorithm with selectable optimisation criteria. The routing in this case was done based on the minimum travel time criterion. The "SPIN-ALP Planner" is a routing information tool for European intermodal transport based on a database of train connections offered by all relevant intermodal operators. The route calculation depends primarily on available train connections between two terminals in the proximity of a chosen origin and destination location. Also non-direct connections via a hub terminal are considered. The tool calculates the fastest road connection between the points of origin or destination and the adjacent terminals. For the train connection between these terminals, travel distance and scheduled travel time are given.

The functional unit for comparing different transport modes was the shipment of a given freight load from an origin to a destination. Calculations are on a shipment basis with net shipment weight in tonnes and door-to-door distance in kilometres.

2.2 Life cycle inventory of road transport

The most relevant source for road transport emission data in Switzerland, Germany and Austria is the Handbook of Emission Factors (HBEFA) (INFRAS, IFEU, TU Graz, RWTÜV 2010): a database of highly disaggregate emission data on the operation of road vehicles, which originate from test series. For these test series, different real traffic scenarios (e.g. free flowing motorway traffic or dense intra-urban traffic) with different vehicle types were simulated. Data on

evaporative and cold start emission for heavy goods vehicles are not provided by HBEFA and are therefore not included in the model.

In this project, data from version 3.1 for the vehicle category "LZ/SZ >34-40 t Euro-V SCR" (articulated trucks of the European emission category Euro 5 with a maximum total weight of over 34 t) was used. HBEFA differs between three load factors for a truck as follows: "empty", "average" and "loaded". Since the "average" load factor comprises also the empty run data, and since all case studies were trips with an average net shipment weight of 18 t (equalling a load factor of ca. 0.75), the emission factors for an "average" truck were applied. The route used by the truck was split into several sections according to the type of road (e.g. motorway, inner-urban road, etc.). The corresponding emission data, which is provided in HBEFA on a vehicle–kilometre basis, was then multiplied by the length of each section. The results of all sections were then summed up to calculate the overall energy consumption and emissions (CO, CO_2, HC, CH_4, NMHC, NO_x, N_2O, NH_3, Pb and PM10) of the particular shipment.

Since HBEFA covers only the operation process, emissions and resource uses of the supply chain and infrastructure were considered adding the following unit processes from the ecoinvent v2.2 database (Swiss Centre for Life Cycle Inventories (2013) (ecoinvent process names in brackets):

- Fuel production ("diesel, at regional storage/CH U")
- Vehicle production ("lorry 40 t/RER/I U")
- Vehicle maintenance ("maintenance, lorry 40 t/CH/I U")
- Road construction ("road/CH/I U") and
- Road maintenance ("operation, maintenance and road/CH/I U")

2.3 Life cycle inventory of rail transport

For rail-based transport processes (in rail-only and intermodal transport), emissions per tkm depend (a) on topographical conditions and (b) on whether it is a main haulage or shunting process (due to the use of electric or diesel traction). Energy consumption was calculated based on the empirically determined equations of the online calculation tool "EcoTransIT World", differentiating firstly between electric and diesel traction, and secondly between "flat", "hilly" and "mountainous" territory (IFEU Heidelberg 2011):

$$EC = \alpha^* GW^{-0.5}/LF \qquad (1)$$

Where

EC is energy consumption (watts per tonne per kilometre (electric traction) or grams per tonne per kilometre (diesel traction))

α is dimensionless parameter

GW is gross weight of train (tonnes)

LF is load factor (ratio of net weight to gross weight)

Concerning electric traction, the parameter α equals 810, 675 and 540 for mountainous, hilly and flat territory, respectively. For diesel traction, it is equal to 184, 153 and 122 for mountainous, hilly and flat territory, respectively (IFEU Heidelberg 2011).

We assumed that for rail main haulage in Switzerland (including border-crossing traffic), electric traction is used, while diesel traction is relevant only for shunting operations. Therefore, direct emissions from main haulage are limited to particulate emissions due to abrasion, for which Spielmann et al. report a specific emissions factor of 0.0163 g/tkm (PM10).

For the train load factor, an average value of 0.5 was assumed. This assumption is based on the classification used in "EcoTransIT World", which differs between volume (load factor 0.3), average (load factor 0.5) and heavy goods (load factor 1.0). With all products shipped in the analysed case studies being packaged goods (i.e. no bulk or liquid/gaseous shipments), all transports can be classified as average goods.

