Environmental and economic assessment of current and future freight transport systems by road and rail in Switzerland

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Abstract

The transport sector represents 36% of the final energy consumption in Switzerland, and 14% of the CO_2 emissions of this sector are coming from heavy duty vehicles (Swiss Federal Office for Statistics, BFS 2013). Freight transport, involved in all supply chains, is a key component to achieve the goals of the Swiss Energy Strategy 2050.

This study presents a life cycle assessment (LCA) and a cost assessment of current and future goods transport by road and rail in Switzerland. The focus of the LCA lies on both infrastructure and vehicles, investigating impacts from climate change, terrestrial acidification and Particulate Matter (PM) formation. Concerning road transport, Liquefied Natural Gas (LNG) and Fuel Cell Vehicles (FCV) were explored in addition to conventional diesel trucks.

It was found that European vehicle tailpipe emission and fuel standards, have led to significant reduction of environmental impacts of trucks in the last decade. In particular, terrestrial acidification and PM formation impacts were reduced respectively by 66% and 48% for diesel trucks between 2000 and 2013. Expected near future fuel consumption standards could reduce fuel consumption by up to 30%, greatly improving the climate change potential of road freight in 2030. For FCV in 2030, climate change potential was found to be lower than that of conventional powertrains. Impacts are mostly due to the fuel production processes, with different hydrogen production pathways causing 30 to 70% of the total climate change impacts. FCVs were found to have higher impacts than other trucks in all other impact categories examined.

Regarding freight trains, mainly powered with hydro electricity, very high efficiency is already achieved and impacts of rail transport were found to be dominated by the infrastructure construction phase, accounting for 41 to 45% in the three impact categories considered. Climate change impacts of goods transported by train are in the range of 22 to 30% of the ones transported by diesel truck in the corresponding period. For terrestrial acidification and PM formation, trains were found to have 40 to 60% lower impacts than diesel trucks.

The cost assessment was designed to use comparable categories, including external costs, for all transport modes and technologies in order to improve consistency. It was determined that the total societal costs were higher for all road transport technologies than those for rail transport. However the costs are perceived in a different way by operators because rail transport, unlike road transport, pays the full costs of its infrastucture, representing more than 60% of the final expenses. The external costs of noise, global warming and human health impacts were found to be roughly equal for both modes, contributing 10-18% of total costs.

On the methodological side further research was found to be most necessary on infrastructure allocation and potential nonlinear effects of axle load on road pavement wear.

Keywords: Life Cycle Assessment, Life Cycle Inventory, Transport, Rail, Cost Assessment, Infrastructure allocation, Heavy Duty Vehicles, Freight train

Table of Contents

List of figures

List of tables

List of abbreviations and units

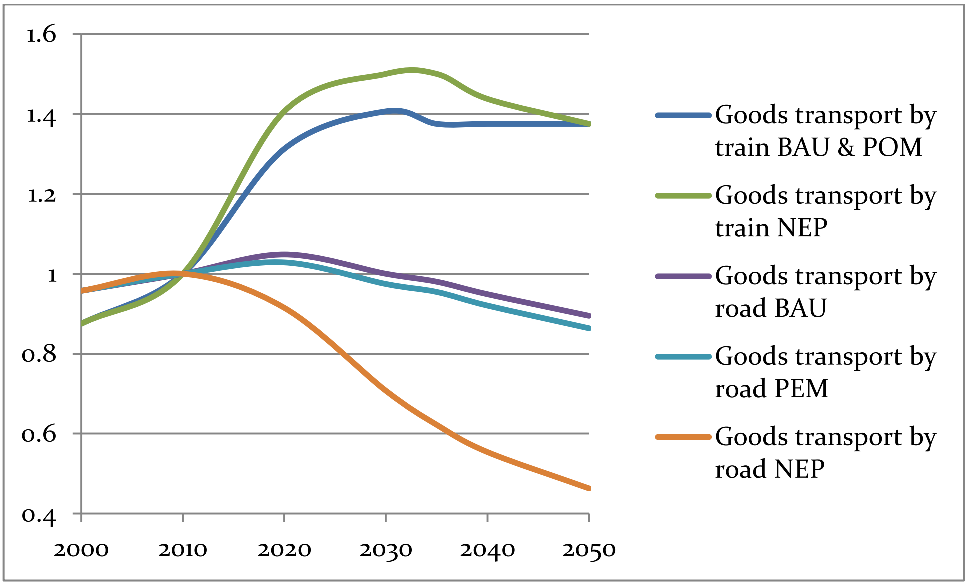
ARE	Swiss Federal Office for Spatial Development
ASTRA	Swiss Federal Office for Roads
BAV	Swiss Federal Office for Transports
BFE	Swiss Federal Office for Energy
BFS	Swiss Federal Office for Statistics
bn	billion
CHF	Swiss Franc
CO_2-eq	Carbon dioxide equivalent
EMPA	Swiss Federal Laboratory for Material Science
EU	European Union
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gas
Gtkm	Gross ton kilometer
HDV	Heavy Duty Vehicle
ICEV	Internal Combustion Engine Vehicle
kg	kilogram
kWh	kilowatt hour
LCA / LCIA	Life Cycle Assessment / Life Cycle Impact Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LNG	Liquefied Natural Gas
m	million
m.y.	meter*year
NG	natural gas (methane)
NH_3	ammonia
NOx	Nitrogen Oxides
NMVOC	Non Methane Volatile Organic Compounds
p	piece
PC	Passenger car
PEM	Polymer Electrolyte Membrane
pkm	Passenger kilometer, transport performance for passenger vehicles
PM	Particulate Matter
PSI	Paul Scherrer Institut
SBB	Swiss Federal Railways
SCCER	Swiss Competence Center for Energy Research
SMR	Steam Methane Reforming
SO_2	Sulfur dioxide
tkm	Ton kilometer (Net), transport performance for freight vehicles
TtW	Tank to Wheel
vkm	Vehicle kilometer, vehicle performance
WtT	Well to Tank
y	year

1. Introduction

1.1. Background and motivation

In 2011, the Swiss Federal Council and Parliament engaged a profound restructuring of the energy system, known as the Energy Strategy 2050 (BFE 2013). A package of policy measures has been implemented and suggested, respectively, to face the challenges of nuclear phase out, CO2 emission reduction and energy independency. The transport sector, representing 36% of the final energy consumption in Switzerland in 2011 (BFS 2013) is therefore one of the key topics investigated within this energy policy. In this context, the company Prognos AG has developed energy demand scenarios (Prognos AG 2012) which give an idea of the relevance of the energy challenges in this sector. Results for all Switzerland are presented in the graph below (base year 2010; BAU stands for Business As Usual, POM for Political Measures and NEP for New Energy Policy).

FIGURE 1-1 EVOLUTION OF ENERGY DEMAND FROM GOODS TRANSPORT IN SWITZERLAND (PROGNOS 2012)



The general aim of this thesis was to contribute to the Swiss Competence Center for Energy Research (SCCER) Mobility[1], exploring environmental and costs aspects of the current and future transport system in Switzerland.

The transport sector is a challenging topic regarding environmental impact assessment: it requires inputs from the energy sector, infrastructure allocation and traffic assumptions, and has experienced in the last decade the development of new drivetrain technologies. However, until now, most of the public attention was drawn to passenger cars (54 bn vehicle km in 2012

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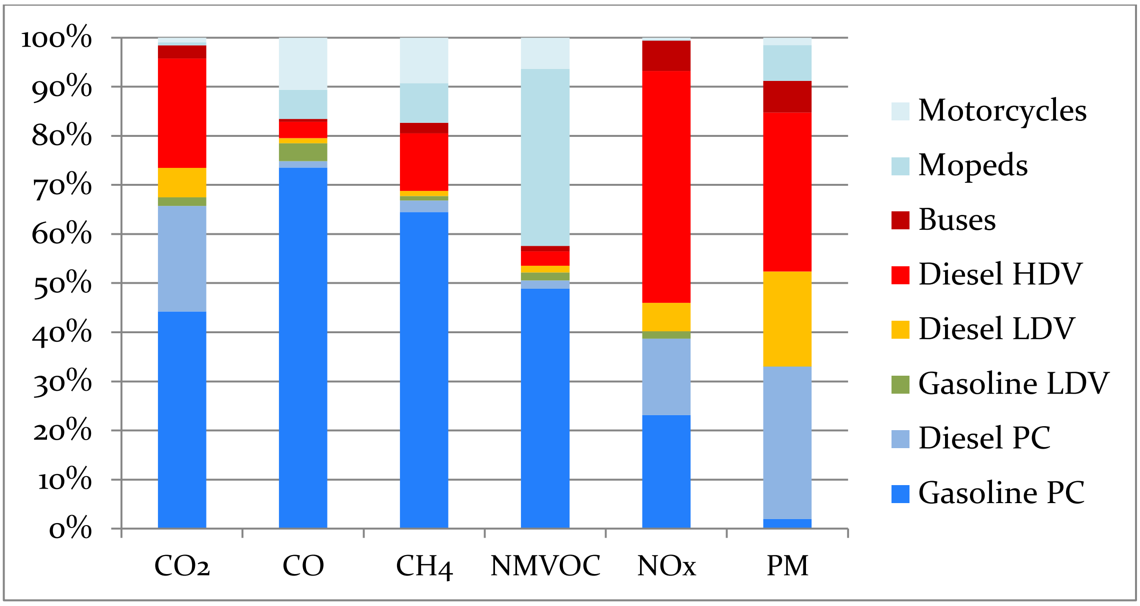
[1] SCCER mobility, retrieved 04.12.2014 from www.sccer-mobility.ch

to compare with only 1.7 bn vehicle km for heavy duty vehicles, BFS 2013) and infrastructure network was neglected for decision making (Chester and Horvath, 2009).

Today, buses and trucks are contributing 14% of CO2 emissions of the transport sector (BFS 2013) and freight trains represent 20% of the trains on the Swiss network in terms of vehicles (SBB 2013). Freight transport is a key component of supply chains and still remains related to economic growth (McKinnon 2007). In the last ten years the growth in freight transport was quite similar for both rail (+22% ton km, SBB 2013) and road (+25% ton km, ARE 2012) modes, but still reducing the modal share of rail from 44% in 2000 to 38 % in 2012 (CFF 2014). However a very high diversity in trip profile has been shown, with for example three out of five tons of cargo crossing the Alps by train (UTP 2014).

The graph below shows the importance of emissions of different vehicle categories as percentage of the EU totals for road transport

FIGURE 1-2 EMISSIONS AS PERCENTAGE OF THE EU TOTALS FOR ROAD TRANSPORT (EUROPEAN ENVIRONMENT AGENCY, 2006)



The current analysis can help to refine existing life cycle assessments (LCA), considering that freight transport datasets are among the most used datasets in ecoinvent (Dr. Chris Mutel, oral communication 22.10.2014, PSI).

The purpose of the economic assessment is to examine the total costs to society of freight transport technologies and to compare them. Fair price evaluation is needed to implement new taxing schemes. Taxes are a key intrument to influence demand, and are therefore necessarily part of the policy measures for an integrated energy policy strategy.

1.2. Scope and objectives

This thesis was focused on long distance goods transport by electric freight train and heavy duty trucks >32t using the Swiss road and rail network conditions. Smaller trucks for regional and urban delivery were not considered in order to make the comparison with train relevant. Air and water modes were excluded considering their marginal share in the Swiss national freight transport system (BFS 2013). The transport system is defined as the combination of vehicles, trains and trucks, and their corresponding infrastructure, respectively railway track and road (see system boundaries). Loading and unloading infrastructures as well as handling operations were not included due to the high variability depending on the type of goods and customer equipment.

The first objective was to assess the current technologies regarding environmental impacts and costs, including external costs estimates. Then, the 2030 transport system was explored with different technology scenarios.

The main research questions of this study can be written as follows:

What are the life cycle environmental impacts and life cycle costs of road and rail long distance freight transport in Switzerland and how do their results compare to each other? How the results change with the prospective technical development scenarios until 2030?

The tasks involved cover:

1. Update existing transport related datasets in ecoinvent v3.1 for vehicles and infrastructure.
2. Perform a Life Cycle Assessment (LCA) and cost assessment of goods transport by train and by truck in Switzerland.
3. Provide a robust framework for further LCA of freight transport system for European countries, with explicit formulas adapted to the data sources available.
4. Explore scenarios for future vehicle technologies in 2030 and perform corresponding LCA and cost assessment.

Technology scenarios are not intended to have a forecasting value but are presented to explore and draw attention on future technology perspectives. Therefore the analysis focuses on the vehicle level and no assumptions were made about fleet composition and aggregated impacts. Demand trends were derived from statistical data sources and used to assess the future infrastructure demand.

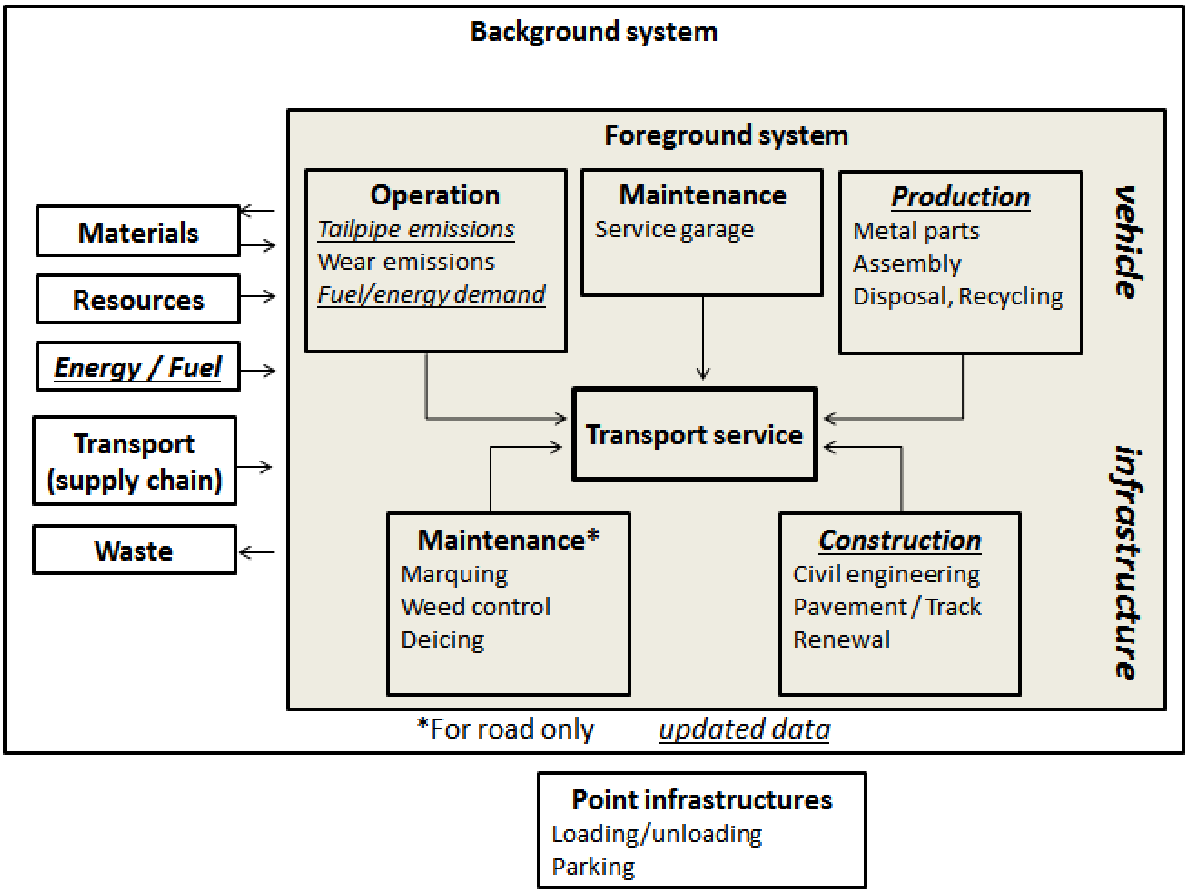
Fuel and material inputs were taken using the existing datasets in ecoinvent v3.01. Specific scenarios for hydrogen production pathways and electricity for Swiss Federal Railways (SBB) were made for 2030.

Three different models of trucks were considered for 2030 and compared to a generic current EURO VI truck available on the market: an advanced diesel internal combustion engine vehicle (**Diesel 2030**), a liquefied natural gas fueled vehicle (**LNG 2030**) and a hydrogen powered vehicle using a polymer electrolyte fuel cell (**H_2 2030**) (see section 4.2).

For trains, only one technology was considered: the electric train, which dominates the Swiss traffic. Diesel engines are only used in short distance switching work (shunting) and sidetrack connections to industrial railroads. Minor efficiency improvements have been considered on the vehicle side for 2030 (see section 4.3), due to the lifetime of locomotives approaching 40 years.

The transport system was represented as follows:

FIGURE 1-3 SYSTEM BOUNDARIES



Valid for both cost and environmental impacts.

1.3. Outline

This thesis aims to present a comprehensive overview of the current status and future trends of environmental impacts and cost structure from freight transport system in Switzerland as well as the life cycle implications of various alternative energy and propulsion options. It is structured as follows: a short literature review presenting papers that influenced this thesis; an overview of the life cycle assessment (LCA) and life cycle cost (LCC) modeling techniques for transport systems; the current status of Swiss freight transport sector, including traffic performance; technologies that can reasonably be expected to be adopted by 2030 are analyzed; Life cycle inventory (LCI) datasets are created and compiled and then results from LCA and LCC are examined and compared; finally conclusions are drawn.

2. Literature review

This section is intended to give an overview of some of relevant studies and work done in the topic of environmental and economic assessment of freight transport. The purpose of this thesis wasn't to complete a literature review of freight LCA, but rather to update the ecoinvent data for road and rail. Thus only the papers that influenced the analysis methodology and with a comparable scope are described here. Another major component of literature review was searching for updated values for the costs and demand factors. Although these studies are not explicitly described here, significant effort has been spent to collect and review these studies in order to ensure correct input data for the LCA and LCC models. The table below presents how the different aspects of this thesis are covered in literature.