All further emissions are related to energy production and other background processes, the data for which was taken from ecoinvent v2.2. Relevant unit processes for rail transport in Switzerland are (ecoinvent process names in brackets) as follows:

- Electricity production ("electricity, high voltage, SBB, at grid/CH U")
- Diesel production ("diesel, at regional storage/CH U")
- Locomotive production and maintenance ("locomotive/RER/I U")
- Production of goods wagon ("goods wagon/RER/I U")
- Maintenance of goods wagon ("maintenance, goods wagon/RER/I U")
- Track construction ("railway track/CH/I U")
- Track operation/maintenance ("operation, maintenance, railway track/CH/I U")
- Disposal of track ("disposal, railway track/CH/I U")

Since emission data on energy production varies significantly between different countries, for international transport chains, the sections outside Switzerland were evaluated separately using the following unit processes:

- "Electricity, high voltage, production UCTE, at grid/UCTE U"
- "Diesel, at regional storage/RER U"

For diesel-powered shunting operations, direct emissions of the combustion process must be added. The applied values are listed in Table 1 of the Electronic supplementary material.

2.4 Life cycle inventory of intermodal transport

For intermodal transport chains, each part of the chain is calculated separately using the data of the according transport mode (i.e. main haulage by rail, pre- and post-haulage by road) before summing up the results. Energy consumption of the transhipment process between road and rail was assumed to be 4.4 kWh electricity per transhipment process (IFEU 2011).

2.5 Life cycle impact assessment and integration of traffic accident damages

The "ReCiPe 2008" method (Goedkoop et al. 2009) was applied in the impact assessment for all impact categories contributing to human health and ecosystem health damages. This method includes a variety of impacts, e.g. climate change, acidification, eutrophication, ionising radiation, human toxicity and ecotoxicity. This was important in this study, as traffic emissions are known to contribute to all these impacts. However, it should be noted that risks are not assessed in LCA so far, which may be debatable, e.g. for nuclear power generation and may cause a bias when electric-driven transport systems are compared to fossil fuel-driven ones, as done here. For the assessment of resources, we did not use the "resources cost" endpoint factor of the ReCiPe method because we were not able to fully comprehend some of the assumptions taken in ReCiPe. For example, (a) the assumption of a positive discount rate and (b) the assumption of static exploitation technologies (i.e. not taking into account future technological development). Resource consumption was instead accounted for by calculating the non-renewable (nuclear and fossil) cumulative energy demand (CED) of a transport according to the method of Jungbluth and Frischknecht (2004). This method has been shown to strongly correlate with the abiotic resource depletion category of the CML method (Guinée 2002) for transport processes (Petterson and Hertwich 2008). In a sensitivity assessment (supplementary material page 2), we also assessed the CED.

Accidents with an impact on human health are relevant in several industrial production processes and especially in road transportation (European Commission 2012). So far, none of the common LCIA methods include accident damages as an impact category, and literature sources in this context are scarce. We therefore extended the ReCiPe method by a corresponding impact category, which contributes to the "human health" endpoint factor. For this purpose, the approach of Petterson and Hertwich (2008) in the field of work safety on oil and gas rigs was adapted for application in the Swiss freight transport sector.

This approach comes from a generic cause–consequence model as proposed, e.g. by Udo de Haes HA and Lindeijer (2002). For the application to traffic accident analysis, this cause–consequence chain can be rewritten as follows:

"Vehicle movement"→"Accident"→"Injury event"→"Gravity of injury"→(DALY)

The number of damaged persons of injury type i was calculated as follows:

$$V_{i,GV,j} = V_{i,j}{}^*A_{GV,j}/A_j \qquad (2)$$

Where

$V_{i,GVj}$ is the number of damaged persons of injury type i from accidents caused by goods vehicles of transport mode j

$V_{i,j}$ is the total number of damaged persons of injury type i

$A_{GV,j}$ is the number of accidents caused/impacted by goods vehicles

A_j is the total number of accidents per year for transport mode j

i (minor injuries; major injuries; fatalities)

j is the index for transport mode (rail; road)

In order to apply this method to freight transport processes, detailed statistical data on traffic accidents was needed. While in most European countries figures for injuries and fatalities from traffic accidents are published, the main challenge in this context laid in identifying in general accident statistics only such accidents, which were actually caused by freight transport vehicles. Freight transport operation cannot account for damage from accidents, in which freight transport vehicles were only passively involved. For road traffic, the Swiss Statistics online database "Superweb" (Swiss Federal Statistical 2013) provides data on (a) the yearly total number of accidents in Switzerland (A_{road}), (b) the number of accidents caused by goods vehicles (all classes included, i.e. heavy goods vehicles and light goods vehicles below 3.5 t) ($A_{GV,raod}$) and (c) the number of damaged persons per year differing between minor and major injuries and fatalities ($V_{i,road}$). For this analysis, averaged values for the period between 1992 and 2007 were extracted.

For rail traffic, a similar database was not available. Instead, for the reference year 2005, comparable data was used as reported by ARE and BAFU (Federal Office for Spatial Development ARE 2008). This source also reports the number of injured or killed persons plus the responsible party for each accident. Therefore, in analogy to the approach for road transport, accidents, in which freight trains were only passively involved (e.g. a car passing a closed railway crossing), were not counted. Therefore, the only chargeable ones were mostly accidents during manoeuvres in shunting yards or rail sidings with damage to shunting operators. In total, 1 killed and 35 injured persons were counted, of which 25 suffered from minor and 10 persons from major injuries.

In order to translate these results to the human health endpoint category of the ReCiPe method, the number of damaged persons per category from Eq. 2 must be weighted

with weight and duration of the according health damage type as follows:

$$DV_{i,j} = (V_{i,GVj}/V_{t,GV,j}){}^*d_i{}^*w_i \qquad (3)$$

Where

$DV_{i,j}$ is the DALY per damaged person from transport mode j for damage of type i

$V_{t,GVj}$ is the yearly total of damaged persons from accidents caused by goods vehicles

d_i is the duration of damage of type i (years)

w_i is the weight of damage of type i (−)

The sum of all $DV_{i,j}$ represents the average damage to human health per damaged person.

As proposed by Petterson and Hertwich (2008), weight and duration for injuries were taken from Murray and Lopez (1996); for major injuries values for the category "short-term intracranial injuries" were used; for minor injuries, the ones for "open wounds" were applied. By definition of the DALY unit, the corresponding weight for fatalities equals 1. This value is calculated from its lifespan at birth minus average age as follows:

$$d_{fatality,j} = a - l_j \qquad (4)$$

Where

$d_{fatality}$ is the years of life lost due to fatal accident

a is the lifespan at birth of the Swiss residential population

l_j is the average age of the accident victims for transport mode j

Note that using the expected lifespan at birth (81.3 years) in Eq. 4 represents a simplification, since the expected lifetime is conditional to the age, at which the accident occurs. For instance, a 90-year-old person still has a positive life expectancy, although having exceeded the expected lifespan. However, a more precise calculation is difficult because more detailed data would be required on the age of all accident victims.

The value for duration in road traffic ($d_{fatality,road}$) is the average remaining lifetime of the Swiss residential population. Since victims of accidents in rail freight traffic are mainly employees of railway companies, we replaced the average age of the Swiss residential population (l_{road}=40.6 years) by the average age of the Swiss working population (l_{rail}=39.8 years). An overview of parameters and the results from the damage assessment calculation are given in Table 1.

Since the statistical data represents average values for the entire Swiss road and rail network, the damage was related to 1 tkm (and later for the benchmark multiplied

Table 1 DALY for damages to human health from traffic accidents in Switzerland (variables refer to notations in Eq. 2 to 4)

j	TP_{GVj} [tkm/a]	A_j [1/a]	A_{GVj} [1/a]	$V_{t,j}$ [1/a]	V_{ij} [1/a]	i	$V_{i,GVj}$ [1/a]	$V_{i,GVj}/V_{t,j}$ [-]	d_i [a]	w_i [-]	$DV_{i,j}$ [DALY/victim]	D_j [DALY/tkm]
Road	1.58E+10	22'800	1'550	1'850	21'700	Minor injuries	1'470	0.795	0.024	0.108	2.06E-03	2.41E-10
					5060	Major injuries	344	0.186	0.067	0.359	4.47E-03	5.23E-10
					409	Fatality	28	0.015	40.7	1.00	0.616	7.20E-08
										Σ	0.623	7.27E-08
Rail	1.17E+10	n/a	12	36	n/a	Minor injuries	25	0.694	0.024	0.108	1.80E-03	5.55E-12
					n/a	Major injuries	10	0.278	0.067	0.359	6.68E-03	2.06E-11
					n/a	Fatality	1	0.028	41.5	1.00	1.15	3.55E-09
										Σ	1.161	3.58E-09

by distance and shipment size of each transport sample). The conversion to tkm was performed as follows:

$$D_j = \sum_i \left(DV_{i,j} * V_{t,GV,j} / TP_{GV,j} \right) \tag{5}$$

Where

D_j is the DALY per tkm and transport mode j
$TP_{GV,j}$ is the yearly freight transport performance in Switzerland per mode, measured in tkm

3 Benchmark results

3.1 Environmental improvement potential for the analysed transport chains

The benchmark results are summarised in Table 2. Data for rail-only transport is missing, if it is not a realistic option (e.g. due to infrastructure restrictions). For all categories, percentage values were added to analyse the gain or loss of environmental performance relative to the status quo transport mode.