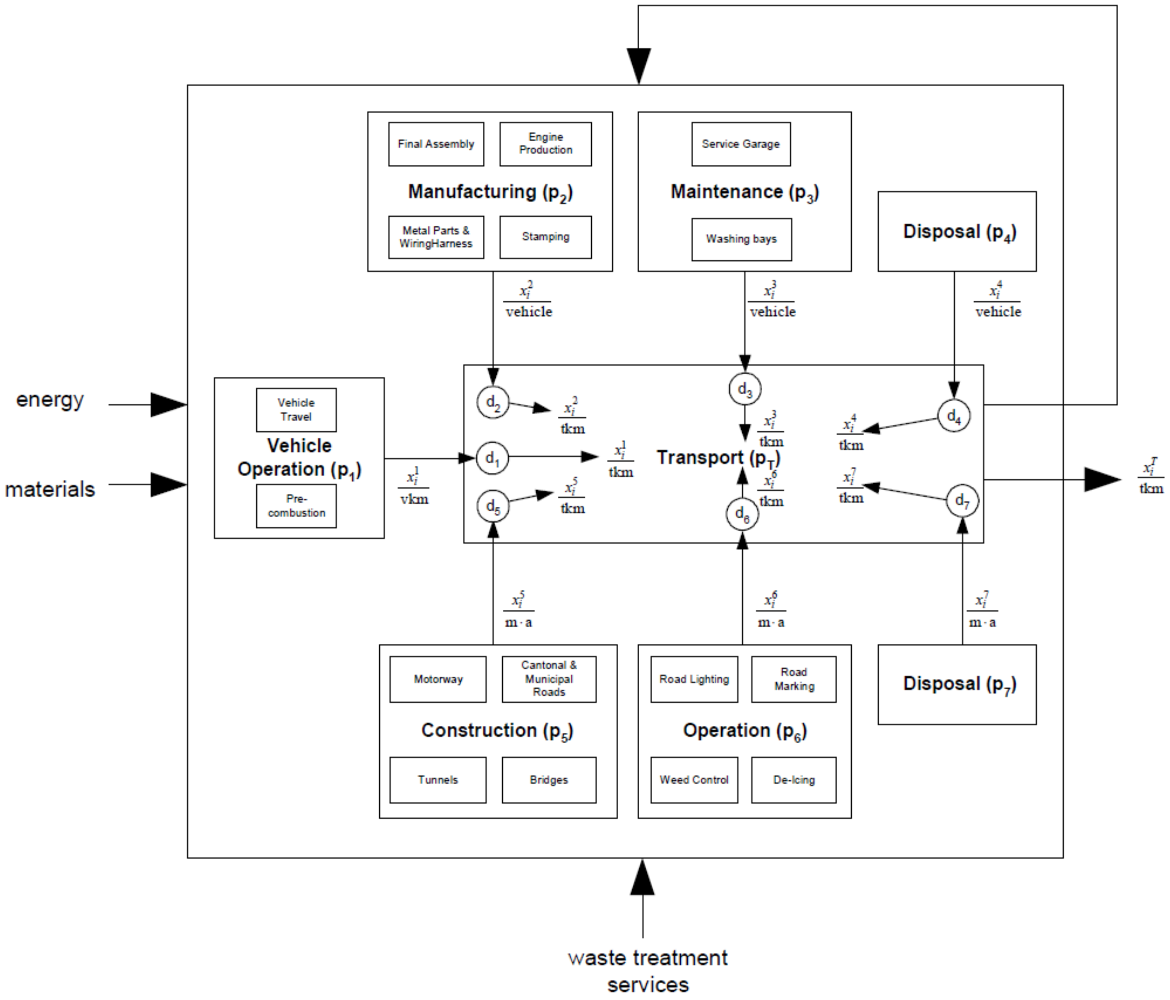
TABLE 2-1 LIST OF STUDIES AND THEIR COVERED ASPECTS INCLUDED IN LITERATURE REVIEW

	Road vehicles	Rail vehicles	Road infrastructure	Rail infrastructure	Future scenarios	LCI	LCA	Costs
Spielmann and Scholz (2005)	X	X	X	X		X		
Facanha and Horvath (2006)	X	X	X	X			X	
Sahin et al. (2009)	X		X					X

Spielmann and Scholz (2005)

Michael Spielmann and Roland W. Scholz (Swiss Federal Institute Zürich) are the authors of several transport related datasets in ecoinvent. This paper was the basis for current ecoinvent datasets, and was also used as the basis of this thesis. This is the most complete and comprehensive life-cycle inventory so far of road, rail and water transportation of goods in Europe. The same methodology was used in this thesis, while updating the demand factors. The LCI model structure used in ecoinvent and the formulas for demand factors are detailled. The breakdown in vehicle operation, vehicle maintenance and manufacturing, as well as infrastructure construction and operation is modeled in this paper. The allocation rule for infrastructure using kilometric vehicle performance for operation and gross ton kilometer performance for construction is also implemented here. Results are presented for the following pollutants: NOx, Benzene, NMHC, CO_2, PM and heavy metals, and are not converted into impact categories. The approach for vehicle modeling is to use average fleet composition and not individual technologies as it is done in this thesis. Intermodal comparison between road, rail and barge transport shows that rail emissions are 65 to 92% lower than road emissions, and also reveals the importance of infrastructure processes with 15 to 30% of emissions of NOx and CO_2. This paper has shown the relevance of an integrated model of infrastructure and vehicles, providing the necessary tools for further improvements. It shows the relative importance of different transport processes within the life cycle and recommends developing more specific data for transport-focussed LCAs. However only relative shares of life cycle phases are presented and absolute values of emissions are not given.

FIGURE 2-1 MODEL STRUCTURE DEVELOPED IN SPIELMANN AND SCHOLZ 2005



Facanha and Horvath (2006)

Dr. Cristiano Facanha and Dr. Arpad Horvath develop in this paper an environmental assessment of freight transportation in the U.S. Road, rail and air are the three modes covered and line infrastructures (interstate highway and railway track) are included. Long distance transportation is emphasized to enable the comparison of these modes. Four different emissions to air are covered: CO_2, NOx, PM10 and CO. It confirms that tailpipe emissions are insufficient to estimate total emissions of freight transport. First and last miles are excluded as they are not mode specific. This result justifies the boundaries and scope adopted in this thesis. It also confirms that rail freight, in this case performed by diesel trains, has the lowest associated air emissions, being 50-94% less polluting than road depending on the pollutant. The model was found to need country specific data and more accurate infrastructure allocation between freight and passenger transport as no specific model was developed.

Sahin et al. (2009)

Bahri Sahin, from Yildiz Technical University, Istanbul, Turkey, explores freight and passenger costs. This paper provided the methodology for the cost analysis. A general framework is modeled independently of the mode used, and then detailed for road, rail and sea transport using data of year 2005. The costs components selected are: capital (investment), fuel and lubricants, operational and maintenance costs (including insurance cost), and external costs. The sharing of infrastructure investment costs per vehicle is made according to equivalent factors for wear and tear of the road surface. In this model an articulated lorry uses 13 times more the infrastructure than a passenger car. However the calculation rule used to develop these equivalent factors is not documented. Regarding external costs, they are given per tkm or pkm for different modes. The categories selected are accident, emissions and noise, and are developed using data concerning Turkey. Simplistic assumptions are made for cost evolution over the lifetime of vehicles, with an escalation rate of 3% for operational costs and external costs, and 5% for fuel costs. Rail results are not comparable because Turkish trains are diesel powered and not electric as in Switzerland. Regarding road transportation the total cost consists of 14% investment costs, 60% fuel costs, 17% operational and maintenance costs and 9% external costs. Some assumptions in this paper are very different to the ones applicable to the Swiss sector with for example of lifetime of 10 year per truck (instead of 6.3y), 50km/h operating speed, investment cost including infrastructure estimated at 85 000$ for one truck. However this paper validates the selection of cost categories, except for human resources expenses which are excluded, and the general framework.

None of these studies adopts both comparable boundaries or conditions and comparable technologies as this thesis. In addition future technologies are not explored.

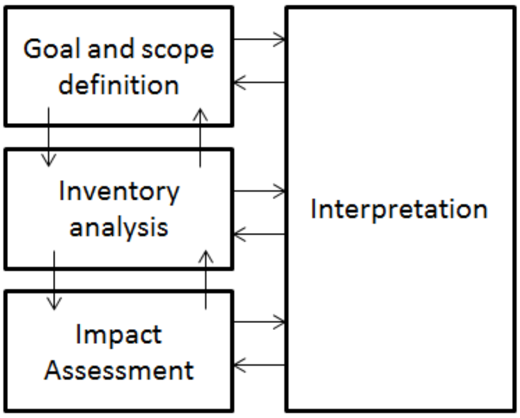
3. Methodology

3.1. Life cycle assessment (LCA)

Life cycle assessment (LCA) is a standardized method used to quantify environmental exchanges and potential impacts on human health and environment of a specific good or service during its entire life cycle. The general framework is described in the ISO documents 14040 and 14044, first introduced in 1997 and revised in 2006 (Rebitzer et al 2004). The life cycle covers all the stages from cradle to grave, i.e. resource extraction, manufacturing, operation or use and end of life or disposal. This LCA study is carried out with v8.0.2 of the SimaPro software (Pré Consultants), using background processes from ecoinvent 3.01 and updating and correcting foreground processes from ecoinvent 3.1 (which was not implemented in SimaPro when this thesis was written).

The LCA method described in the international standards ISO 14040 and 14044 comprises four phases.

FIGURE 3-1 ISO FRAMEWORK



Goal and scope definition

The scope is characterized by the boundaries and the functional unit, which allows for a consistent and unbiased comparison of different goods delivering a similar service. The functional unit has to be consistent with the goal of the study, for example we can use passenger kilometer, pkm (one km travelled by one person) to assess the environmental performance of passenger transport, whereas we will use ton kilometer, tkm (one net ton of freight transported over one km) for freight transport. We will mention impacts associated to one tkm, the main functional unit of this study. The boundaries indicate to which extent we define our system. In our case we decided to exclude the handling and storage of freight, and the loading and unloading infrastructure (see Fig 3-2).Facanha and Horvath (Facanha and Horvath, 2006) have estimated that excluding terminals would account for less than 5% of total emissions and therefore, does not affect the overall ranking of modes.

The final goal is to compare environmental impacts of current and future road and rail freight technologies in Switzerland, and to identify environmental hotspots in the life cycle stages of road and rail transport. The intended application here is to improve further bottom-up modeling studies in the context of the SCCER Mobility. This study was done to provide up to date LCI data to the LCA community, and a solid basis for future LCA studies in the field of freight transport. A varied audience is targeted with the LCA community and stakeholders in the energy and mobility sector in general.

Inventory analysis

The inventory analysis, also called life cycle inventory (LCI), is the compilation of all exchanges with the product system, from and to the technosphere, and from and to the environment, also called the biosphere. This step requires the extensive use of databases mapping and compiling all these interdependencies. For this study the Swiss database ecoinvent v3.01 and v3.1 (www.ecoinvent.ch) was used. Alternatives LCA databases exists such as GaBi (PE International). In this thesis, the inventory represents a hypothetical average generic vehicle, in the average conditions for a specific propulsion technology. Unusual operating conditions and accidents are not included. References to specific datasets in ecoinvent, will be made as follows: (*activity name,* creation date, ecoinvent version).

Impact assessment

LCI results are finally converted into several impact categories. The impact assessment is based on the perspective hierarchist (H) used in the ReCiPe method v1.09 (Goedkopp et al 2009). The ReCiPe method translates all environmental flows into 18 potential impact categories, or midpoints of environmental impacts, which are reported as the results of the LCIA. These categories and the units in which they are presented are shown next page in table 3-1.

TABLE 3-1 RECIPE MIDPOINTS IMPACT CATEGORIES, NAMES AND UNITS

Impact Category Name	Unit	Impact Category Name	Unit
climate change	kg (CO2 to air) air)	freshwater ecotoxicity	kg (14DCB* to freshwater)
ozone depletion	kg (CFC-115 to air)	marine ecotoxicity	kg (14-DCB* to marine water)
terrestrial acidification	kg (SO2 to air)	ionising radiation	kg (U235 to air)
freshwater eutrophication	kg (P to freshwater)	agricultural land occupation	m2×yr (agricultural land)
marine eutrophication	kg (N to freshwater)	urban land occupation	m2×yr (urban land)
human toxicity	kg (14DCB* to urban water)	natural land transformation	m2 (natural land)
photochemical oxidant formation	kg (NMVOC to air)	water depletion	m3 (water)
particulate matter formation	kg (PM10 to air)	mineral resource depletion	kg (Fe)
terrestrial ecotoxicity	kg (14DCB* to industrial soil)	fossil resource depletion	kg (oil)

*14DCB : 1,4 Dichlorobenzene

In this thesis a specific attention was given on the following midpoints indicators: Climate change, Particulate Matter formation and Terrestrial acidification potential. These categories are the most important when assessing the transport sector and are also the most representative for the evolution of this sector with technologies and processes targeting specifically these impacts (see chapter 4).

TABLE 3-2 IMPACT CATEGORIES CHOSEN FOR THE ANALYSIS

Impact category name	Indicator name	Unit
Climate change	Infra-red radiative forcing	kg CO2 eq to air
Particulate Matter (PM) formation	PM10 intake	kg PM10 to air
Terrestrial acidification potential	Base saturation	kg SO2 to air

- Climate change: represents potential impacts on both human health and ecosystems due to the emissions of greenhouse gases (GHG). The perspective H (hierarchist) focus specifically on a 100 y timeframe.
- Particulate matter formation: represents potential impacts on human health due to both primary PM emissions and secondary PM formation in the atmosphere due to nitrogen oxides (NOx), sulphur dioxide (SO_2)and ammonia (NH_3) emissions. These particles penetrate deep in the lungs causing respiratory diseases.
- Terrestrial acidification potential: indicates potential impacts on the environment as a result of NOx and SO_2 emissions. Soil acidification modifies the internal biology and affects vegetation growth.

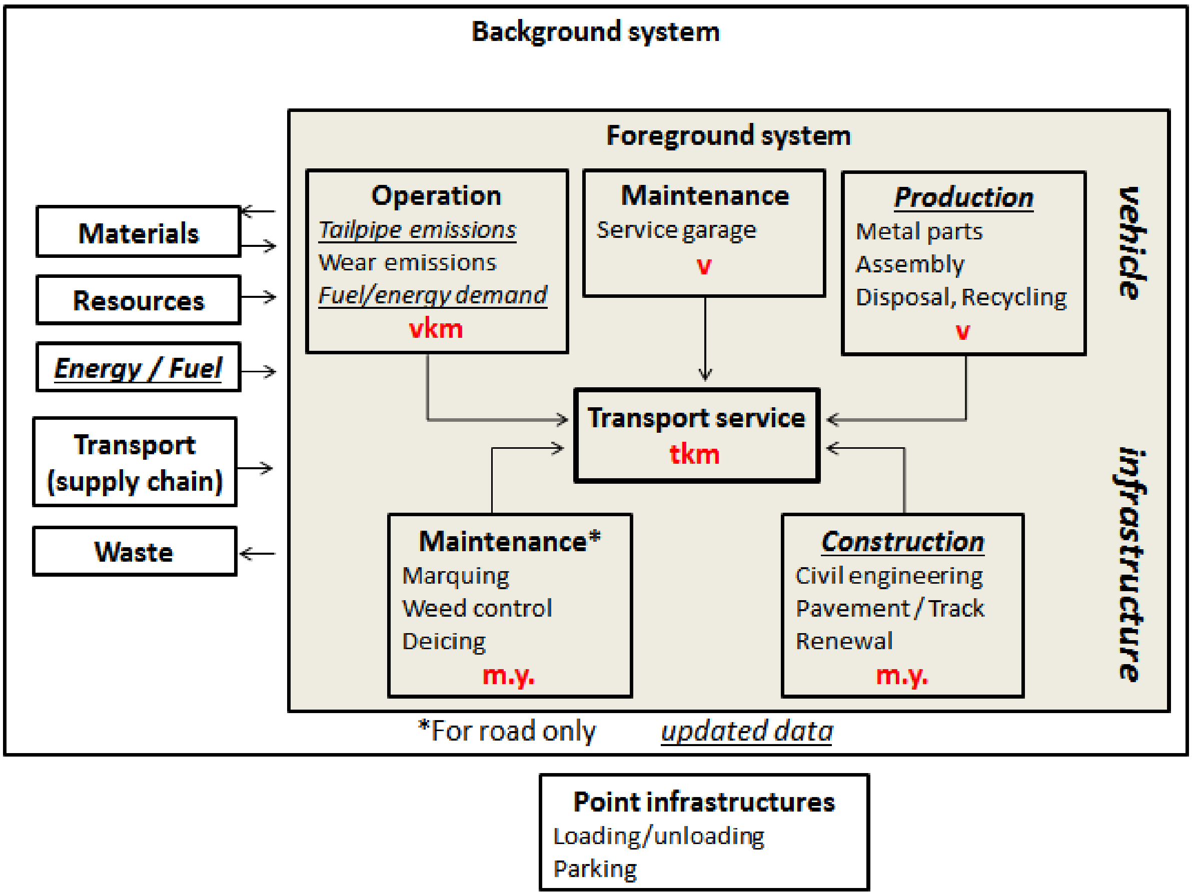
More information about the ReCiPe method and the characterization factors used can be found in the ReCiPe report (Goedkopp et al 2009).

Interpretation

The interpretation phase requires a critical analysis of the overall consistency of the results, and can be refined with several iterations of the whole process of LCA. Based on these interpretations recommendations can be made according to the initial goal.

In order to observe where the most significant emissions occur within the transport system, the results are differentiated by their life cycle stage and by infrastructure component associated, the so called main process elements (MPE) or product categories (Rozyki et al 2003).

FIGURE 3-2 LIFE CYCLE STAGES OF TRANSPORT SYSTEM AND CORRESPONDING FUNCTIONAL UNITS (ADAPTED FROM SPIELMAN AND SCHOLZ, 2005)



For this thesis the following functional units were used (highlighted in bold in the main process elements boxes in figure 3-2):

- Vehicle kilometer (vkm): represents the distance travelled (1 km), for vehicle operation.
- Ton kilometer (tkm): represents the net load transported (1 ton of goods over 1km), for final goods transport performance assessment**.** Alternatively Gross ton kilometer is sometimes used taking into account the mass of the vehicle.
- Vehicle (v): for vehicle maintenance over the entire lifetime, manufacturing and disposal.
- Meter year (m.y.): for infrastructure operation and maintenance (use of 1 m during 1 year).

Demand factors are used to integrate the results from all main process elements into our primary functional unit: tkm. The yearly kilometric performance, the lifetime and the load factor were some of the essential factors for the calculation and determination of demand factors. The required information was derived from statistics and literature (see chapter 4).

One important issue in LCA is to know where to stop the investigation. A deep experience and a good understanding of the topic are required to make these judgments without spending too much effort in processes that wouldn't be that significant in the end. Successive iteration to trace back the main contributors of a specific impact, needing further investigation, is often necessary.

Nothing was changed with respect to resource extraction and end of life phases compared to ecoinvent datasets. Steel, aluminum and copper are already considered as fully recycled, 50% of all used tyres are used as a secondary fuel in Swiss cement works, and for the remaining material (glass, mineral oil, plastics) complete disposal is assumed (*treatment of used lorry*, 2010, ecoinvent 3.1). Cut off approach is used to model the recycling of metals (secondary metals, i.e. recycled, are considered according to the recycled content in the product).

3.2. Life cycle costing (LCC)

The total cost of a product over its lifetime is broken down into a series of cost elements, analogously to the main process elements in LCA, allowing for individual assessment (Hokstad 1998 & Sahin et al 2007). The final results of the LCC are expressed with respect to the same functional unit as the LCA analysis: tkm.