For 9 of the 13 transport chains, significant environmental improvements could be achieved by changing the transport mode. In five cases, the impact score for the categories human health, ecosystem health and non-renewable energy demand could be more than halved. For all except one, transport (independent of sector and distance) road has the lowest environmental performance across all three endpoint categories, followed by intermodal transport and rail-only transport. However, some exceptions exist. The differences between road and intermodal transport depend mainly on the margin between actual transport distances of the two modes, i.e. the distance in intermodal transport may be much longer than the direct route taken by the lorry, if origin and/or destination are located far from the nearest suitable terminal (the suitability of a terminal depends on its available train connections).

Rail-only transport (if applicable) had the best environmental performance in the case studies investigated (or at least equal to intermodal transport) because it avoids long pre- and post-haulage by road and can normally take more direct routes than intermodal transport. However, also in wagonload transport (which was assumed for this benchmark—in contrast to block trains on point-to-point connections), detours cannot be completely avoided because of the hub and spokes networks using central classification yards to establish connections between different trains (Wichser 2010). Such longer transport distances in rail transport are reflected in the figures on energy consumption, which in such cases is comparable to the other modes (e.g. in the Givisiez–Regensdorf example). The impact of
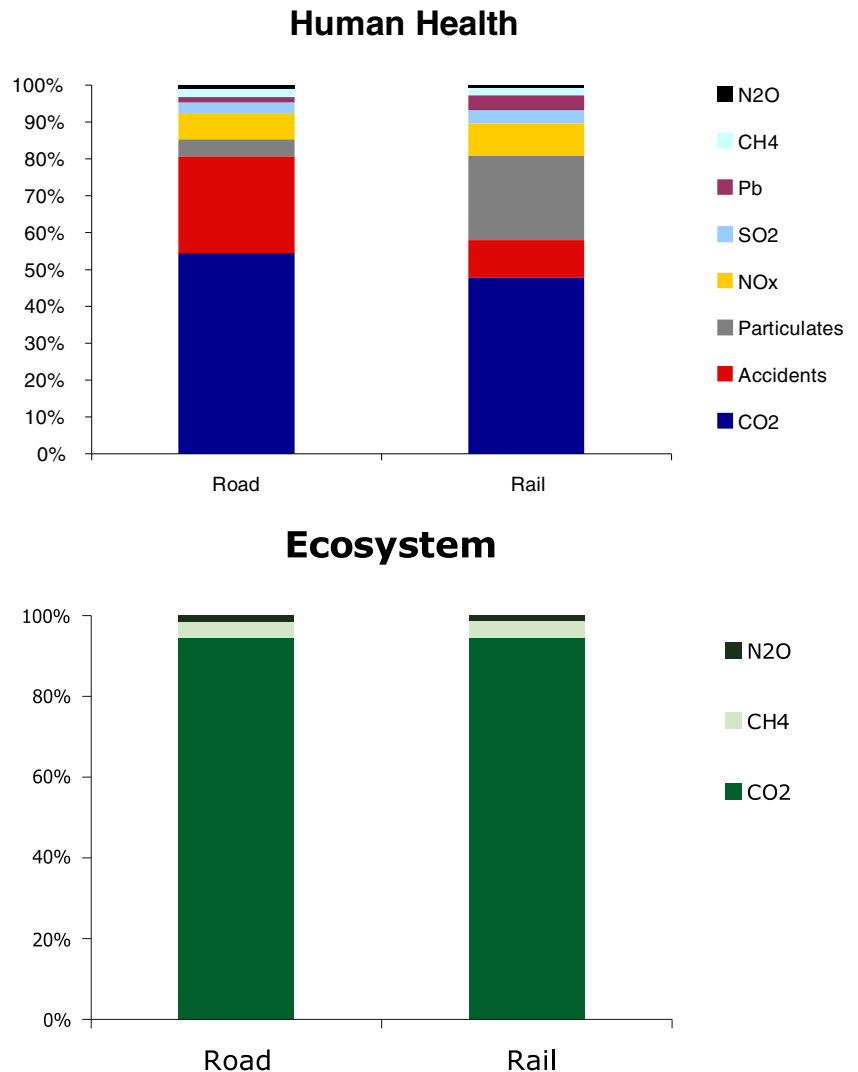
Table 2 Environmental impact per category per sample shipment with specified weight and transport distance

Origin/destination	Net shipment size	Transport model	distance		Human health	Impact difference relative to status Quo	Ecosystem	Impact difference relative to status Quo	Cumulative energy demand non-renewable	Impact difference relative to status Quo
	[t]		[km]		[DALY]		[species/a]		[MJ]	
Altstetten SG (CH) - Basel (CH)	20	Road	207		8.72E-04	100 %	2.96E-06	100 %	8.28E+03	100 %
		Intermodal	225		2.88E-04	33 %	9.42E-07	32 %	3.07E+03	37 %
Neuenegg (CH) - Wangen b. Olten (CH)	16.5	Road	77		2.89E-04	100 %	2.96E-06	100 %	2.73E+03	100 %
		Rail	182		1.30E-04	45 %	4.19E-07	41 %	1.38E+03	50 %
		Intermodal	152		2.05E-04	71 %	7.90E-07	78 %	2.35E+03	86 %
Bruttisellen (CH) - Luzern (CH)	15.4	Road	71		2.55E-04	100 %	9.12E-07	100 %	2.40E+03	100 %
		Intermodal	92		1.92E-04	75 %	6.69E-07	73 %	1.79E+03	74 %
Givisiez (CH) - Regensdorf (CH)	25	Road	151		7.42E-04	100 %	2.41E-06	100 %	7.08E+03	100 %
		Rail	302		2.62E-04	35 %	8.22E-07	34 %	2.69E+03	38 %
		Intermodal	221		3.36E-04	45 %	1.08E-06	45 %	2.56E+03	36 %
Stabio (CH) - Neuendorf (CH)	15	Road	246		8.65E-04	328 %	3.11E-06	351 %	8.17E+03	266 %
		Rail	312		1.67E-04	63 %	5.27E-07	59 %	2.18E+03	71 %
		Intermodal	294		2.64E-04	100 %	8.87E-07	100 %	3.07E+03	100 %
Rorschach (CH) - Zutphen (NL)	22	Road	723		3.24E-03	100 %	1.08E-05	100 %	3.08E+04	100 %
		Rail	922		1.26E-03	39 %	5.10E-06	47 %	1.16E+04	38 %
		Intermodal	1454		2.69E-03	83 %	1.06E-05	98 %	2.48E+04	80 %
Visp (CH) - Frankfurt/Main (DE)	16	Road	617		2.25E-03	100 %	8.00E-06	100 %	2.13E+04	100 %
		Rail	530		4.75E-04	21 %	1.87E-06	23 %	4.44E+03	21 %
		Intermodal	848		1.40E-03	62 %	5.08E-06	64 %	1.35E+04	63 %
Monthey (CH) - Rotterdam Waalhaven (NL)	20	Road	932		3.93E-03	335 %	1.34E-05	285 %	3.73E+04	343 %
		Rail	989		1.17E-03	100 %	4.69E-06	100 %	1.09E+04	100 %
		Intermodal	1032		2.01E-03	171 %	7.55E-06	161 %	1.87E+04	172 %
Basel (CH) - Rotterdam Waalhaven (NL)	18	Road	732		2.88E-03	323 %	1.00E-05	270 %	2.73E+04	335 %
		Rail	737		9.13E-04	102 %	3.79E-06	102 %	8.26E+03	101 %
		Intermodal	726		8.93E-04	100 %	3.72E-06	100 %	8.16E+03	100 %
Rotterdam Waalhaven (NL) - Basel (CH)	11	Road	730		2.17E-03	100 %	8.32E-06	100 %	2.03E+04	100 %
		Intermodal	735		5.72E-04	26 %	2.37E-06	29 %	5.24E+03	26 %
Antwerpen (BE) - Zurich (CH)	18	Road	684		2.70E-03	161 %	9.35E-06	146 %	2.55E+04	164 %
		Rail	740		8.78E-04	52 %	3.58E-06	56 %	7.96E+03	51 %
		Intermodal	902		1.68E-03	100 %	6.39E-06	100 %	1.56E+04	100 %
Nancy (FR) - Landquart (CH)	20	Road	403		1.69E-03	100 %	5.68E-06	100 %	1.60E+04	100 %
		Intermodal	697		3.88E-03	230 %	6.25E-06	110 %	1.82E+04	114 %
Trier (DE) - Dagmersellen (CH)	18.5	Road	388		1.55E-03	269 %	5.32E-06	228 %	1.46E+04	287 %
		Rail	451		5.76E-04	100 %	2.33E-06	100 %	5.09E+03	100 %
		Intermodal	724		1.51E-03	262 %	5.67E-06	243 %	1.41E+04	276 %

detours on human health and ecosystems, however, is low because in Switzerland and many other European countries, mainly electric traction is used. Since (at least in Switzerland) electric energy is produced mainly from water and nuclear power, emissions to air and soil are much lower than the ones of lorry operation (even if the transport distance is shorter). The same can be said about accident damage; no significant impact on human health can be observed for increased distances due to its lower overall relevance for rail transport.