The following elements are considered in our LCC:

- Fuel or energy costs for vehicle operation.
- Vehicle investment and maintenance.
- Personnel and overhead costs.
- Infrastructure costs: annual network expenses, covering both maintenance and renewal, allocated to the total traffic performance.
- External costs (ARE 2014): with a focus on noise, local air pollutants, and GHG emissions.

Specific transport taxes (mineral oil tax, motor vehicle tax and performance related heavy vehicle charge) are not taken into account because their benefits are reallocated to the same sector to cover external costs and infrastructure expenses, and these costs are fully taken into account in a separate category (see section 6.1 for more details). VAT is also excluded.

The cost structure depicted is very similar to the structure of the life cycle inventory. The only difference concerns personnel expenses and vehicle operation which is the combination of fuel, maintenance and personnel. In the end the same main process elements are used to describe the system. Assumptions and scope are chosen in order to be similar between the two modes, and comparable sources are used for both.

Most of these costs are either distance related (fuel, energy), or already available as annual costs (maintenance, external costs), and therefore we can easily express them in CHF per tkm dividing the result by the average net load or the annual transport performance. I didn't take into account that some expenses are increasing with the age of the vehicle (e.g. oil consumption), keeping the same idea to represent a hypothetical generic vehicle as for LCA. To account for the influence of the production volume on component costs, two different investment costs were considered for prospective vehicle technologies (LNG 2030 and H_2 2030). Scenarios for energy prices were also considered. All the results are expressed in CHF 2010 (i.e. inflation is not considered for 2030 cost estimates) and no corrections were made for sources from year 2000 (Baumgartner 2001). The bias of not correcting 2000 values for 2010 is approximately 8% [2], but the only category affected is investment cost for wagons and locomotives, whose prices can vary within this margin of 8%, and in the end contribute to less than 5% of total costs (see section 5.2). For data available in euro €, a conversion rate of 1.21 CHF/€ has been applied.

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[2] Historic inflation Switzerland, retrieved 04.11.2014 from: http://www.inflation.eu/inflation-rates/switzerland/historic-inflation/cpi-inflation-switzerland.aspx

For investment, several cost integration methods are mentioned in the literature (Gu Taek K et al 2009). However due to the high diversity in financing schemes, it was found more relevant to use directly the same demand factors as the ones developed for the LCA part of this study, eliminating bias from discount factors and interest rates.

Infrastructure expenses are calculated on the basis of actual data (Swiss road account 2011, BFS 2012 and SBB annual report, SBB 2013), with the assumption that the individual amount per tkm will remain constant for 2030. Thus cost developments are only affected by vehicle, environmental and fuel related expenses.

External costs were considered using a study from the Swiss Federal Office for Spatial Development (ARE 2014). Costs from climate change are computed based on the avoidance cost approach using a mean cost rate of 107 CHF per ton of CO2. LCA results from the climate change category are used to derive these costs. Thus the entire life cycle emissions are taken into account, even the ones which are not occurring in Switzerland (e.g. vehicle production). The underlying assumption used here is then that CO2 avoidance costs are the same everywhere in the world, which is a conservative estimate. For noise the monetary value is obtained using the damage cost approach considering the loss of rental income per decibel of noise. Contrary to CO2 emissions, only the operating phase is considered with this approach, but noise is also less subject to a switch from one life cycle phase to another as CO2 might be (e.g. hydrogen trucks). The per tkm value for 2030 is given as a rough estimate, taking into account expected noise reduction in the operating phase. Number of cases of illness and death that are related to air pollution, is the proxy used to assess external costs of air pollution. '*These are composed of medical treatment costs, loss output, employers' replacement recruitment costs and intangible costs*' according to ARE study (ARE 2014). This cost category is updated for 2030 with the percentage variation in the LCA impact category "PM formation". Results from this study are detailed in chapter 5, other external costs categories are presented, but for consistency reasons and to focus on categories subject to significant changes only climate change, noise and air pollution are taken into account (the full list of calculation methods for external costs is provided in the appendix).

3.3. Infrastructure allocation

The specificity of road and rail network is that they are used by different user types (passenger and goods traffic) and impacts and costs should be allocated to these different users.

Transport infrastructure is modeled using two components: construction and maintenance (maintenance for road only, dataset not available for railway tracks). We are considering only line infrastructure (road and rail network), point infrastructures (stations) are not considered in this study. Data is expressed in meter and year, m.y., and accounts also for civil engineer works (i.e. tunnels and bridges).

The demand factor for infrastructure is calculated taking into account the total length of the Swiss network concerned. For maintenance, the annual traffic in number of vehicle (vkm) is employed as the allocation rule and for construction, the gross mass of the traffic (Gtkm) is used (Spielman and Scholz 2005).

This last assumption is further discussed in chapter 6 of this thesis. As a first approximation, the common sense indicates that expenses such as lighting, weed control and deicing are related to the number of vehicles using the road (*road maintenance,* 2014, ecoinvent 3.1), whereas road and track damages, i.e. infrastructure degradation, is related to the overall mass transited over the section considered (*road construction*, 2010, ecoinvent 3.1).

3.4. Air pollutants

In this section we clarify assumptions regarding air pollutants from fuel combustion and other processes. The challenge for comparative studies is to define equivalent systems responding to the same functional unit and also to adopt similar calculation rules. Considering that emissions in the operating phase of train (shunting vehicles) and trucks are both coming from internal combustion engines, it was found necessary to adopt the same calculation rules.

For consistency and data availability reasons, we have selected a list of major contributors in exhaust emissions according to the UNECE recommendations (UNECE 2013) from the original list of pollutants available in ecoinvent 3.1 (available in the appendix). With a simulation on a EURO 5 truck it has been shown that this reduced list gives the same results in 16 of the 18 impact categories. For human toxicity 99.2% of the impacts are represented and for terrestrial ecotoxicity we obtain 99.7%.of the impacts. Similarly we have tested this simplification procedure on the existing freight train dataset available in ecoinvent 3.1, the only difference was observed on terrestrial ecotoxicity, reaching 96.7% of the effects with the complete list (which contains in particular heavy metals such as arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc found in trace concentration in fuel). A lot of early estimates were included in this list and terrestrial ecotoxicity is not an impact category in our focus for this study. Therefore this simplifying assumption doesn't impact final conclusions of this thesis.

The list of combustion products and others pollutants considered in this thesis, with their main origin is presented next page in table 3-3.

TABLE 3-3 LIST OF AIR POLLUTANTS CONSIDERED

		Effects [a]	Main source [b]
Emissions to air			
Ammonia	NH3	Toxic to aquatic animals	Urea additives, used to trap NOx
Carbon dioxide	CO2	Greenhouse gas	Carbon content of the fuel, lubricants and additives
Carbon monoxide	CO	Reduce oxygen carrying capacity of the blood	Combustion product. Lack of air
Dinitrogen monoxide	N2O	Affects ozone layer, greenhouse gas (GWP* ~310)	Combustion product. Excess of air
Methane fossil	CH4	Greenhouse gas (GWP* ~21)	Combustion product. Lack of air and leakage
Nitrogen oxides	NOx	Respiratory symptoms	Combustion product. Excess of air and excess temperature
Non Methane Volatile Organic Compound	NMVOC	Formaldehyde content contribute to cancer effects	Combustion product. Lack of air
Particulate Matter	PM10	Particles with diameter of 10 micrometers or less. Can get deep into the lungs, respiratory symptoms	Combustion product. Lack of air and excess temperature
Sulphur dioxide	SO2	Terrestrial acidification	Sulphur content of the fuel and lubricants
Sulphur hexafluoride	SF6	Greenhouse gas (GWP* ~23 900)	Gas insulated substations in electricity system

*Global warming potential, values from the Intergovernmental Panel on Climate Change (IPCC) for 100y timescale[3]

[a] United States Environmental Protection Agency (EPA)[4] and Kollamthodi 2014

[b] MOOC Sustainable Mobility IFPEN 2014

Air to fuel ratio, temperature conditions in combustion chamber and fuel composition plays a central role in the pollutants emissions (MOOC Sustainable Mobility, IFPEN 2014). Emissions were derived from EMEP Handbook for road transport emissions (EMEP 2014). Better combustion conditions and improved refining can helps to reduce it, as well as after treatment techniques. Improvements due to learning rate of after treatment technologies implemented and fuels used are developed in chapter 4. For CO_2 emissions, direct calculations based on fuel composition are used.

Remark concerning PM emissions: this section gives only primary PM emissions, in a later phase, for impact assessment, the ReCiPe method takes into account atmospheric chemistry processes which are responsible for the creation of secondary PM emissions, and aggregates primary and secondary emissions in the indicator PM formation.

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[3] Intergovernmental Panel on Climate Change IPCC, Direct Global Warming Potentials, retrieved 04.11.2014 from: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

[4] United States Environmental Protection Agency, EPA, Six Common Air Pollutants, retrieved 04.11.2014 from: http://www.epa.gov/airquality/urbanair/

4. Life cycle inventory of Swiss goods transport

This chapter develops the life cycle inventories of the Swiss goods transport system. General information regarding demand in freight transport are presented in section 4.1, section 4.2 focuses on road system and section 4.3 on rail system. The following outline is adopted: first the general regulatory environment and an overview of technologies are presented, the database design is explained, next current demand factors are calculated and technological developments are discussed, in the end all demand factors are summarized in a table. The resulting LCIA is presented in chapter 5.

4.1. The Swiss goods transport system

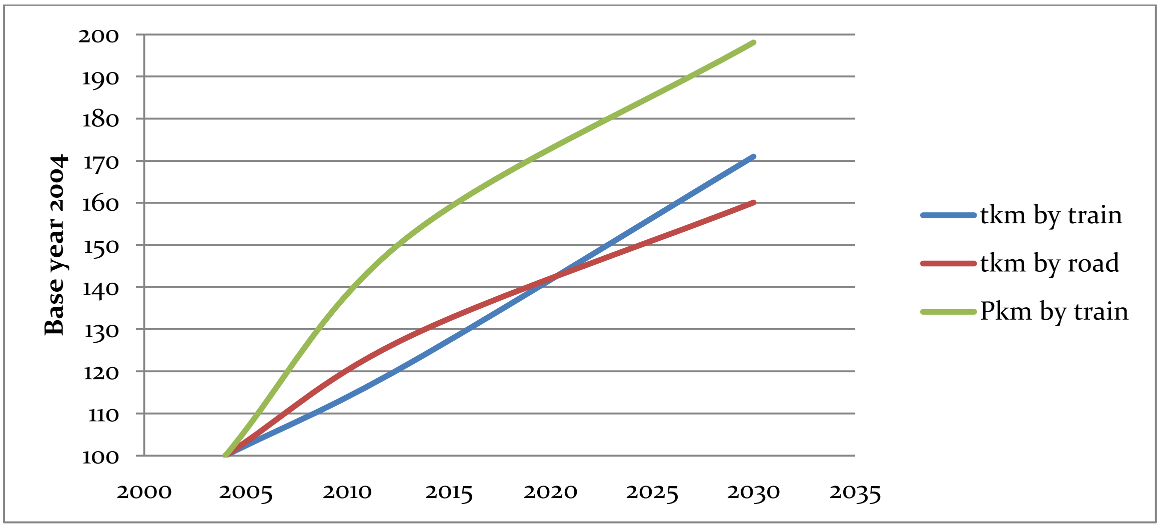
Rail was the dominant freight transport mode until the end of the eighties. The development of the road network, offering more flexibility regarding vehicle characteristics and regulations, has led to a modal shift to road transport (CFF 2014).

Between 1980 and 2012 the rail share of goods transport fell from 53% to 38% (ARE 2012) In the same period the overall demand for goods transport services increased by 85%. Today rail represents a share of 38% of goods transport performance, reaching 12.3 bn tkm in 2013 (ARE 2012).

Market calls for small and flexible shipments, while railways address primarily bulk transport. Growing ecological concern, driven by integrating external costs and infrastructure costs of rail and road transport might help the modal shift from road to rail. However the trend is still not heading towards this direction (see chapter 7).

The graph below depicts the perspectives for traffic development, which has implications for the overall infrastructure allocation presented in section 4.3.

FIGURE 4-1 TRAFFIC DEVELOPMENTS (ARE 2012)



Due to the infrastructure allocation principle described in section 2.3. it is also necessary to consider the traffic developments for other vehicles,such as passenger cars, which are using the same network. The annual traffic performance of passenger cars is expected to grow by 18.7% from today to 2030, reaching 66 billion vkm in 2030. Light and medium duty vehicles traffic (below 16t) will grow by 16.8% and heavy duty vehicle traffic (over 16t) by 21.1% (ARE 2012) in 2030 compared to 2012 figures. Similarly, traffic predictions for passenger trains were also considered.

Intrinsic properties of the Swiss network and vehicles are presented in the table below.

TABLE 4-1 COMPARISON OF GENERAL CHARACTERISTICS OF ROAD AND RAIL SYSTEMS

	Road	**Rail**
Network length	71 500 km (a)	2300 km (2004) 2360 km (2013) 2525 km (2030) (b)
Vehicle lifetime	6.3 years (c)	40 years (locomotive) 20 years (freight wagon) (d)
Annual distance travelled per vehicle	112 000 km (c)	71 000 km (e)
Average gross weight	33.2 t (c)	750 t (e)
Average net load	20 t (c)	400 t (e)

Sources :
(a) BFS 2013
(b) two way equivalent, SBB 2013 and SBB 2012
(c) CNR 2014 and TREMOVE
(d) Baumgartner 2001
(e) calculated from SBB 2013 (see details below)

More detailed values for weight data are provided in the end of this section considering variations of vehicle mass between 2013 and 2030.

It can be noted that the total mileage of a heavy duty vehicle is equal to 705 600 km, to be compared with the value used in ecoinvent v3.1 (*transport, freight, lorry>32 metric ton EURO6*, 2014, ecoinvent 3.1): 540 000 km. This last value, used for all heavy duty vehicles categories from 3.5t to 40t, is not documented and therefore not adopted in this thesis as we assume that different vehicle categories can have different lifetime mileage.

Gross tkm traffic gives an idea of the total charge on infrastructure, and is used as a proxy for infrastructure damages allocation according to the methodology used in Spielman et Scholz (see section 3.3). A summary of traffic performance indicators is presented next page in table 4-2.

TABLE 4-2 ROAD TRAFFIC DEVELOPMENTS

		Road Traffic	
	Year	**2010**	**2030**
Passenger traffic	In vkm	5.56E+10	6.60E+10
	In Gtkm	*8.84E+10	*8.38E+10
Low and medium Goods traffic	In vkm	3.64E+9	4.25E+9
	In Gtkm	*2.07E+10	*2.42E+10
Heavy Goods traffic	In vkm	2.23E+9	2.70E+9
	In Gtkm	*5.04E+10	*6.1E+10
Total Goods	In tkm	1.71E+10	2.1E+10
Total	In vkm	6.15E+10	7.30E+10
	In Gtkm	1.59E+11	1.69E+11

*calculated

Source : ARE 2012 (vkm and tkm figures only). Road traffic data for year 2000 was not investigated due to different calculation rules and fleet composition (truck >32t are allowed on the Swiss network only since 2005). Therefore, for year 2000, infrastructure demand factors were taken from the current ecoinvent datasets (*transport, freight train, electricity,* 2012 and *transport, freight, lorry >32 metric ton, EURO3,* 2010, ecoinvent 3.1).

Assumptions to derive the gross ton traffic figures:

- Average passenger car mass loaded: 1489kg +1.2*80kg (ICCT 2013 value for german car and 1.2 passenger per vehicle) in 2010. German market average was preferred to EU average to reflect the Swiss conditions. For 2030, 20% total weight reduction was assumed based on Ricardo 2014.
- Low and medium duty category: 3.5t to 16t. The average mass of vehicles from this category is calculated using the fleet composition predicted by TREMOVE (TREMOVE 2010): 5.70t gross average.
- Heavy duty vehicles category aggregates 16t-32t and >32t vehicles, the average gross mass is also taken from TREMOVE : 22.59t gross average.

Average gross mass of the fleet might change due to the introduction of new vehicle types, this effect is neglected (except for passenger cars), as no assumptions for fleet composition are made in this thesis.

TABLE 4-3 RAIL TRAFFIC DEVELOPMENTS

		Rail traffic		
	Year	2004	2010	2030
Passenger traffic	In vkm	1.08E+8	1.40E+8	*1.57E+8
	In pkm	1.26E+10	1.78E+10	2.65E+10
	In Gtkm	*4.97E+10	*5.92E+10	*7.43E+10
Goods traffic	In vkm	2.96E+7	3.13E+7	*4.40E+7
	In tkm	1.01E+10	1.23E+10	1.73E+10
	In Gtkm	*1.95E+10	*2.37E+10	*3.33E+10
Total	In vkm	1.38E+8	1.71E+8	*2.01E+8
	In Gtkm	*6.92E+10	*8.29E+10	*10.76E+10

*calculated

Source: ARE 2012, using “Referenzzustand 2030”, with middle demographic scenario

Assumptions to derive the gross traffic figures:

- Development of double deck passenger train, increasing the passenger capacity per ton of train and seats per vehicle (Bombardier 2012) and also the effective number of passenger per train (passenger traffic performance/vehicle traffic performance, SBB 2013).

$$mass\ of\ pass.train = \frac{seats\ per\ vehicle}{pass.capacity\ per\ ton\ of\ train} + \frac{80kg}{1000} \times effective\ number\ of\ pass.$$

TABLE 4-4 PASSENGER TRAIN MASS CALCULATION

	2004	2013	2030
Seats per vehicle*	461	461	615
Pass. Capacity per t*	1.02	1.12	1.34
Effective pass.	117	127	169
Mass of pass. train	461	422	472

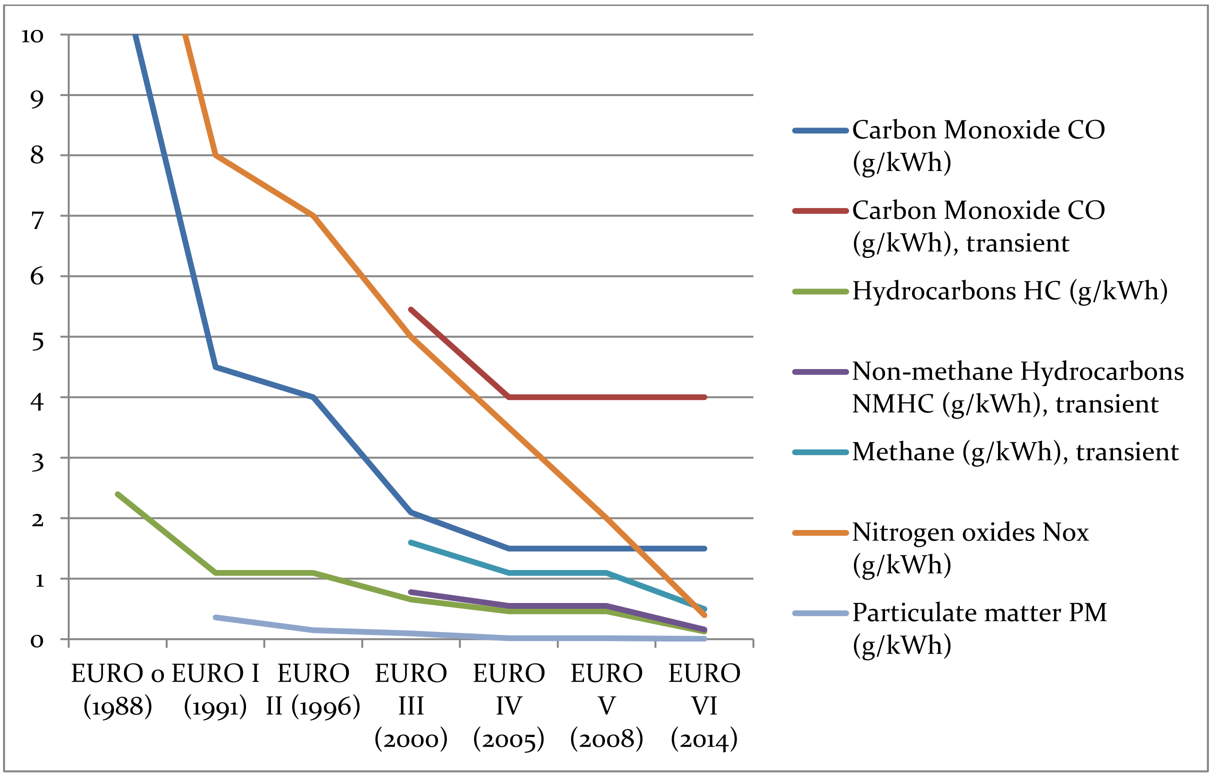
*from Bombardier 2012

- A net/gross load ratio of 0.52 from EcoTransIt 2011 (p 21) was used. We can approach this value by using the net load per vehicle (total tkm/total vkm) and approximate an average wagon load in addition to one locomotive.