In the Basel–Rotterdam example, environmental performances of rail-only and intermodal transport are almost the same because both origin and destination are located in direct proximity of two transhipment terminals, between which a direct train connection exists. In this context, we underline that conditions for intermodal transport are generally good in case of seaport connections because either origin or destination are necessarily located directly at a container terminal, which is almost always accessible also by rail. This avoids the pre- or post-haulage leg of the transport chain.

3.2 Relevant environmental interventions

The question of which data is most relevant for practitioners is of particular interest concerning the communication of information on freight transport environmental performance to shippers. One possibility would be to use the endpoint categories of the ReCiPe method, but since these values are rather abstract and hence not easy to understand by practitioners, the direct use of the most relevant environmental interventions might be a more suitable alternative. This would also help to better understand the environmental impact and, if possible, mitigate directly the environmental intervention of concern.

In order to identify these environmental interventions, the ones with a share above 1 % in at least one of the human health and ecosystems endpoints are illustrated in Fig. 1 for the Stabio–Neuendorf example, which is representative also for the remaining case studies in terms of relevant environmental interventions. Note that in this context, the cumulative energy demand could be considered as a separate indicator for

Fig. 1 Contribution of environmental interventions to the "human health" and "ecosystem" endpoints (case study of Stabio–Neuendorf transport chain)

communication purposes. With respect to the "human health" endpoint, there is a significant difference between road and rail; while in rail transport, the share of damage from accidents (measured in DALY) is of comparable relevance as the impact of NO_x emissions (10 %); in road transport, this share is between 23 and 31 % of the total damage to human health for the analysed case studies. On the other hand, in rail transport, particle emissions reach a share of 23 % in the Stabio–Neuendorf example, compared to only 5 % in road transport (although in absolute numbers, values for road and rail are quasi-identical). Concerning the remaining emissions, differences are less significant, with a maximum of 6 % points between road and rail.

Interestingly, the share of CO_2 emissions is rather similar for both transport modes and both endpoints; for "human health", it is about 50 %, while reaching ca. 95 % in the case of the "ecosystem" endpoint. Obviously, only four environmental interventions represent 90 % and more of the overall environmental impact; these are CO_2, NO_x, particles and accident damages. These four interventions (plus energy consumption) might, therefore, be directly used for communication, instead or as an additional explanation of the aggregated endpoint values.

3.3 Comparison with simplified modelling approaches

For broader LCA applications (which are not focusing on transportation processes), it would be quite complicated to calculate freight transport processes with the same level of detail as in this project. In fact, most existing LCA studies calculate with fixed average emissions per tkm, without further differentiation. The ecoinvent database, for example, reports freight transport inventory data per tkm, without adapting load factor, topography or type of road used to the specific conditions of the transport chain assessed (Spielmann et al. 2007) (although calculation tools exist allowing the user to define load factors, e.g. the abovementioned "EcoTransIT World"). To test which level of detail is needed to provide reliable decision support, the model was reduced to only one road type, i.e. motorway (HBEFA category "Agglo/AB-Nat./

100/dicht"), since in the case of medium- and long-distance transports, motorways are used for most of the trip. Furthermore, the same transport was benchmarked using the averaged values from ecoinvent v2.2 and results for all transport modes compared to the original benchmark results. The percentage values listed in Table 3 are the average biases of the according model against the values of the detailed benchmark model (Table 2) over all benchmarked case studies. The maximum bias is given in brackets. Accident data is missing because our data could not be differentiated between specific road types.

Basically, the main difference between these models lies in the operational data, since the process data for all underlying processes (i.e. energy production, vehicles and infrastructure demand) is commonly based on the same ecoinvent v2.2 data.

The bias in operational energy demand and emissions, respectively, between the detailed and the "motorway" data does not exceed 4 %. This is because both models have their operational data drawn from the same HBEFA data source. Furthermore, since all case studies are medium- or long-distance transports, the detailed model uses the same HBEFA motorway categories for the largest part of the calculated total distance as the average "motorway" model. Therefore, the proposed simplification appears justified using average motorway data instead of the section-specific data.

The comparison with the ecoinvent results shows a larger bias. This is also due to the differences in energy demand and emissions from operation. Of all analysed transport modes, the general bias is lowest for road transport with a fairly good match for the energy demand and particles data (average bias of −13 and −1 %, respectively). The large differences for rail and intermodal NO_x emissions result from the fact that for operations outside Switzerland, ecoinvent assumes a fixed mix of electric and diesel rail traction, while direct emissions from electric operation, as assumed for the main haulage part in the detailed model, are zero (except for PM emissions from abrasion).

Furthermore, the assumptions of vehicle-load factors have a considerable impact; ecoinvent assumes load factors of about 0.4 (road transport) and 0.42 for rail, respectively. In the detailed model, we calculated with a load factor of 0.5 for

Table 3 Comparison of results according to data sources indicated in column "alternative data source" to the results of the detailed benchmark model applied in this research

Transport mode	Alternative data source	Energy demand [MJ]	CO_2 [kg]	NO_x [kg]	PM10 [kg]
Road	Motorway[1]	−1 % (+0 %)	−2 % (+0 %)	+1 % (+4 %)	+0 % (+0 %)
	Ecoinvent v2.2[2]	−13 % (−28 %)	+24 % (+48 %)	+45 % (+67 %)	−1 % (−8 %)
Rail	Ecoinvent v2.2	+22 % (+55 %)	+13 % (+20 %)	+95 % (+166 %)	−24 % (−34 %)
Intermodal	Ecoinvent v2.2	+6 % (+59 %)	+24 % (+84 %)	+87 % (+193 %)	−16 % (−26 %)

Percentage values are given as relative to the detailed benchmark model, i.e. "+" means a higher value than the detailed model, "−" a lower value

[1] Values of the benchmark model with average HBEFA data for motorways applied ("Agglo/AB-Nat./100/dicht") (INFRAS et al. 2010)

[2] Results of the same transport (distance and weight) calculated with ecoinvent v2.2 data; process for road: "transport, lorry >32 t, Euro5" process for rail: "transport, freight, rail/CH" and "transport, freight, rail/RER", depending on lane

both road and rail. In other words, the ecoinvent load factors are about 20 % lower. This explains the average difference of the CO_2 values between both models.

Since the assumed load factor is often a source of uncertainty in modelling results, this issue should be reviewed carefully in each application. If the load factor is not a selectable model input parameter, global average values of 0.4 for road and 0.42 for rail transport, respectively, appear reasonable, since average volume–weight ratio of the cargo and empty return trips must be accounted for. However, uncertainty can be reduced significantly, if (as in the case of this detailed model) the load factor is known.

3.4 Sensitivity analysis

A sensitivity analysis was carried out on certain input parameters, including transport distance and load factor. A comparison between door-to-door transport distance and energy demand of the three transport modes showed that rail and intermodal transport clearly performed better than road transport on long-distances, but were not necessarily more energy-efficient than direct road haulage for distances smaller than 100 km due to necessary detours. This conclusion for short distances is not significantly impacted by the assumed load factors. For longer distances, however, load factors have a clear impact on total energy consumption. The detailed results are provided in the Electronic supplementary material.

4 Discussion

4.1 Impact of transport mode choice

Our first research question was how large the potential for environmental impact reduction would be when choosing an alternative transport mode. Based on the environmental benchmark of the presented case studies, we conclude that in 9 of 13 cases, the improvement potential was very large. In six cases, the impact score could be more than halved simply by choosing another transport mode. Therefore, using these results in actual decision making could lead to a substantial impact reduction and should be a major concern for practitioners. Independent of sector and distance, road transport generally has the worst environmental performance across all three environmental endpoint indicators (human health, ecosystem and energy consumption), followed by intermodal transport and rail-only transport. This may be different though, if detours in rail and intermodal transport are particularly long, or if load factors in rail transport are low (see Electronic supplementary material). A case-specific evaluation remains, therefore, necessary.

4.2 Impact of traffic accidents on human health

The integration of damage from traffic accidents into the benchmark model had a significant impact on the results. Most important is the difference in magnitude between road and rail; for road traffic, it is the second largest contributor to the "human health" endpoint category with 26 %, while for rail, the impact share is at only 10 %. Even though there are uncertainties attached to the assessment of accidents, such as the broad classification of injury severity or the limited availability of rail accident data for only 1 year, this overall result is not likely to be significantly affected.

4.3 Methodology for assessing traffic accidents

The method shown here for the assessment of accidents allows for a direct integration into existing damage-based impact assessment methods, as illustrated for the ReCiPe method. Since accident data on background processes was missing, the analysis could not be performed over the whole life cycle of transport chains. Other studies (Burgherr and Hirschberg 2008; Hirschberg et al. 2004) have investigated accidents of energy systems for various geographical regions. Such data could be used in future work to complement the analysis and quantify the importance of accidents also in other sectors. In spite of the data gaps, the relevancy of accident data in traffic operations could clearly be demonstrated.

Another point to mention is the limited availability of statistical data on traffic accidents caused by freight transport activities. Although the DALY values listed in Table 1 are calculated based on data from Switzerland, they were applied to all benchmarked case studies including also trans-border transport chains. Comparable data from all countries involved would be required for a more precise estimation of accident damages, but especially road transport data at a comparable level of detail seems not to be publicly available for EU countries. However, since the number of road accidents in Switzerland are comparable to the one in the EU25 (0.0029 vs. 0.0028 accidents with personal injuries per inhabitant (Udo de Haes HA and Lindeijer 2002)), the bias introduced by the extrapolation from Swiss data to other countries is expected to be small.