4.2. Road

In this section we explore the biggest truck category allowed in Switzerland in order to make the comparison with freight train on long haul transportation relevant: the 40t lorry. Such HDVs are authorized in Switzerland since 1st January 2005 [5]. 40t HDVs have a typical engine power of 320kW, a maximum gross mass of 40 tons, distributed over fixe axles (ecoinvent). They are subject to the EURO standards for tailpipe emissions. The graph below shows the evolution of EURO standards since their introduction in the late 80's [6].

FIGURE 4-2 EURO STANDARDS FOR HDVS



N.B.: for light vehicles the entire vehicle is tested and emissions are measured in grams per kilometer (g/km). For heavy vehicles the engine is bench tested and the results are expressed in relation with the energy output of the engine as grams per kilowatt-hour (g.kWh). The regulation for heavy vehicles starts for vehicles over 3.5t.

Along with the emissions standards on the vehicle side, a European regulation on diesel fuel quality has been developed: EN 590. Fuel quality requirements have direct implications for upstream processes and for tailpipe emissions and therefore affects the life cycle impacts of diesel trucks. The most important reduction was implemented on sulphur content: from a maximum of 2000 ppm in the first version of the EN590 standard in 1993 to 10 ppm since 2009.

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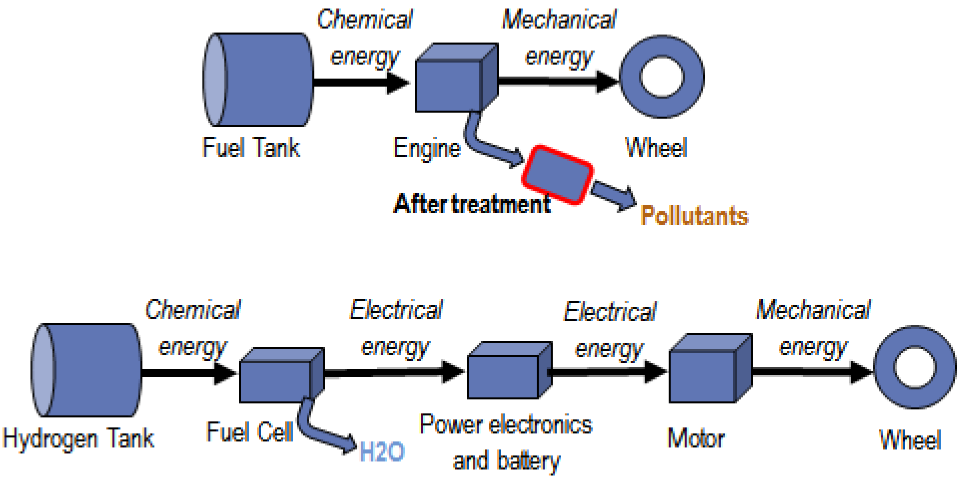
[5] Federal Office for Roads, Poids total des véhicules augmenté pour le 1er janvier 2005, retrieved 04.11.2014 from : http://www.astra.admin.ch/dokumentation/00109/00113/00491/index.html?lang=fr&msg-id=8626

[6] Regulatory Framework, retrieved 04.11.2014 from: https://www.dieselnet.com/standards/eu/hd.php

Two different drivetrain technologies were explored for 2030: the traditional internal combustion engine (ICE) including after treatment solutions for exhaust emissions and an electrical powertrain using a fuel cell derived from Marco Miotti's thesis (Miotti 2013). The drivetrain for trucks fueled with diesel and truck fueled LNG is similar, the only change considered is the cryogenic tank for LNG.

FIGURE 4-3 DRIVETRAIN TECHNOLOGIES



Battery electric vehicles are not considered: the current and also the envisaged future (until 2030) energy density and cost of batteries are not adequate for use in long haul freight vehicles. In addition they are associated with long recharging times. Hybrids vehicles, using both ICE and electric motor do not provide significant benefits in terms of fuel efficiency due to the driving cycle of long haul trucks based mainly on highway driving, therefore they are also excluded. Advanced technologies in the field of autonomous vehicle and platooning[7] were considered less likely to penetrate the Swiss market until 2030 compare to straight American highways and are also not considered.

4.2.1. Database design

Table 4-4 below shows all the categories taken into account for the life cycle inventory for a truck in the Swiss conditions for one tkm, and represents the database design in version 3.1 of ecoinvent (*transport, freight, lorry>32 metric ton EURO6*, 2014, ecoinvent 3.1). Treatment of wear emissions are new datasets in ecoinvent version 3.1, and were implemented manually into SimaPro.

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[7] European Commission FP7, Safe Road Trains for the Environment, retrieved 04.11.2014 from http://www.sartre-project.eu/en/Sidor/default.aspx

TABLE 4-4 ROAD DATABASE DESCRIPTION

Transport, freight, lorry >32t	Unit	Description
Known outputs to technosphere per tkm		
Treatment of brake wear emissions, lorry	kg	Material from brake lining, mainly iron and particles
Treatment of road wear emissions, lorry	kg	Material from road surface, particles
Treatment of tyre wear emissions, lorry	kg	Compounds used to formulate tyres, mainly particles
Known inputs from technosphere per tkm		
Maintenance, lorry 40 metric ton	p	Electricity, heat, lead, lubricating oil, reinforcing steel, rubber
Lorry 40 metric ton, production	p	Mainly steel, aluminum and energy, used lorry included as a byproduct. Electronics are also included.
Operation and maintenance, road CH	m.y.	Weed control, salt for deicing, paint
Road provision, CH	m.y.	Renewal and disposal of road pavement
Fuel, at fuelling station	kg	Upstream processes : refining and transport
Emissions to air per tkm		
Fuel combustion related emissions (tailpipe)	kg	Exhaust emissions

Wear emissions are not available as separate outputs for rail datasets. Therefore to make a consistent comparison with rail sector, for impact assessment brake wear emissions, tyre wear emissions are aggregated in the main process element vehicle operation and road wear emissions are attributed to road operation.

4.2.2. Demand factors

Wear emissions

TABLE 4-5 OUTPUT TO TECHNOSPHERE, ROAD

Transport, freight, lorry >32t	EURO III 2000	EURO VI 2013	Diesel 2030	LNG 2030	H_2 2030	Unit
Known outputs to technosphere per tkm						
Treatment of brake wear emissions, lorry	1.41E-5	1.41E-5	1.41E-5	1.41E-5	0.7E-5	kg
Treatment of road wear emissions, lorry	1.21E-5	1.21E-5	1.21E-5	1.21E-5	1.21E-5	kg
Treatment of tyre wear emissions, lorry	1.39E-4	1.39E-4	1.39E-4	1.39E-4	1.39E-4	kg

This subsection doesn't consider any changes between 2004 and 2030 except for the fuel cell vehicle. The source for these data is the Emission inventory guidebook 2013 from EMEP (EMEP 2013). Results are given for one vkm and then converted into tkm using a typical average net load of 20t (CNR 2014).

For brake wear emissions, the amount of material loss is measured on the brake lining. No significant material changes and driving behavior are assumed. The 50% reduction for the fuel cell vehicle is due to the electric drivetrain, allowing the use of regenerative braking systems and thus increasing the lifetime of brake linings.

For road wear emissions, an asphalt based surface is considered, and no significant changes in parameters affecting road wear would justify any changes for this value.

And finally for tyre wear emissions the same approach as for brakes is used, measuring the loss in tyre material.

Remark: theses datasets are specific to lorries (datasets are also available for passenger cars, taking into account different material concentrations in tyres and brakes, as well as different lifetimes).

Technosphere inputs

TABLE 4-6 INPUTS FROM TECHNOSPHERE, ROAD 1/2

Transport, freight, lorry >32t	variable	EURO III 2000	EURO VI 2013	Unit
Known inputs from technosphere per tkm				
Maintenance, lorry 40 metric ton	D_1	7.12E-8	7.12E-8	p
Lorry 40 metric ton, production	D_2	7.12E-8	7.12E-8	p
Operation and maintenance, road CH	D_3	5.83E-5	5.83E-5	m.y.
Road provision, CH	D_4	7.87E-4	7.87E-4	m.y.
Diesel, at fuelling station	D_5	1.70E-2	1.39E-2	kg

For this set of demand factors the following formulas where used:

- $D_1 = \frac{1}{economic\ lifetime\ of\ the\ vehicle \times annual\ distance\ travelled \times average\ net\ load}$

- $D_2 = D_1$

The data source for these calculations comes from CNR 2014, and no variations were considered between 2004 and 2013.

- $D_3 = \frac{1}{average\ net\ load} \times \frac{network\ length}{total\ traffic\ in\ vkm}$

- $D_4 = \frac{1}{average\ gross\ load} \times \frac{network\ length}{total\ traffic\ in\ gross\ tkm}$

Total traffic comprises passenger cars, light and medium duty vehicles as well as heavy duty vehicles. Demand factors were calculated for the year 2010 and the same value was used for 2004 and 2013 due to the fact that 40t trucks were not allowed on the Swiss road network in 2004. Data source for annual traffic performances is ARE 2012, network length comes from BFS 2013, and average mass of vehicles categories from TREMOVE and ICCT 2013.

- $D_5 = \frac{1}{average\ net\ load} \times fuel\ density \times fuel\ consumption\ in\ l/km$

Data source : CNR 2014. From 38l of diesel/100km in 2000 to 33.4l/100km in 2013.

TABLE 4-7 INPUTS FROM TECHNOSPHERE, ROAD 2/2

Transport, freight, lorry	variable	Diesel 2030	LNG 2030	H_2 2030	Unit
Known inputs from technosphere per tkm					
Maintenance, lorry 40 metric ton	D_1	6.68E-8	7.12E-8	8.54E-8	p
Lorry 40 metric ton, production	D_2	6.68E-8	7.12E-8	8.54E-8	p
Operation and maintenance, road CH	D_3	4.62E-5	4.62E-5	4.62E-5	m.y.
Road provision, CH	D_4	7.22E-4	7.22E-4	7.22E-4	m.y.
Fuel, at fuelling station	D_5	9.21E-3	8.82E-3	3.50E-3	kg

- D_1 and D_2

Increasing use of aluminum and plastics provides weight reduction potential (1300kg estimated[8]) allowing a slightly increased average net load (for Diesel 2030, from 19.94t to 21.24t). For LNG 2030 demand factor from Diesel 2013 was kept to account for the extra weight of the cryogenic tank (184kg) and the more experimental use. For Hydrogen truck an additional penalty of 20% due to a shorter expected lifetime is assumed. More experience is needed to ensure the durability of such fuel cell systems. A study from Ally and Pryor (Ally and Pryor, 2007) estimated the durability of fuel cell stack for hydrogen bus to 5000 hours, thus, using an average speed of 67 km/h (CNR 2013), we obtain a durability of 335 000km. It was found reasonable to assume that 588 000 km could be achieved in 2030, but the impacts of a replacement of the fuel cell and the battery is investigated in section 7.1. Specific modifications of maintenance and lorry production datasets for hydrogen trucks are developed in subsection 4.2.3.

- D_3 and D_4

Regarding road provision and operation and maintenance of road, the traffic predictions from ARE 2012 lead to a more intensive use and therefore a lower individual demand for one tkm.

- D_5

2030 scenarios consider 30% total improvement in energy efficiency due to developments explored in the technology roadmap from IEA (IEA 2012): aerodynamic trailer (12-15%), predictive cruise control (2-5%), driver support system (5-10%), active aerodynamics (5%). LNG fueled ICE is assumed to have the same energy efficiency as a diesel fueled one. This assumption is based on the results from a study from the Institute of Transportation Studies, University of California, Davis (Zhao et al 2013). They have shown that LNG engines using compression ignition have similar thermal efficiency as Diesel engines. Lower efficiency values found in literature (THELMA project [9]) consider spark ignition engines, which could be up to 10% less efficient than Diesel engines. Regarding hydrogen fuel consumption estimates are coming from den Boer et al. 2013.

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[8] The Aluminum Transportation Group, The Benefits of Lightening the Load, retrieved 04.11.2014 from: http://www.aluminumintransportation.org/vehicle-uses/commercial-vehicles

[9] Swiss Federal Institues of Technology, Technology-centered Electric Mobility Assessment, retrieved 07.10.2014 from http://www.thelma-emobility.net/index.html

Emissions to air

TABLE 4-8 EMISSIONS TO AIR, ROAD 1/2

Transport, freight, lorry >32t, *Diesel ICE*	EURO III 2000	EURO VI 2013	Unit
Emissions to air per tkm			
Ammonia	1.45E-7	5.52E-7	kg
Carbon dioxide fossil	5.38E-2	4.42E-2	kg
Carbon monoxide fossil	8.98E-5	4.44E-5**	kg
Dinitrogen monoxide	3.51E-7	2.46E-6	kg
Methane fossil	3.82E-7**	3.50E-8**	kg
Nitrogen oxides	3.73E-4	2.54E-5	kg
NMVOC*	1.54E-5	6.02E-7	kg
PM 2.5	7.57E-6	2.03E-7**	kg
Sulphur dioxide	9.51E-6	2.23E-7	kg

*Non Methane Volatile Organic Compounds

** Data copied from corresponding datasets in ecoinvent 3.1

see below for the others pollutants

If not stated differently, all the references in this subsection are coming from the EMEP/EEA emission inventory guidebook 2013 (EMEP 2014) and from the online version of Handbook for Emission Factors for Road Transport (HBEFA 3.2). No increase of emissions due to vehicle age is considered. When we observed more than one order of magnitude difference between HBEFA and EMEP data, the arbitrage was to take the data from the existing corresponding dataset in ecoinvent v3.1. High variability is observed in literature due to the many factors affecting these emissions such as fuel composition, operating conditions and topography, and after treatment modules.

When primary data was computable it was preferred to handbook emissions factors, because it allows more consistency and flexibility for further modeling. Numerical results are scaled for one kg of fuel burned in an ICE before being implemented in the model. Tier 2 emissions factors from EMEP used in this thesis are proposed aggregated for all driving conditions (urban, rural, highway) and comprise as well the emission effects of cold start and catalyst wear. The main weakness of scaling emissions with respect to fuel consumption for future scenarios is that cold start emissions are also reduced. This aspect is not covered in this thesis.

- Ammonia (p101 EMEP 2014)

Increase in ammonia emissions is due to selective catalytic reduction (SCR). From 3 mg/km with EURO III HDVs it has increased to 9 mg/km with EURO VI HDVs. Urea (~3% of total diesel consumption in a separate tank) is used to reduce NOx emissions in SCR since EURO V standards.

Principle of NOx reduction with ammonia:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$

- Carbon dioxide (p23 EMEP 2014)

  For diesel (in kg): $CO_2 = 3.170 \times fuel\ consumption$

  For LNG (in kg): $CO_2 = 2.750 \times fuel\ consumption$

- Carbon monoxide, NMVOC, NOx, PM2.5 (pp 33-34 EMEP 2014)

  Tier 2 method is employed and HBEFA 3.2. Tier 2 mehod is the intermediate methodological complexity used in EMEP report and is recommended for country and technology specific emissions factors.

- Dinitrogen monoxide (p96 EMEP 2014)

  Diesel vehicles equiped with deNOx after treatment have significantly higher emissions , due to the non optimal operation of SCR systems[10] . Emissions factors varies from 7 mg/km with EURO III HDVs to 48 mg/km for EURO VI HDVs operating on highway.

- Methane

  Not updated: data available in ecoinvent 3.1

- Sulphur dioxide (p24 EMEP 2014)

  All the sulphur content of fuel is assumed to be converted into sulphur dioxide. The calculation rule is as follows (in kg):

$$SO_2 = 2 \times mass\ ppm\ content \times fuel\ consumption$$

The factor 2 comes from the fact that SO2 has a molecular mass of two times the atomic mass of sulphur. Average market levels were assumed to be 20% below the maximum authorized level. Sulphur is also a poison for catalyst, and therefore low sulphur diesels are in many ways advantageous.