The choice to include only accidents, in which rail or truck vehicles were at fault, can be debated. For example, Vickery (1968) and Forkenbrock (2001) argue that all accidents need to be taken into consideration for external cost accounting, independent of guilt. However, within LCA, such a procedure would lead to double counting. For example, if a freight train collides with a truck, double counting would result if all accidents were taken into consideration for both modes of transport, while this is not the case with the approach taken in this paper. It is clear that some accidents will not be accounted for in LCA with this approach, for instance, if a

pedestrian crosses a street at red light and gets hit by a lorry, or if someone commits suicide on a railway line.

4.4 Level of detail of the benchmark model

The third research question focussed on the required level of detail for the benchmark model, since a complex calculation may represent an obstacle for their use in practise. In order to examine this question, a detailed analysis was performed, and the results were compared to certain simplifications. As evaluated above, simplification of the applied model by applying averaged emission factors is justified for more general LCA applications. For long-distance road transport with long motorway sections, we recommend the application of the average HBEFA emission factors for motorway traffic (INFRAS et al. 2010).

For rail transport, we consider the model described in Sect. 2 as applicable also for broader LCA applications, since unit processes are all calculated on a tonne–kilometre basis, which can be multiplied directly with shipment weight and transport distance per country involved (due to the country-specific topography factors). However, attention should be paid to shunting processes. Since in wagonload operation, each freight car is routed via one or several classification yards, the associated shunting processes should also be included in the calculation. In the investigated cases, shunting operations were on average responsible for 10 % of the human health impact score. In the model, each yard shunting process is represented by a movement of 5 km with diesel traction. As a guideline value for national transports in smaller countries, such as Switzerland, one classification yard per trip can be assumed, while for larger countries and international transports at least two yards are normally necessary for routing a freight car. Furthermore, two shunting processes of approximately 2–3 km must be added at either end of the transport chain to access the sender's and receiver's rail sidings. Therefore, in total for each rail transport, shunting operations with a total length of $(6+x*5)$ kilometre should be added to the main haulage operation, where x is the number of classification yards passed. For intermodal transport, the transhipment processes in intermodal terminals can be neglected because the energy required for shunting and crane operation (as against shunting in rail classification yards) does not exceed 3 % in any of the benchmarked samples.

The biggest challenge in the entire modelling process is the reliable estimation of transport distances. While for road transport where online trip planners deliver detailed results, no comparable aid exists for rail or intermodal transport. The "SPIN-ALP Planner" (ETH Zurich 2009) used in this study delivers reasonable results but is neither free of charge nor openly available to the general public. EcoTransIT World, on the other hand, is a public tool, but needs exact waypoint information to deliver precise estimates. If such information

is not available from an operator, assumptions must be made based on general system knowledge. Only in the case of point-to-point block train shipments (not subject of this study), which include no intermediate shunting processes, distances calculated in EcoTransIT World could be used for the benchmark. Therefore, in a context of LCA applications, the use of EcoTransIT World as a simple model for freight transport cannot be recommended without reservations.

4.5 Research perspectives

Concerning the environmental benchmark method as well as transport LCA in general, we showed in this project that traffic accidents have a relevant impact. Therefore, further research should be performed in providing detailed accident data also for other regions than Switzerland—for road transport in a first step but also for rail. Especially rail accident, statistics should be evaluated for a larger time span and on an international (European) level to increase their validity. Due to the low absolute number of victims per year and country, the results will spread significantly when comparing between single years. The same effect can be expected of a comparison between different countries because severe rail accidents are rather singular events, which impact the accident statistics of the affected country overproportionally.

Moreover, to allow for a routine assessment of accidents in LCA, inventory databases should include data of accidents for all background processes as well. In addition, there is an urgent need for an operational approach for also integrating damage to human health from traffic noise into the existing LCA methods. Although sophisticated traffic noise models exist for road traffic (Forkenbrock 2001; Althaus et al. 2009; Cucurachi et al. 2012), no methodologically sound method has been published so far, which allows a comparison between different transport modes.

With regard to the application of the results, the background survey data (Fries et al. 2010) showed that there is a demand of shippers for environmental information and a limited willingness to pay for high environmental performance of logistics service providers. However, the survey did not provide any results about the format and the level of detail, in which the information should be communicated. Future research should investigate whether decision makers prefer rather aggregated (and thus abstract) indicators or a larger number of indicators with physical units.

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