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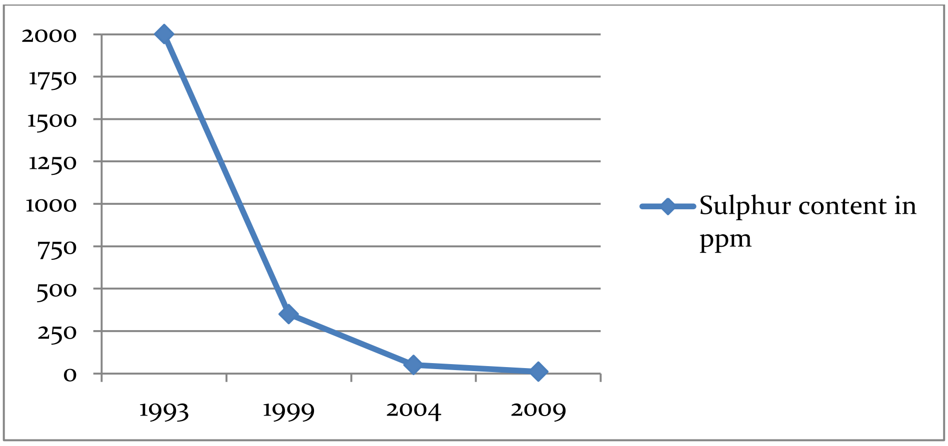
[10] Yang et al.(2014), Mechanism of N2O formation during the low temperature selective catalytic reduction of NO. Environmental Science and Technology http://www.ncbi.nlm.nih.gov/pubmed/25105802

FIGURE 4-4 HISTORY OF DIESEL FUEL SPECIFICATION EN 590 REGARDING SULPHUR CONTENT



The last EN 590 revision has been amended in 2009, introducing a 10ppm limit in road fuel. Low sulphur diesel require an additional step in the refining process: the hydrodesulfurization. It is estimated (*diesel production, low-sulphur,* 2010, ecoinvent 3.1.) that this process increases the overall energy consumption of refining by 6%.

For LNG, 2.67E-5 kg of SO_2 per kg of fuel was used, based on THELMA.

TABLE 4-9 EMISSIONS TO AIR, ROAD 2/2

Transport, freight, lorry >32t	Diesel 2030	LNG 2030	H_2 2030	Unit
Emissions to air per tkm				
Ammonia	2.92E-7	1.58E-7	0	kg
Carbon dioxide fossil	2.92E-2	2.43E-2	0	kg
Carbon monoxide fossil	2.35E-5	1.55E-5	0	kg
Dinitrogen monoxide	1.30E-6	3.23E-7	0	kg
Methane fossil	1.85E-8	5.92E-6	0	kg
Nitrogen oxides	1.69E-5	3.88E-5	0	kg
NMVOC*	3.18E-7	7.05E-7	0	kg
PM 2.5	1.27E-7	8.82E-8	0	kg
Sulphur dioxide	1.47E-7	2.35E-7	0	kg

Hydrogen vehicle is assumed to have no exhaust emissions except water, which is not mentioned as no LCA impacts are associated to emissions of water.

Considering that after treatment technologies were already implemented in EURO VI trucks, we have estimated 20% improvement in emissions per kg of fuel (except for carbon dioxide, not affected by after treatment), corresponding to a learning rate of 1% per year over 18 years. Only diesel particle filters were assumed to improve by only 5%, because further improvement has some drawbacks regarding fuel consumption. Nitrogen oxides are also reduced by only 5% relative to fuel consumption, because improvement in SCR efficiency is already considered by reducing ammonia emissions.

4.2.3. Comments on vehicle related developments

This subsection discusses assumptions made for future emissions and provides details regarding vehicle construction datasets.

LNG and hydrogen vehicles are assumed to be developed to ensure 600km autonomy. Considering that the average daily distance is equal to 487km (CNR 2014), this range corresponds to the minimal requirements of the market. For comparison, Diesel HDVs on the market offer tank capacity up to 1000 liters, providing 2700 km of autonomy.

Input data for the production of vehicles is based on work from Spielman, compiled in ecoinvent and published in Life Cycle Inventories of Transport Services, Final report ecoinvent data v2.0, 2007.

TABLE 4-10 DENSITY AND LOWER HEATING VALUE OF FUELS

	Diesel	LNG	Hydrogen (700bar)
Lower Heating Value (MJ/kg)	43.1	45.1	120.1
Density (kg/m³)	832	410	39.3

Source: Edwards et al. 2011 and Den Boer 2013

LNG vehicle

LNG is preferred over compressed natural gas (CNG) for long haul and offers potential for CO2 reduction (Le Fevre 2014). LNG, stored at -161°C, requires a highly insulated cryogenic container to prevent rapid evaporation. The lorry construction dataset has been updated accordingly, considering a tank capacity of 106kg LNG. Such tank are available on the market, and the specifications from the HLNG72 tank sold by the company Ferox[11] have been used to estimate the empty weight of the tank : 184kg (composed of steel and glass fiber). The engine and the rest of the powertrain is assumed to be the same as the diesel truck.

Hydrogen vehicle

Hydrogen vehicle is the most hypothetic scenario investigated, but some field experiments are already conducted with hydrogen buses[12] and long haul trucks[13]. The lorry production dataset was updated with an electric drive train and a compressed hydrogen tank (capacity 42kg H_2) similar as the one already available for hydrogen buses. Emissions associated with vehicle testing are set to 0.

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[11] Chart Ferox, HLNG Vehicle Tanks, retrieved 04.11.2014 from: http://www.chart-ferox.com/getattachment/cbe66c42-2bd1-4ceb-8fc6-a42662ac2cad/14771738.aspx

[12] PostBus, Reducing dependence on fossil fuels, retrieved 04.11.2014 from: http://www.postauto.ch/en/pag.../pag-nachhaltigkeit-antriebssysteme

[13] Vision motor corp, Tyrano Heavy-duty Class 8 truck, retrieved 04.11.2014 from: http://visionmotorcorp.com/tyrano.asp

The lorry construction dataset has been modified using the results and datasets from project THELMA. It is assumed that this equipment will last the entire lifetime of the truck (5.25years).

- PEM fuel cell with disposal 2020, 300kW peak
- E drivetrain 2030
- Fuel tank, compressed hydrogen 700 bar, made of akuminum, steel, carbon and glass fiber
- Li-ion battery, 200kg. By analogy with fuel cell passenger car we have assumed a typical energy of 38kWh

These elements were added to the existing lorry construction dataset (*lorry production, 40 metric ton*, 2010, ecoinvent 3.1). Thus material inputs might be overestimated due to the fact that internal combustion engine and original drivetrain materials are not removed. This is assumed to have a marginal impact on final LCA results. These parts, mainly consists of low alloyed steel which contribute to less than 1% to environmental impacts. By comparison, impacts of the fuel cell are in the range of 10-30% of the total lorry construction activity, hydrogen tank in the range of 7 to 12% and reinforcing steel 13 to 24% (depending on the impact category).

Regulatory context

Until now EURO standards were targeting air quality, and not GHG and climate change.

Except for CO_2, EURO VI standards have achieved 90-95% emission reduction compare to 1990. Brake wear remains however a significant contributor of primary PM. NOx and PM emissions regulations have impacted fuel consumption over the last decade (Muncrief, 2014) therefore, for the next round of emissions regulation, the focus will probably be on fuel consumption (as there are no after treatment solutions to reduce CO_2 emissions) and includes GHG limits in the regulatory package. This pursues a combined objective of economic efficiency and greenhouse gases emissions reduction (European Commission, Memo 14/366). A date has not be set for now. Consultation is still needed, to agree on measurement rules, baseline level and transparency of the monitoring scheme. Cost effectively, a reduction of 30% could be reached in fuel consumption and CO_2 emissions reductions in 2030 compare to 2010 (European Commission 2014). In the same time Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR), Diesel Particulate Filter (DPF) and Three way catalysts will become more largely adopted and integrated, in order to further reduce local pollutant emission, while limiting fuel consumption penalty[14].

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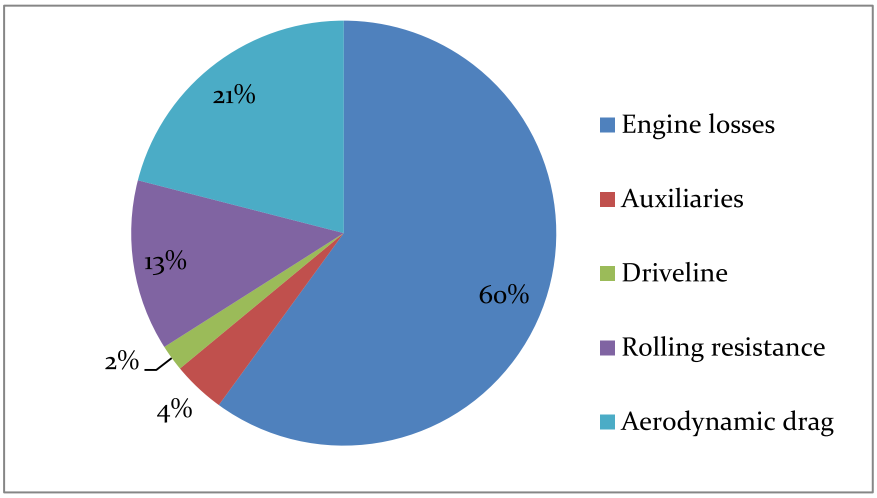
[14] Automotive World, Life beyond EURO VI, retrieved 04.11.2014 from http://www.automotiveworld.com/megatrends-articles/life-beyond-euro-vi/

Confrontation of efficiency assumptions with market realty

Some features, independent from the propulsion technology, such as aerodynamic improvements with advanced body designs, intelligent driving recommendations, and low rolling resistance tyres, can be implemented with no further requirements in terms of fueling or recharging infrastructures.

FIGURE 4-5 DISTRIBUTION OF TOTAL ENERGY IN HDV OPERATION



Source : Leduc 2009

The expected percentage gains used in this study are already achieved in some advanced vehicles and prototypes. For example Renault optifuel[15] training and technology for fuel consumption achieve 6.4 % reduction in fuel consumption ; Wal Mart[16] has developed a concept with advanced aerodynamics (20% reduction in aerodynamic drag) as well as Mercedes Benz[17]. Volvo has implemented Controllable air compressor (not used for up to 90% of the time) achieving 3.5% fuel consumption benefit, and predictive cruise control coupling GPS and topographic data (I-see system[18]) with 5% consumption reduction.

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[15] Renauls Trucks, Optifuel solutions win an award, retrieved 04.11.2014 from: http://corporate.renault-trucks.com/en/press-releases/renault-trucks-optifuel-solutions-win-an-award-in-germany.html

[16] Business Insider, by Benjamin Zhang, Wal-Mart Says This Is The Delivery Truck Of The Future, retrieved 04.11.2014 from: http://www.businessinsider.com/walmarts-truck-of-the-future-2014-3

[17] The Verge, by Chris Welch, Mercedes built a self-driving truck that could save thousands of lives every year, retrieved 04.11.2014 from: http://www.theverge.com/2014/10/7/6939809/mercedes-self-driving-truck-could-save-thousands-lives-each-year

[18] Volvo Trucks, I-See, retrieved 04.11.2014 from: http://www.volvotrucks.com/trucks/uk-market/en-gb/trucks/volvo-fh-series/key-features/Pages/i-see.aspx

4.2.4. Non vehicle related developments

Impacts of traffic management and control measures (reducing congestion, managing dedicated lanes, efficient routing, dynamic speed limit) are not investigated from the perspective of environmental impact of infrastructure.

Infrastructure

Datasets for road maintenance and road provision were not updated for 2030 scenarios. However demand factors were updated using traffic predictions from ARE 2012 presented in section 4.1. and assuming that in the same time the total length of the network will remain stable with 71 500 km of roads, a value which doesn't change significantly since 2000[19].

The infrastructure will be more intensively used and demand factors for road maintenance and road provision for a same functional unit compared to 2013 will decrease.

Fuel production pathways and fuel quality

For 2030 scenarios, three different fuels have to be considered: Diesel, LNG and Hydrogen.

- Diesel

  The same production pathway, and fuel quality standard as for today are assumed. Indeed the EN590 is already the most restrictive regulation in application over the world, and further improvement would be at the expense of higher Well-to-Tank emissions and refining costs.

- LNG

  Datasets developed for THELMA have been used.

- Hydrogen

  The environmental impacts of hydrogen trucks via different production pathways are examined. As hydrogen is not yet available on industrial volumes on the market three different scenario for hydrogen production pathway were considered: electrolysis with the average Swiss electricity mix in 2030 (Swiss mix 2030), electrolysis with a renewable certified electricity mix (Renewable 2030), and a methane reforming option (NG reforming, or steam mthane reforming SMR). These datasets were developed for the THELMA project (Simons and Bauer, 2011).

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[19] Statistique Suisse, Infrastructure et longueur des réseaux, retrieved 04.11.2014 from : http://www.bfs.admin.ch/bfs/portal/fr/index/themen/11/03/blank/01.html

4.2.5. Summary of LCI data

TABLE 4-11 SUMMARY OF LCI DATA FOR ROAD

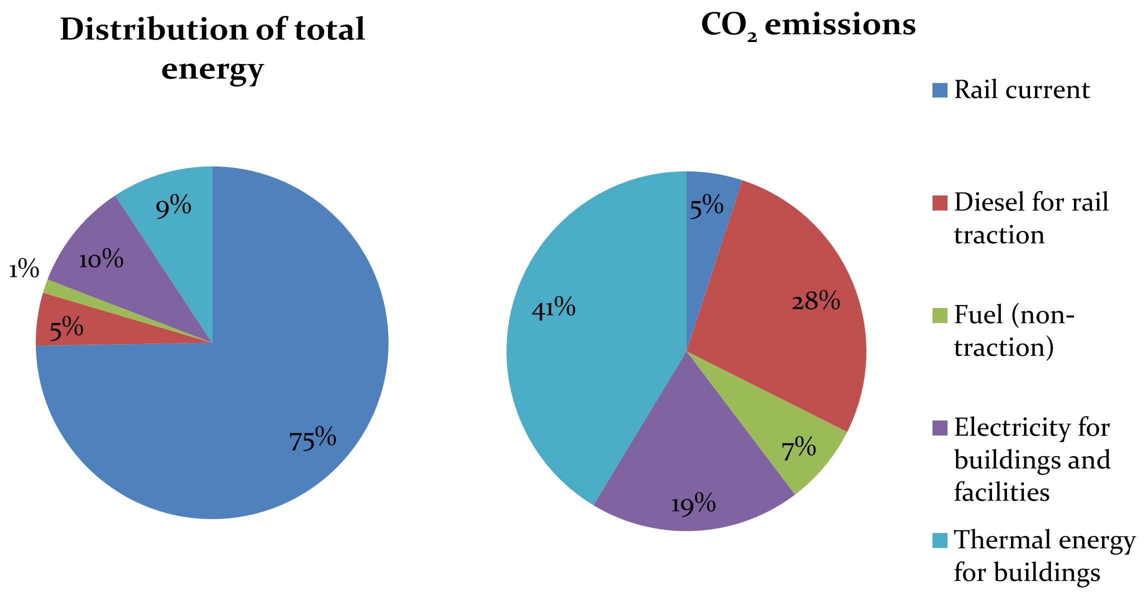
Transport, freight, lorry >32t	EURO III 2004	EURO VI 2013	Diesel 2030	LNG 2030	H_2 2030	Unit
Known outputs to technosphere per tkm						
Treatment of brake wear emissions, lorry	1.41E-5	1.41E-5	1.41E-5	1.41E-5	7E-6	kg
Treatment of road wear emissions, lorry	1.21E-5	1.21E-5	1.21E-5	1.21E-5	1.21E-5	kg
Treatment of tyre wear emissions, lorry	1.39E-4	1.39E-4	1.39E-4	1.39E-4	1.39E-4	kg
Known inputs from technosphere per tkm						
Maintenance, lorry 40 metric ton*	7.12E-8	7.12E-8	6.68E-8	7.12E-8	8.54E-8	p
Lorry 40 metric ton, production*	7.12E-8	7.12E-8	6.68E-8	7.12E-8	8.54E-8	P
Operation and maintenance, road CH	5.83E-5	5.83E-5	4.62E-5	4.62E-5	4.62E-5	m.y.
Road provision, CH	7.87E-4	7.87E-4	7.22E-4	7.22E-4	7.22E-4	m.y.
Fuel, at fuelling station*	1.70E-2	1.39E-2	8.62E-3	8.26E-3	3.50E-3	kg
Emissions to air per tkm						
Ammonia	1.5E-7	4.5E-7	2.92E-7	1.58E-7	0	kg
Carbon dioxide fossil	5.39E-2	4.41E-2	2.92E-2	2.43E-2	0	kg
Carbon monoxide fossil	8.95E-5	4.44E-5	2.35E-5	1.55E-5	0	kg
Dinitrogen monoxide	3.5E-7	2.4E-6	1.30E-6	3.23E-7	0	kg
Methane fossil	3.82E-7	3.50E-8	1.85E-8	5.92E-6	0	kg
Nitrogen oxides	3.71E-4	2.53E-5	1.69E-5	3.88E-5	0	kg
NMVOC*	1.54E-5	6E-7	3.18E-7	7.05E-7	0	kg
PM 2.5	7.6E-6	2.03E-7	1.27E-7	8.82E-8	0	kg
Sulphur dioxide	9.51E-6	2.23E-7	1.47E-7	2.35E-7	0	kg

*specific dataset linking for 2030 HDVs

4.3. Rail

In this section, the focus is on electric freight trains. Rough assumptions are also made for passenger trains to estimate the total load on infrastructure. This sector is less regulated in terms of emissions in comparison to the road sector.

FIGURE 4-6 ENERGY AND CO2 EMISSIONS REPARTITION IN RAIL SECTOR



Source : SBB facts and figures 2013

Point infrastructures are not considered in this thesis, and therefore electricity and thermal energy for buildings is not considered (non directly transport related, see section 3.1). The focus is on 16.7 Hz electricity (power traction) and not 50Hz (buildings).

It is important to note that SBB operates its own power plants and distribution network. Therefore the development perspectives for electricity mix are not coupled with the national scenarios. Electricity mixes are discussed in subsection 4.3.3.

Switzerland has the densest railway network in Europe[20]. This implies a very challenging management of congestion and optimized travel plans. Increasing the average network train velocity by a few percent can save a lot in capital and expenses annually (GE Railedge movement planner[21]). However the potential limitations and bottlenecks due to the network capacity are not considered, and we assume that the traffic predictions from ARE are

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[20] Federal Office of Transport, Railways, retrieved 04.11.2014 from: http://www.bav.admin.ch/org/aufgaben/00510/index.html?lang=en

[21] Railedge movement planner reduces train emissions, retrieved 04.11.2014 from: http://www.ecomagination.com/ar2010/innovation/efficiency/railedge-movement-planner/

consistent with the infrastructure development plans (FDRI, Rail Infrastructure Development Plan[22]).

4.3.1. Database design

Table 4-12 below shows all the categories taken into account for the life cycle inventory for a freight train in the Swiss conditions for one tkm, and represents the database design in version 3.1 of ecoinvent (*transport, freight train, electricity*, 2012, ecoinvent 3.1).

TABLE 4-12 TRAIN DATABASE DESCRIPTION

Transport, freight train, electricity, CH	Unit	Description
Known inputs from technosphere per tkm		
Locomotive production	p	Materials and energy inputs (mainly steel)
Maintenance locomotive	p	
Goods wagon production	p	Materials and energy inputs (mainly steel)
Maintenance goods wagon	p	
Diesel	kg	Used for shunting
Electricity high voltage for Swiss Federal Railways	kWh	Used for traction power
Railway track construction	m.y.	Track bed, gravel, rails, civil engineering (mainly steel, concrete and diesel burned in building machine)
Emissions to air per tkm		
Tailpipe emissions from shunting locomotives	kg	Exhausts emissions
Emissions to soil per tkm		
Iron	kg	From rail, brake and wheel abrasion

To make a consistent comparison with road sector, for impact assessment locomotive production and wagon production are aggregated into vehicle production, and locomotive maintenance and wagon maintenance are aggregated into vehicle maintenance. Rail, brake and wheel abrasion are predominantly composed of iron, however a further decomposition in wear emissions, similar to the one available for trucks can be made for future ecoinvent updates using the work from Burkhardt (2007).

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[22] SBB, FDRI : the service improvements, retrieved 04.11.2014 from: http://www.sbb.ch/en/group/the-company/projects/upgrading-the-rail-network/zeb/angebotsverbesserungen.html

4.3.2. Demand factors

TABLE 4-13 INPUTS FROM TECHNOSPHERE, TRAIN 1/2

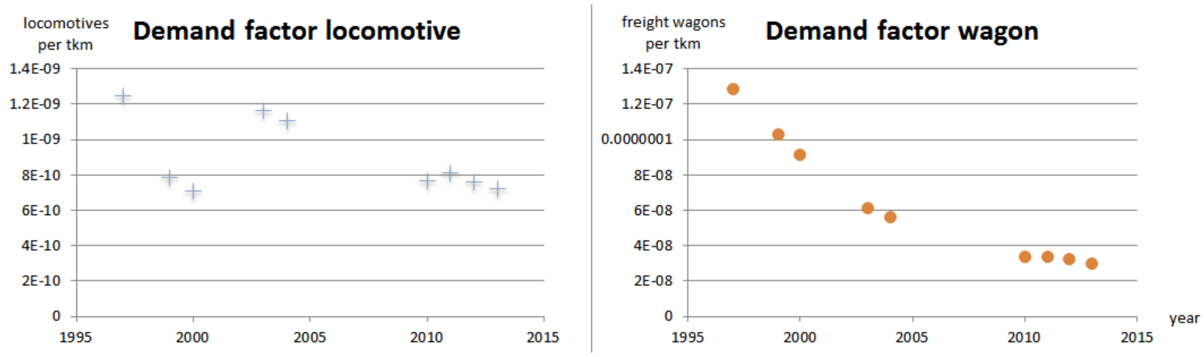
Transport, freight train, electricity, CH	2004	2013	2030	Unit
Known inputs from technosphere per tkm				
Locomotive production	1.10E-9	7.23E-10	7.23E-10	p
Maintenance locomotive	1.10E-9	7.23E-10	7.23E-10	p
Goods wagon production	5.59E-8	2.99E-8	2.10E-8	p
Maintenance goods wagon	5.59E-8	2.99E-8	2.10E-8	p

These values are based on logistic efficiencies. The total fleet of vehicles of SBB was divided by the annual transport performance times the lifetime of the vehicle considered.

For 2030, historical data from SBB annual reports were used to extrapolate trends in vehicle use. The results are shown in the graphs below. Therefore no changes were considered for demand factor of locomotives, and an extrapolated value of 2.10E-8 freight wagon per tkm has been derived by prolonging the graph of historical trends.

Actual datasets for vehicle construction and maintenance were not updated.

FIGURE 4-7 HISTORICAL TRENDS OF RAIL VEHICLE USE



We assume that this logistic improvement is not at the expense of more shunting operations.

Wagons are mainly made out of steel and aluminum, the current dataset from ecoinvent (*goods wagon production*, 1993, ecoinvent 3.1) has been used for the three time points considered. Closed and open wagons are treated as closed wagons. 65% of transport performance is performed by closed wagons and 35% of the transport performance is allocated to tank wagons. The dataset is the average of these different types. Recycling is not considered in wagon dataset, created in 1993[23], but plastic, glass and mineral oil are considered for locomotive disposal (*treatment of used locomotive*, 1993, ecoinvent 3.1).

TABLE 4-14 INPUTS FROM TECHNOSPHERE,TRAIN 2/2

Transport, freight train, electricity, CH	2004	2013	2030	Unit
Known inputs from technosphere per tkm				
Diesel	6.84E-4	6.66E-4	3.47E-4	kg
Electricity high voltage for Swiss Federal Railways	8.50E-2	7.30E-2	6.40E-2	kWh
Railway track construction	6.40E-5	5.47E-5	4.51E-5	m.y.

Diesel

Annual diesel consumption from SBB is allocated to freight transport with respect to the fleet of shunting vehicles (passenger trains require fewer shunting operations). Therefore in 2004 93% of the diesel consumption was allocated to freight, and in 2013 85%. Total diesel consumption for 2030 was derived from SBB statement predicting 6500t annual CO2 emissions reductions from 2020 onwards due to the use of new hybrid shunting vehicles[24].

Electricity

Current ecoinvent data was considered valid for 2004. 2013 electricity consumption was calculated with the online tool EcoTransIT[25]. To prevent bias from topography differences, two different routes have been compared: on the north-south axle Schaffhausen-Chiasso (289km) and on the east-west axle Geneva-Scuol (459km). The total electricity consumption, divided by the net load times the distance gave us the energy consumption per tkm: 6.6E-2kWh/tkm in average. Adding 10% transmission losses (to keep the same assumptions as in the 2004 dataset) we obtain the value of 7.3E-2kWh/tkm adopted in this thesis. The change compare to 2004 is consistent with the one of 10% observed in the Ecotransit report (Ecotransit 2011) between 2003 and 2009. Due to the relative importance of this figure, it is also compared with the specific energy consumption mentioned in diesel equivalent in SBB facts and figures 2013 : 0.63kg diesel equivalent per 100 tkm, i.e. (using 43.1MJ/kg for the lower heating value of diesel), we obtain 7.5E-2kWh/tkm. It is unclear if the diesel from shunting processes is included, which would reduce the electricity consumption to 6.8E-2kWh/tkm.

For 2030 scenario, electricity consumption was additionally reduced by 12%. Several measures can justify this value such as improving driving cycle with in cab speed recommendations (smart drive control taking into account topography) and signals for locomotive drivers, reducing unnecessary stops at red lights and excessive braking, improving timetabling processes. An increase in use of electric brakes is not applicable to freight train due to the low

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[23] The wagon is nearly pure steel, so the recycling process is only the separation of the different materials in the wagon and their transport, and thus negligible. End-of-life phase is also neglected in Facanha and Horvath 2006.

[24] SBB, Climate protection, retrieved 04.11.2014 from: http://www.sbb.ch/en/group/the-company/der-umwelt-verpflichtet/klimaschutz.html

[25] Ecotransit, Calculation, retrieved 04.11.2014 from: http://www.ecotransit.org/calculation.en.html

ratio of powered axles. Similarly, efficiency gains with improvements in embedded systems such as ventilation systems, and wagons preheating (Plan d'économie d'énergie des CFF, 2007) are only applicable to passenger trains.

Studies ordered by the Federal Office for Energy and conducted by the engineering company Emkamatik[26] (BFE 2007 and BFE 2009) have estimated the following quantitative breakdown for energy gains: Unexpected event management and driving conditions: minimum 5%. Achieved with signals (2-3%), information about operational conditions in the locomotive (1-2%), include energy consumption in the objective function for route selection (0.5-1%). This set of measures if particularly promising for freight trains, which are not facing the same challenges as passenger trains with tight schedules and timetables. Vehicle improvement: up to 3%. These are short term conservative objectives, therefore 12% reduction for 2030 is a realistic assumption.

Railway track construction

Passenger and freight transport are in competition for the same infrastructure as well as passenger car and HDVs compete for motorways. The gross weight allocation rule was used for this calculation. Average gross mass of passengers trains was estimated with Bombardier 2012 (see table 4-4 in section 4.1.) and for freight trains the ratio from EcoTransIT was used. Thus we have the following vehicles mass:

TABLE 4-15 AVERAGE MASS OF TRAINS

	Year 2004	**Year 2013**	**Year 2030**
Passenger train	461 t (117 passengers)	422 t (127 passengers)	472 t (169 passengers)
Freight train	657 t	757 t	757 t

TABLE 4-16 EMISSIONS TO SOIL AND AIR, TRAIN

Transport, freight train	2004	2013	2030	unit
Emissions to soil per tkm				
Iron	1.27E-4	1.27E-4	1.27E-4	kg
Emissions to air per tkm				
Tailpipe from diesel combustion	EURO III eq	EURO III eq	EURO VI eq	
Sulphur hexafluoride	3.74E-9	3.30E-9	2.81E-9	kg

Original value for iron emissions to soil was much lower : 1.78E-5 kg per tkm (*transport, freight train, electricity*, 2012, ecoinvent 3.1). These emissions are related to the abrasion of rail. 1912t of brake material were emitted in 2003 (based on brake pad use), 67 % of it are attributed to freight trains. The total was divided by the corresponding annual transport performance. (Burkhardt 2007). We do not consider any development in this field.

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[26] http://www.emkamatik.com/index_en.html

With the use of new hybrid shunting vehicles (Eem 923), CO_2 emissions from rail traction are expected to drop by 18%. The long term objective for rail current is to reach zero emissions. Tailpipe emissions due to the combustion of diesel are calculated using the same per kg fuel emissions of the mentioned EURO standard for HDVs, as they are implementing similar after treatment solutions such as particle filters, but with a delay of one decade.

Sulphur hexafluoride, from electricity substations (this gas is used for current interruption in high voltage circuits), is calculated using an emission factor of 4.4 E-8 kg/kWh according to the current rule in ecoinvent 3.1.

4.3.3. Non vehicle related developments

The greatest potential for reducing environmental impacts of freight train is not in rail operations but in supporting processes such as shunting operations for train sorting and infrastructure efficiency.

Electricity mix

By 2025 SBB intends to operate exclusively on electricity from renewable sources. For this purpose new generating power is built, with for example the pumped hydro electrical storage in Nant de Drance[27].

TABLE 4-17 ELECTRICITY MIX FOR TRAINS

	2004	2013 (ecoinvent 3.1)	2030
Electricity mix	Hydropower 71% Nuclear 29%	Hydropower 72.77% Nuclear 27.01% Renewable 0.23% (biomass and wind)	100% run of river and alpine hydro reservoirs

Railway track

The original dataset from ecoinvent (*railway track construction,* 2010, ecoinvent 3.1) was mainly based on results from a semester project from year 1993. This dataset was therefore updated using 2004, 2013 and 2030 network estimates.

If the total length of the network is not expected to grow excessively during the next 20 years a lot of civil engineering work will be performed, increasing the share of bridges +12% and tunnels +93 % per km of railway track (SBB 2012). This consideration has major implications because, according to Stripple and Uppenberg (2010), tunnels and bridges contributes both to 16% of environmental impact in the category global warming, due to the additional amounts of steel and cement required. Track and track foundations contribute to 45%, and the rest is

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[27] Alpiq, Centrale de Nant de Drance, retrieved 04.11.2014 from : http://www.alpiq.com/fr/news-articles/communiques-de-presse/media_releases.jsp?news=tcm:97-108309&tag=Nant-de-Drance&taxid=8049&schema=52638

due to stations and power signaling and telecom. Steel and cement together cause 75% of the total CO2 emissions.

Railway track capacity is a big issue, involving several parameters such as number of train, stability, average speed and heterogeneity. This issue was not explored, assuming that the network planned will cover the traffic planned in 2030. However quality of service, punctuality or timetable robustness could be degraded. Numbers of crossing, doubling line and capacity increase work is planned (FABI, Financing and upgrading Swizerland's rail infrastructure[28]).

The main components of a railway track are: sleepers (either concrete or wood), track ballast (crushed rock), embankment fill, catenary foundations, steel and communication and signaling systems.

The assumption of a double way track is equal to two single way tracks is challenged by the fact that some infrastructures are not doubled for example the service road, and catenary work. Currently 49% of the Swiss network is composed by single way lines.

Detail of modelling using Rozycki et al. (2003) and civil engineering infrastructure developments from SBB 2012:

TABLE 4-18 CIVIL ENGINEERING STRUCTURES IN RAIL NETWORK

	2004	2013	2030
Km of tunnels	248	269	411
Km of bridges	87	92	101
Total network*	2300 km	2360 km	2525 km

*in double way track equivalents

TABLE 4-19 LCI DATA FOR RAIL NETWORK

	2004	2013	2030	unit
Known inputs from technosphere per m.y.				
Glyphosphate	5.8E-4	2.9E-4	2.9E-4	kg
Gravel crushed	198	217	239	kg
Concrete	6.16E-2	6.36E-2	7.34E-2	m^3
Reinforcing steel	15.37	15.61	16.75	kg

Diesel burned in building machine and electricity are also included in the dataset, but the amount is not updated (9.5 MJ/m.y for diesel, corresponding to 0.26l). A simulation made on SimaPro with the 2013 dataset has shown that more than 90% of impacts in climate change, terrestrial acidification and PM formation of railway track construction are related to this list of four materials. Diesel burned in building machine contribution is below 1%. Scaling up with

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[28] SBB, FABI, retrieved 04.11.2014 from: http://www.sbb.ch/en/group/the-company/projects/upgrading-the-rail-network/fabi.html

respect to concrete consumption (around 20%) would also imply that these processes would not improve. Thus we decided to keep the current value.

- Glyphosphate

  Annual consumption of herbicides referenced in SBB 2013, using a glyphosphate concentration of 360g/l and divided by total network length.

- Gravel crushed

  Ballast and gravel consumption referenced in SBB 2013 and divided by total network length.

- Concrete and reinforcing steel

  Share of tunnel and bridges is used to compute the weighted average based on Rozycki figures, the expected working life is mentioned in brackets.

Material requirement per km (using a concrete density of 2400 kg/m^3):

TABLE 4-20 MATERIAL REQUIREMENTS FOR RAIL NETWORK ELEMENTS

	Rail driveway (30y)	**Tunnel (100y)**	**Bridge (50y)**	**unit**
Known inputs from technosphere per km				
concrete	2376	105 600	213 600	m^3
steel	282	2100	4900	t

4.3.4. Summary of LCI data

TABLE 4-21 SUMMARY OF LCI DATA FOR RAIL

Transport, freight train, electricity, CH	2004	2013	2030	Unit
Known inputs from technosphere per tkm				
Locomotive production	1.10E-9	7.23E-10	7.23E-10	p
Maintenance locomotive	1.10E-9	7.23E-10	7.23E-10	p
Goods wagon production	5.59E-8	2.99E-8	2.10E-8	p
Maintenance goods wagon	5.59E-8	2.99E-8	2.10E-8	p
Diesel	6.84E-4	6.66E-4	3.47E-4	kg
Electricity high voltage for Swiss Federal Railways*	8.50E-2	7.30E-2	6.40E-2	kWh
Railway track construction*	6.40E-5	5.47E-5	4.51E-5	m.y.
Emissions to air per tkm				
Ammonia	1.356E-8	5.71E-9	1.37E-8	kg
Carbon dioxide fossil**	2.14E-3	2.11E-3	1.10E-3	kg
Carbon monoxide fossil	1.07E-5	3.59E-6	1.11E-6	kg
Dinitrogen monoxide	6.8E-8	1.38E-8	6.11E-8	kg
Methane fossil	8.84E-8	1.50E-8	8.71E-10	kg
Nitrogen oxides	3.74E-5	1.46E-5	6.32E-7	kg
NMVOC*	3.45E-6	6.07E-7	1.50E-8	kg
PM < 2.5 µm	4.27E-7	2.13E-7	6.34E-9	kg
PM > 10 µm	1.58E-5	7.89E-6	1.97E-6	kg
PM > 2.5 µm and < 10 µm	6.89E-6	3.44E-6	8.61E-7	kg
Sulphur dioxide**	3.83E-7	1.07E-8	5.55E-9	kg
Sulfur hexafluoride	3.74E-9	3.30E-9	2.81E-9	
Emissions to soil per tkm				
Iron	1.78E-5	1.78E-5	1.78E-5	kg

*specific datasets developed for 2030

** calculated with formulas

Ammonia and dinitrogen emissions increase because of the introduction of EUROVI-like aftertreatment solutions in shunting locomotives (detailed in subsection 4.2.3).

5. Life Cycle Impact Assessment

The lifecycle impact assessment is calculated using the ReCiPe midpoint method with the hierarchist perspective in SimaPro v8.02. A selection of impact categories directly relevant to transport sector and typical for LCA of transport modes is presented here (description available in section 3.1): climate change is covered in section 5.1, terrestrial acidification in section 5.2 and particulate matter formation in section 5.3. All results are presented for one tkm. Extended and non aggregated results for all impact categories are available in the appendix.

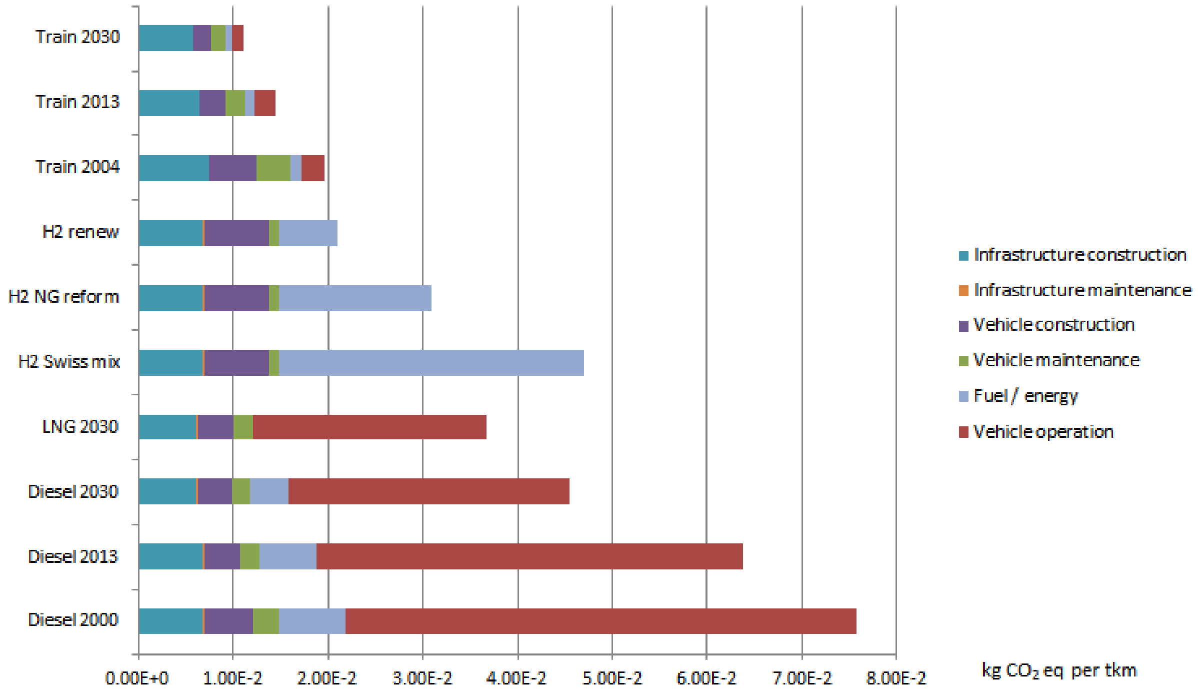
5.1. Climate change

Climate change is one of the most popular indicator when assessing environmental performance of transportation modes and is still not regulated. The results are shown in the table and graph below.

TABLE 5-1 LCA RESULTS, CLIMATE CHANGE

kg CO_2 eq Per tkm	Train 2030	Train 2013	Train 2004	H_2 renewables	H_2 SMR	H_2 Swiss mix	LNG 2030	Diesel 2030	Diesel 2013	Diesel 2000
Total	1.10E-2	1.45E-2	1.96E-2	2.10E-2	3.08E-2	4.71E-2	3.67E-2	4.54E-2	6.38E-2	7.57E-2
Vehicle Operation	3.93E-7	2.19E-3	2.28E-3	0.00E+0	0.00E+0	0.00E+0	2.45E-2	2.96E-2	4.49E-2	5.39E-2
Vehicle Maintenance	1.44E-3	2.00E-3	3.70E-3	1.00E-3	1.00E-3	1.00E-3	2.00E-3	1.88E-3	2.00E-3	2.71E-3
Vehicle construction	2.02E-3	2.71E-3	4.94E-3	6.85E-3	6.85E-3	6.85E-3	3.81E-3	3.59E-3	3.83E-3	5.19E-3
Infrastructure construction	5.73E-3	6.48E-3	7.45E-3	6.75E-3	6.75E-3	6.75E-3	6.19E-3	6.19E-3	6.75E-3	6.75E-3
Infrastructure maintenance	n/a	n/a	n/a	1.92E-4	1.92E-4	1.92E-4	1.52E-4	1.52E-4	1.92E-4	1.92E-4
Fuel / Energy	6.80E-4	1.09E-3	1.20E-3	6.23E-3	1.61E-2	3.23E-2	1.63E-5	4.03E-3	6.08E-3	6.99E-3

FIGURE 5-1 LCA RESULTS, CLIMATE CHANGE



First of all, all truck technologies present higher impacts than freight train. For all periods considered freight train impacts are in the range of 22 to 26% of diesel trucks. The operating phase, which corresponds mainly of the fuel burning, dominates impacts for internal combustion engines vehicles. Regarding Fuel Cell trucks, they clearly outperform ICE trucks, only if hydrogen is produced from methane reforming (-32% compared to Diesel 2030) or renewable energy (-54% compared to Diesel 2030). A hydrogen truck fueled with hydrogen produced by electrolysis with the Swiss electricity mix has however similar climate change impact as Diesel trucks. But on the other hand, switching from Tank-to-Wheel to Well-to-Tank emissions with hydrogen production, makes carbon capture solutions on site feasible. Results for LNG trucks might be underestimated due to new findings regarding leakage from natural gas infrastructure (see section 7.1).

Regarding infrastructure, rail and road have comparable impact per tkm of goods transported.

Hydrogen trucks are strongly penalized by the vehicle production phase, which require more CO2 intensive materials.

Spielmann and Scholz (Spielmann and Scholz, 2005) have reported that 70-75% of CO_2 emissions of diesel trucks occurred during the operating phase, which is consistent with the results presented here: 71% of climate change impact of Diesel 2000 is due to the operating phase. For freight trains, the dominating process elements are infrastructure construction and vehicle construction and maintenance, which represents 77% of the impacts in 2013. A similar value was obtained by Spielmann and Scholz.

To conclude, benefits in this category are coming mainly from better energy efficiency in the use phase of road vehicles and from combined effects of improved logistics, and eliminating diesel consumption in rail sector. Hydrogen truck ranking depends mainly on the production pathway used for hydrogen.

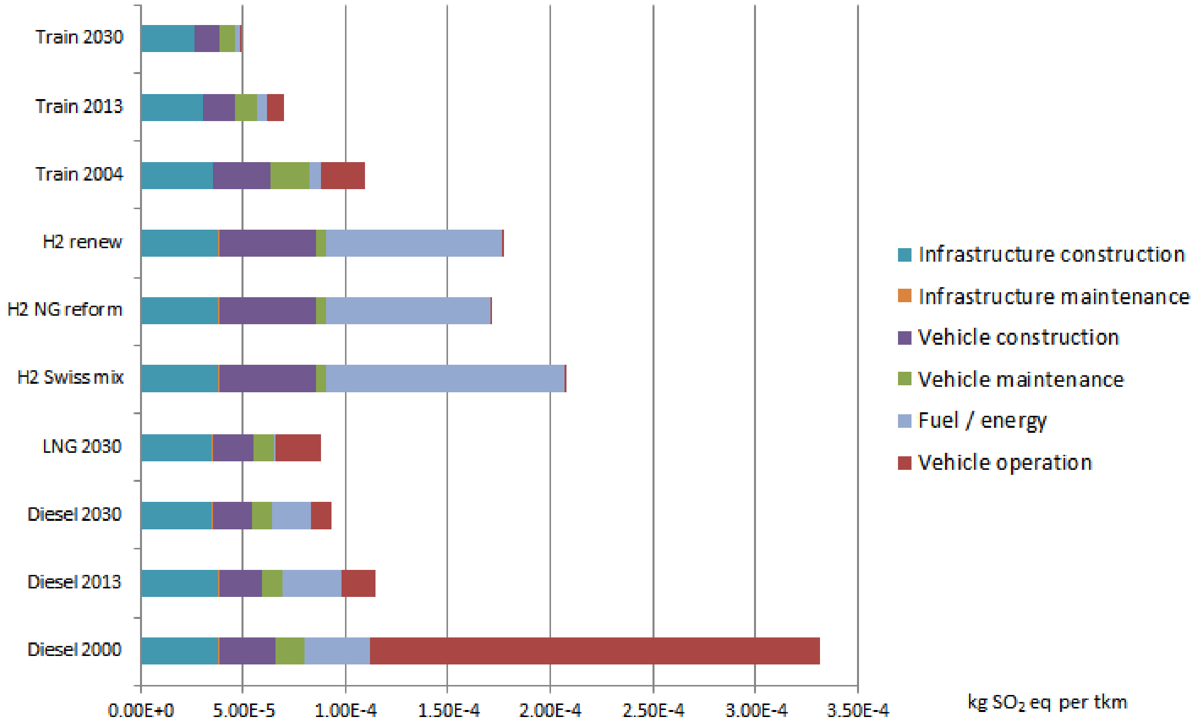
5.2. Terrestrial acidification

Terrestrial acidification highlights the impact of the transport on soils. A significant effect of the regulation EN590 regarding sulphur content is visible here and has completely changed the comparative assessment of modes.

TABLE 5-2 LCA RESULTS, TERRESTRIAL ACIDIFICATION

kg SO_2 eq Per tkm	Train 2030	Train 2013	Train 2004	H_2 renewables	H_2 SMR	H_2 Swiss mix	LNG 2030	Diesel 2030	Diesel 2013	Diesel 2000
Total	4.93E-5	6.98E-5	1.09E-4	1.77E-4	1.71E-4	2.08E-4	8.85E-5	9.34E-5	1.14E-4	3.32E-4
Vehicle Operation	3.93E-7	8.20E-6	2.13E-5	3.31E-7	3.31E-7	3.31E-7	2.28E-5	1.03E-5	1.64E-5	2.19E-4
Vehicle Maintenance	7.50E-6	1.04E-5	1.93E-5	5.17E-6	5.17E-6	5.17E-6	1.03E-5	9.69E-6	1.03E-5	1.40E-5
Vehicle construction	1.22E-5	1.58E-5	2.84E-5	4.70E-5	4.70E-5	4.70E-5	1.98E-5	1.91E-5	2.04E-5	2.76E-5
Infrastructure construction	2.66E-5	3.04E-5	3.50E-5	3.79E-5	3.79E-5	3.79E-5	3.48E-5	3.48E-5	3.79E-5	3.79E-5
Infrastructure maintenance	n/a	n/a	n/a	6.59E-7	6.59E-7	6.59E-7	5.22E-7	5.22E-7	6.59E-7	6.59E-7
Fuel / Energy	2.58E-6	4.89E-6	5.40E-6	8.54E-5	7.98E-5	1.17E-4	2.25E-7	1.89E-5	2.86E-5	3.23E-5

FIGURE 5-2 LCA RESULTS, TERRESTRIAL ACIDIFICATION



By reducing the maximum sulphur content allowed in diesel fuels from 350 ppm in 1999 to 10 ppm in 2009, EN590 regulation has greatly improved the general picture for terrestrial acidification: -65% of kg SO_2 eq per tkm between Diesel 2000 and Diesel 2013 trucks. In the same time, the rail sector has benefited from better logistic efficiency and has reduced its impact by 36%. In the future electric freight trains will remain 44-47% cleaner than Diesel and LNG trucks for this impact category.

Vehicle operation is not anymore the life cycle hotspot for sulphur dioxide equivalent emissions, and it is therefore more difficult to reduce these emissions in the next decades, due to the fact that they are now caused by long lasting infrastructure. The extensive use of concrete and steel causes the majority of these emissions The consequences of new infrastructure allocation schemes are investigated in section 7.1.

The picture for hydrogen trucks is relatively pessimistic in this impact category. The fuel cell materials and the hydrogen production causes significant emissions. The result is that total lifecycle emissions of hydrogen trucks are almost two times the one of diesel trucks in 2030.

5.3. Particulate matter formation

Particulate matter formation is one of the pollutant emission regulated via EURO standards. The low levels enforced by EURO VI has led to the introduction of particle filters. They were later implemented in the rail sector for shunting locomotives.

Theses filter have some drawback regarding fuel consumption and require expensive materials such as platinium. The total amount for a truck is approximately 12 to 15g [29] and is not included in the LCI for truck construction.

Primary and secondary emissions are included in ReCiPe method, taking into account atmospheric chemistry processes.

TABLE 5-3 LCA RESULTS, PM FORMATION

kg PM10 eq Per tkm	Train 2030	Train 2013	Train 2004	H_2 renewables	H_2 SMR	H_2 Swiss mix	LNG 2030	Diesel 2030	Diesel 2013	Diesel 2000
Total	2.66E-5	3.93E-5	6.14E-5	1.18E-4	1.17E-4	1.28E-4	8.78E-5	8.83E-5	1.01E-4	1.93E-4
Vehicle Operation	1.01E-6	6.87E-6	1.56E-5	1.87E-5	1.87E-5	1.87E-5	3.16E-5	2.66E-5	3.16E-5	1.17E-4
Vehicle Maintenance	2.83E-6	3.90E-6	7.18E-6	2.03E-6	2.03E-6	2.03E-6	4.05E-6	3.80E-6	4.05E-6	5.50E-6
Vehicle construction	6.65E-6	8.89E-6	1.61E-5	2.04E-5	2.04E-5	2.04E-5	1.16E-5	1.09E-5	1.16E-5	1.58E-5
Infrastructure construction	1.42E-5	1.63E-5	1.87E-5	3.74E-5	3.74E-5	3.74E-5	3.43E-5	3.43E-5	3.74E-5	3.74E-5
Infrastructure maintenance	n/a	n/a	n/a	6.31E-6	6.31E-6	6.31E-6	6.26E-6	6.26E-6	6.31E-6	6.31E-6
Fuel / Energy	1.82E-6	3.34E-6	3.74E-6	3.30E-5	3.19E-5	4.30E-5	5.02E-8	6.40E-6	9.66E-6	1.08E-5

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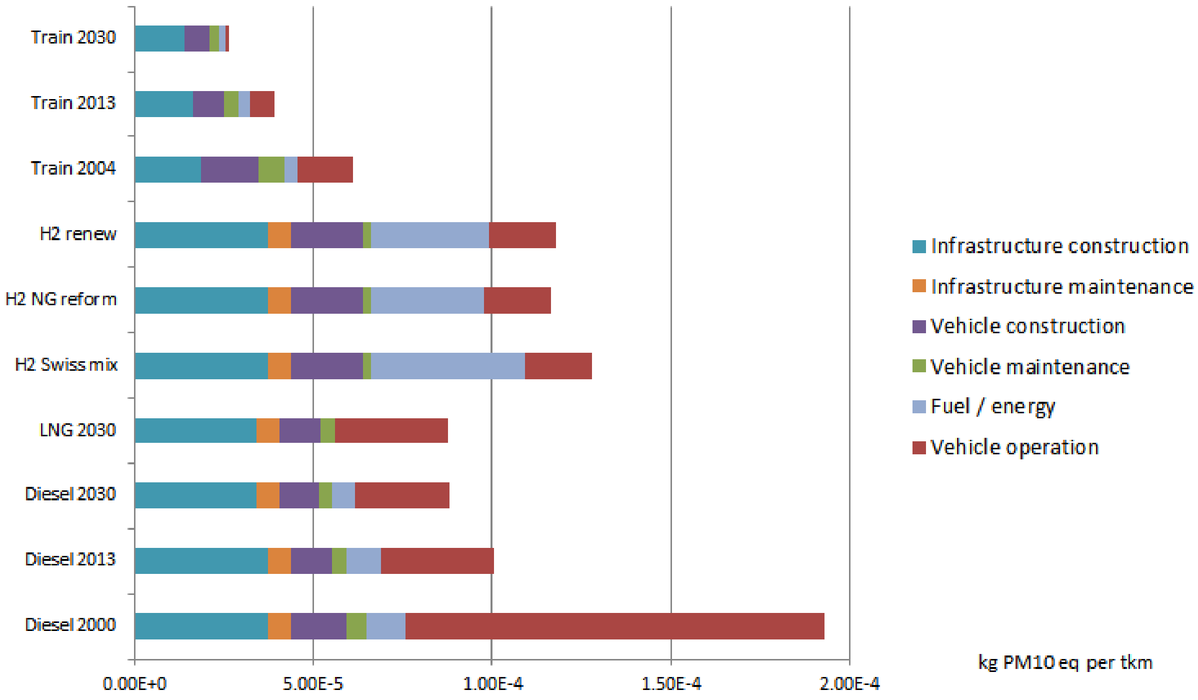
[29] Stephen Dietz, Platinium Group Metal Recovery from Spent Catalytic Converters using XRF, retrieved 04.11.2014 from: http://acceleratingscience.com/metals/platinum-group-metal-recovery-from-spent-catalytic-converters-using-xrf/

FIGURE 5-3 LCA RESULTS, PM FORMATION



For this category hydrogen trucks are not “zero emission” in their operating phase due to brake wear emissions. Adding upstream emissions from hydrogen production neutralizes the benefits of Fuel Cell trucks over ICE trucks.

Infrastructure construction represents 37-39% of the emissions of ICE trucks, and thus justifies further investigation in the infrastructure allocation scheme (section 7.1).

Again, improved vehicle use in the rail sector positively impacts the footprint of freight train.

6. Cost assessment

This chapter depicts the cost structure of freight transport following the decomposition presented in section 3.2. and using the results from life cycle inventories and traffic predictions presented in chapter 4. The scope of life cycle cost and life cycle emissions are very similar. In section 6.1 and 6.2 individual assumptions for each cost elements will be detailed, respectively for road and for rail goods transport. Results comparison is presented in section 6.3.

- Fuel or energy costs for vehicle operation
- Vehicle investment and maintenance
- Personnel and overhead costs
- Infrastructure costs: annual network expenses allocated to the total traffic performance
- External costs (ARE 2014): with a focus on noise, local air pollutants, and GHG

6.1. Road

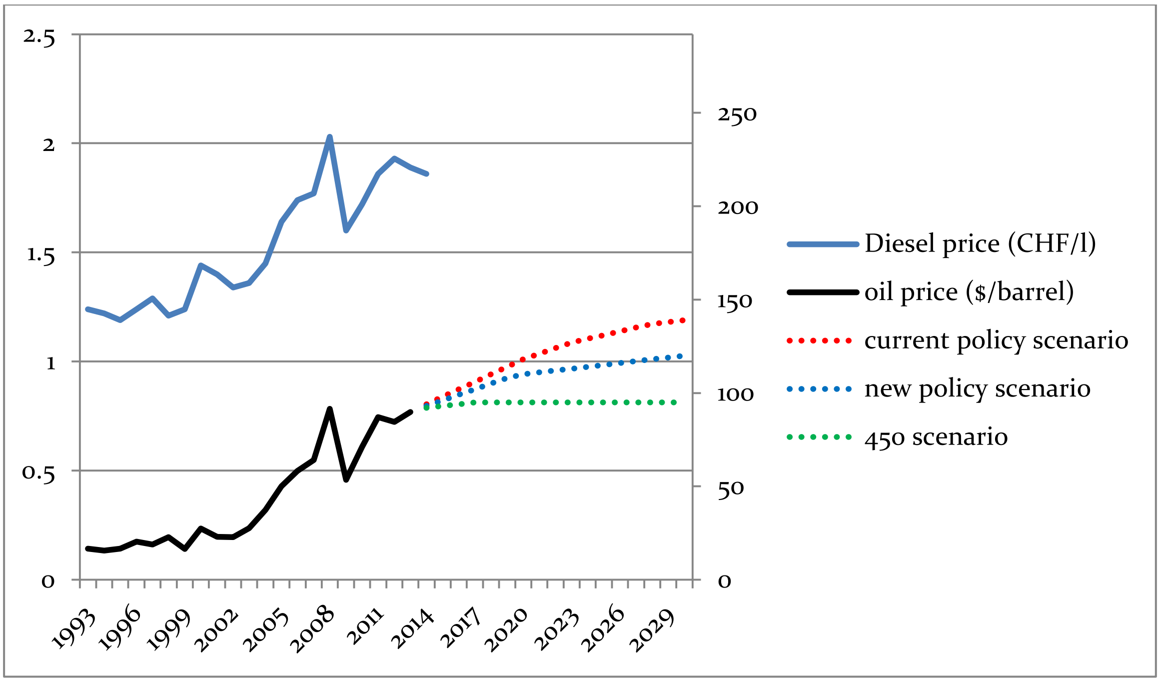
TABLE 6-1 COSTS INPUTS FOR ROAD

Cost category	source	EURO VI Diesel 2013	Diesel 2030	LNG 2030	H2 2030	unit
Fuel (before VAT, but including mineral oil tax)	WEO and den Boer et al. 2013	1.46	1.48 (low) 1.78 (high)	1.57 (low) 1.88 (high)	6.33 (low) 12.98 (high)	CHF per kg
Vehicle investment	Den Boer et al. 2013	157 000	157 000	196 000 (low) 235 000 (high)	209 000 (low 232000 (high)	CHF per vehicle
Vehicle maintenance	CNR 2014	0.0038	0.0038	0.0038	0.0019	CHF per tkm
Personnel and overhead cost	BFS	97 500				CHF per year
Road Infrastructure	BFS 2010	8.3 billion				CHF per year

Fuel

The conversion to kg for diesel has been made using a typical diesel density of 831 kg/m^3, and VAT was deducted. Therefore from 1.89CHF per liter in 2013[30], the per kg value before VAT obtained is 1.46 CHF per kg diesel.

FIGURE 6-1 DIESEL PRICE SCENARIOS (WEO 2012)



Sources : WEO 2012 and BFS[31]

To estimate future diesel prices we assumed that the variability is only related to the price of the oil barrel (keeping tax level 0.7587 CHF, 8% VAT, refineries and infrastructure costs constant). This gives the following formula in CHF (based on 2013 price):

$$
\begin{aligned}
&\mathit{diesel\ price\ per\ liter\ at\ fueling\ station} \\
&\quad = \left[\frac{\mathit{barrel\ price}}{117.35} + 0.286\ (\mathit{infr\ cost} + \mathit{distrib\ margin}) \right. \\
&\quad \left. + 0.7587\ (\mathit{mineral\ oil\ tax})\right] \times 1.08\ (\mathit{VAT})
\end{aligned}
$$

And thus the expected diesel prices in 2030 all taxes included: Current policy scenario : 2.31 CHF/ liter, New policy scenario : 2.14 CHF / liter, 450 scenario : 1.93 CHF/liter (1$ = 0.92CHF, 1barrel = 117.35 liter). We kept only the two extremums in the rest of the analysis.

For LNG similar prices developments as for diesel were assumed, thus we took the low LNG price from the current value[32] and the upper value is assumed 20% higher. The VAT is removed, but mineral oil tax is included based on the energy content.

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[30] Swiss Statistics, Indice des prix à la consommation, retrieved 04.11.2014 from http://www.bfs.admin.ch/bfs/portal/fr/index/themen/05/02/blank/key/durchschnittspreise.html

[31] cf footnote 30

[32] Rouler au gas naturel, retrieved 04.11.2014 from : http://www.vehiculeagaz.ch/economiser/calculs/

For hydrogen two prices scenarios low and high are taken from den Boer (2013). These prices are excluding taxes. Mineral oil tax is also applied on LNG and H2 based on the energy content (0.0212 CHF/MJ).

Vehicle investment

The figures are taken from Den Boer (2013). with low and high scenario. This study takes into account all relevant drivetrain components to produces these estimates.

Vehicle maintenance

CNR 2014 data is used, the scope cover tyres (estimated to account for 0.08cts CHF per tkm), maintenance and repairs costs. Hydrogen trucks benefits from lower maintenance costs due to the intrinsic properties of electric motors compare to internal combustion engines which contains more moving parts vulnerable for wearing out (Van den Bulk 2009).

Personnel and overhead costs

Personnel and overhead cost were calculated assuming an annual distance per driver of 105 000 km (CNR 2014), multiplied by a load factor of 20t and considering a wage of 65 000 CHF (BFS[33]) per year and adding 50% extra costs for overhead as applied in den Boer.

Road infrastructure

Swiss road account is the reference for this calculation (BFS 2012).

In detail the 8.3 billion are distributed in 4.7 billion for investment and 3.6 billion for operation[34]. The typical allocation used in LCA is applied, with a gross ton basis for investment and a vehicle basis for operation.

These expenditures are fully covered with revenues from mineral oil tax and motor vehicle tax (vignette or motorway tax plus heavy vehicle charge).

External costs

With climate change, noise and human health, 66% of road external costs are considered (ARE 2014). The rest, by order of importance is composed by up and downstream processes, nature and landscapes, buildings, damages to soil, biodiversity losses, agricultural losses. Accident contribution is below 1% and therefore not included as opposite to Sahin et al. study (2009).

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[33] BFS Lohnrechner, retrived 04.11.2014 from http://www.lohnrechner.bfs.admin.ch/Pages/SalariumWizard.aspx

[34] Swiss Statistics, Road account, retrieved 04.11.2014 from http://www.bfs.admin.ch/bfs/portal/en/index/themen/11/02/blank/02.html figures from 2011

Climate change is computed using LCA results with an avoidance cost of 107 CHF/t CO2.

The contribution of noise was divided by 3 for hydrogen truck, considering the electric engine. For LNG we have assumed 50% reduction (Hubert, 2013) and Diesel truck external costs from noise are taken equal to the 2013 figure. Further investigation in noise sources repartition between elements such as aerodynamic effects, road surface rolling noise and engine vibrations would be required for advanced estimates in this category.

Human health results are scaled with percentage change in LCA results from Diesel 2013 in impact category PM formation.

Comments on taxes

Mineral oil tax represents 0.7587CHF per liter of diesel. The same evel of tax based on energy content was applied to other fuels (LNG and Hydrogen). For hydrogen, depending on the production pathways, many different tax schemes can be envisaged, however due to the high production costs, in the end the tax level on hydrogen represents a lower share of the energy costs than for diesel or LNG.

The Heavy Duty Performance Related Tax (LSVA) is intended to cover external cost of transport sector, and depend on emissions class, today the rate for a EURO VI truck is and a EURO III truck are respectively 2.05cts CHF/Gtkm and 2.69 cts CHF/Gtkm applied on a fully loaded vehicle[35]. The total revenues of this tax are approximately 1.5 billion CHF. This tax is not mentioned previously as it is used to internalize external costs. Perceived costs are analyzed in the second part of section 6.3.

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[35] Swiss Customs Administration, HVC General/Rates, Retrieved 04.11.2014 from: http://www.ezv.admin.ch/zollinfo_firmen/04020/04204/04208/04744/index.html?lang=en

6.2. Rail

The Swiss Federal Railways are considered representative of the whole freight transport sector by train in Switzerland even if some others actors such as BLS cargo[36] are also operating.

TABLE 6-2 COSTS INPUTS FOR RAIL

Cost category	source	Train 2013	Train 2030	unit
Electricity	Alpiq	0.14	0.17	CHF per kWh
Vehicle investment	Baumgartner 2011	3 600 000 (locomotive) 145 000 (wagon)		CHF per vehicle
Vehicle maintenance	Baumgartner 2011	20% of vehicle investment over the whole lifetime		CHF per vehicle
Personnel and overhead cost	SBB 2013	409 300 000	-	CHF per year
Rail Infrastructure	SBB 2013	262.6 m (rail related freight) 3 848.6 m (total infrastructure)		CHF per year

Fuel and energy

Electricity is produced by SBB. The electricity price that Alpiq[37] charges to industries is used as a proxy for electricity cost estimates.

Diesel cost for shunting processes is considered negligible (even with the high price scenario of 1.88 CHF per liter, relatively to one tkm the cost would be less than 0.1 cts CHF) and therefore excluded.

Vehicle investment

The figures are taken from Baumgartner (2001). No significant prices changes are considered in the future as this paper gives only reference points and order of magnitude for these costs.

Vehicle maintenance

Baumgartner (2001) estimates maintenance costs to be equal of 20% of investment costs over the lifetime of the vehicle. This value is also adopted in this thesis, and assumed as is 2013 for 2030 scenario.

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[36] BLS cargo, retrieved 04.11.2014 from: http://www.blscargo.ch/d/homepage/index.php

[37] Alpiq, Le prix de l'électricité, Retrieved 04.11.2014 from : http://www.alpiq.ch/fr/medias/dossiers/electricity-price.jsp

Personnel and overhead costs

Personnel expenses in freight transport for year 2013 are taken from SBB annual report 2013. We observe a decreasing trend, therefore 10% efficiency gains per tkm were considered for 2030.

Rail infrastructure

Methodology in SBB annual report has been changed between 2004 and 2013. For consistency reasons we started the analysis for year 2013.

Infrastructure costs are composed on rail related operating expenses on the freight account on the income statement (262.6 m CHF) and operating expenses of total infrastructure (3 848.6 m CHF) allocated with respect to gross mass traffic. The electricity price is then deducted from it to avoid double counting.

External costs

With climate change, noise and human health, 75% of rail external costs are taken into account (ARE 2014). The rest, by order of importance is composed by nature and landscapes, up and downstream processes, buildings (details of methods used to calculate these costs are provided in the appendix).

Remark: In ARE study (2014) the climate change category is marginal because shunting processes and the life cycle approach is not used., this requires further investigation.

Noise was assumed to be reduced by 50% in 2030, because this topic is already considered by the Federal government and measures are planned until 2025[38].

Tax level for rail: infrastructure cost is not external for SBB, therefore no tax has to be collected to cover infrastructure expenses.

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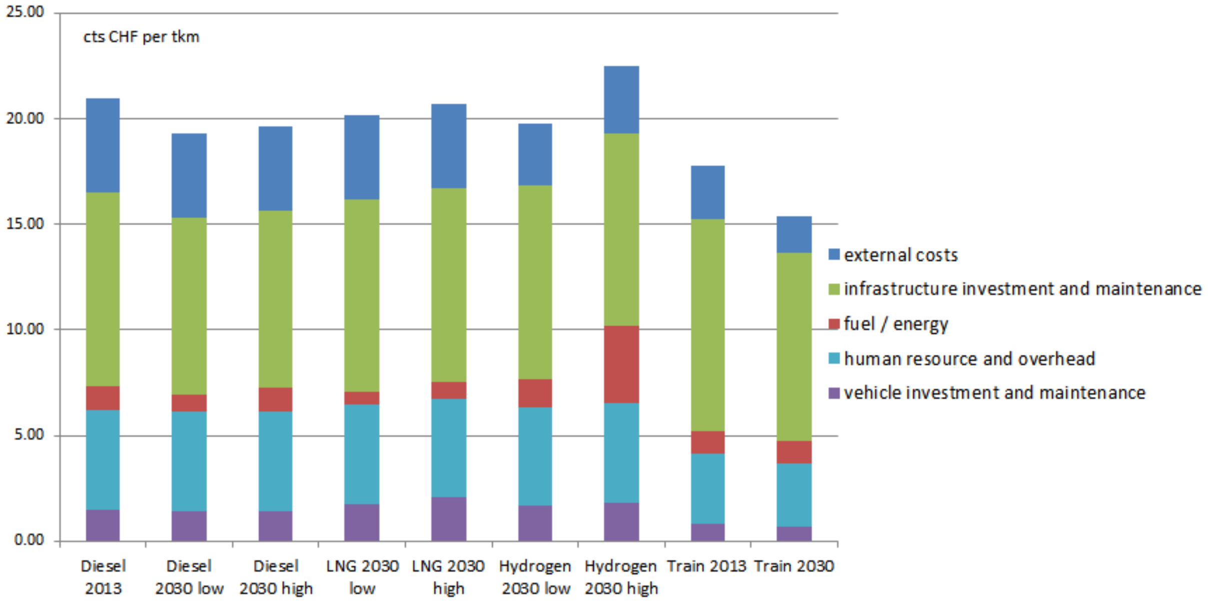
[38] Federal Administration, Loi federal sur la reduction du bruit émis par les chemins de fer, retrieved 04.11.2014 from : http://www.admin.ch/opc/fr/classified-compilation/19994383/index.html

6.3. Cost comparison

Two different approaches are used to compare the costs of road and rail modes. First the total cost to society are presented, including the full amount of infrastructure expenses related to freight transport and external costs due to climate change, noise and human health impacts. Then only the perceveid costs by the operator are retained for cost comparison.

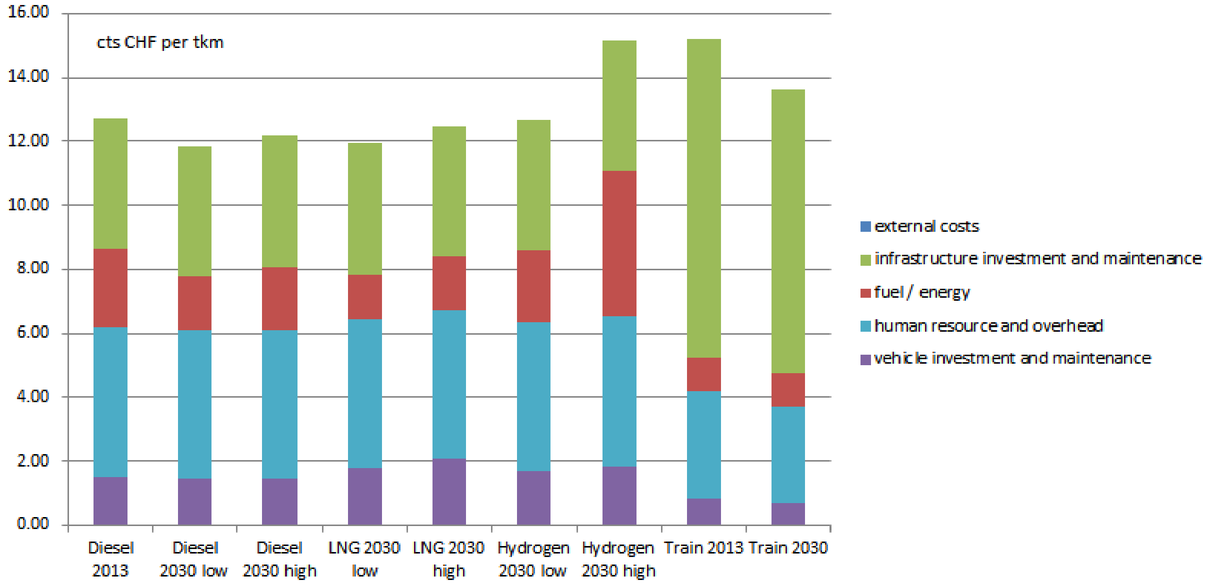
Full tabulated results are available in the appendix.

FIGURE 6-2 COST COMPARISON OF FREIGHT MODES



It is interesting to note that total cost to society looks similar for all freight technologies, with a relative advantage for trains, and hydrogen being the most expensive solution. The main cost drivers are surprisingly not the direct operating costs fuel/energy and salaries but infrastructure expenses. These costs are not perceived in a same way by the operator and therefore the end customer for the two modes.

FIGURE 6-3 PERCEIVED COSTS COMPARISON OF FREIGHT MODES



For the perceived costs, mineral oil tax has been reintroduced in fuel costs, road infrastructure investment and maintenance costs are only perceived via the heavy vehicle charge, and external costs disappear from operator perspective. With this description, train transport, which doesn't benefit from infrastructure as a public good, appears as the most expensive solution. SBB owns the infrastructure and charge users for it. They benefit from the fact that they operate also passenger train allowing for cross compensation between passenger and freight accounts. However the structure of the annual report, separating freight business from passenger business, seems to prevent from this caveat.

This new cost distribution changes the ranking of modes, and road transport becomes more competitive than rail transport.

This graph also shows that road freight transport is very sensitive to fuel prices, which represents 15% of perceived costs. Human resource costs for road transport are penalized by the fact that each truck carrying 20 net tons has a driver, whereas for trains, one driver is responsible for 400 net tons.

Cost of time is not considered, but could play a major role for specific supply chain networks (e.g. perishable goods).

7. Discussion and future work

This chapter comes back on potentially questionable assumptions and considers possible improvements for future work.

7.1. Sensitivity analysis and discussion

A sensitivity analysis is performed for parameters with high uncertainty or when debates within the scientific community was identified and can cause a change in the impacts of the system. Different types of uncertainties are addressed in this part: parameter uncertainty (related to LCI data) and model uncertainties (due to mathematical model choices). The following parameters are selected to study their variability and effects on the LCIA of transport system:

- Infrastructure allocation
- Leak from LNG infrastructure
- Efficiency of Hydrogen truck
- Lifetime of fuel cell
- Net/gross ratio for freight train

In the last part the modal repartition road/rail for goods transport in Switzerland is discussed.

Infrastructure allocation

The allocation rule for road construction was derived from Spielmann and Scholz (2005), using the Gross ton kilometric performance. Assuming linear relationship between gross mass and infrastructure damage is questionable and there is no consensus in the literature on the mathematical relation between infrastructure damages and axle load.

Some authors use equivalent factors or sharing percentages for wear and tear of the road (Sahin et al 2007), but there is a lack of documentation regarding the calculation of these factors. In the 60's the American Association of Highway and Transportation Officials introduced the "fourth power law", concluding after five years of studies that the decrease in "pavement serviceability" caused by a vehicle is related to the fourth power of its static load (AASHO 1962). Later experimental and theoretical research has indicated high variability in the exponent (Cebon 1986), and a factor depending on the layer considered varying between 1 and 7 (NVF 2008). Cebon noted that current conditions are significantly different from the conditions of the AAHSO road test (axle loads and axle group configurations, tyres sizes and pressures, road construction, traffic volumes…). This issue has also been explored in Europe with the Dynamic Interaction between Vehicles and Infrastructure Experiment (DIVINE project, 1998[39]), expressing some reserves regarding the AAHSO test. In the absence of a consensus of the scientific community, the current approach of Spielmann and Scholz (2005)

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[39] OECD, Divine Project, retrieved 04.11.2014 from: http://www.oecd.org/sti/transport/roadtransportresearch/2754516.pdf

(also used in the Cost Allocation of Transport Infrastructure Cost, conducted in 2008, CATRIN[40]), was used in this study, but it was found interesting to assess the impact of a different allocation rule using the fourth power law.

For trains this issue is not as critical as for trucks considering that the difference in gross mass of freight trains and passengers trains is not so important in Switzerland (around 650t for a freight train and 460t for a passenger train, see subsection 4.3.2). The evidence of the existence of a power function by train type is given in some recent studies using econometrics techniques (Gaudry and Quinet, 2010), unfortunately the analysis is not yet strong enough to predict parameter values. In contrast, for road traffic we have a very high diversity in the load of the vehicles involved. Even if we exclude motorcycles, we have a large range of axle loads, and thus, a power function as infrastructure allocation rule can have huge impacts.

TABLE 7-1 PARAMETERS FOR ROAD INFRASTRUCTURE ALLOCATION

Vehicle category	**Average gross mass (TREMOVE)**	**Number of axles, and mass per axle**	**Traffic performance in 2012 (ARE 2012)**	**Equivalent factor using fourth power**	**Share of infrastructure allocated (gross ton)**	**Share of infrastructure allocated (fourth power)**
Passenger car	1.59t	2 0.795t	5.56E10 vkm	0.4	55%	2%
Light and medium duty	5.70t	2 2.85t	3.64E9 vkm	66	13%	20%
Heavy duty	22.59t	5 4.52t	2.23E9 vkm	417	32%	78%

We obtain for a heavy duty truck the following demand factor: **1.94E-3 m.y./tkm** to compare to **7.87E-4 m.y./tkm** with the gross ton allocation rule. LCIA results (applied on Diesel 2013) are then: +15% in Climate change, +48% in terrestrial acidification, +54% in PM formation.

In Facanha and Horvath (2006), investigating the U.S. transport sector, 40% of road infrastructure was allocated to freight, but with no modeling assumptions. Here, with the gorss ton allocation rule 32% was allocated to freight. Another difference is that the entire road network (incl. municipal roads) was included is this thesis, while Facanha and Horvath have preferred to retrict the infrastructure to the highway network. This must be further discussed for Switzerland, looking at the traffic composition per road categories.

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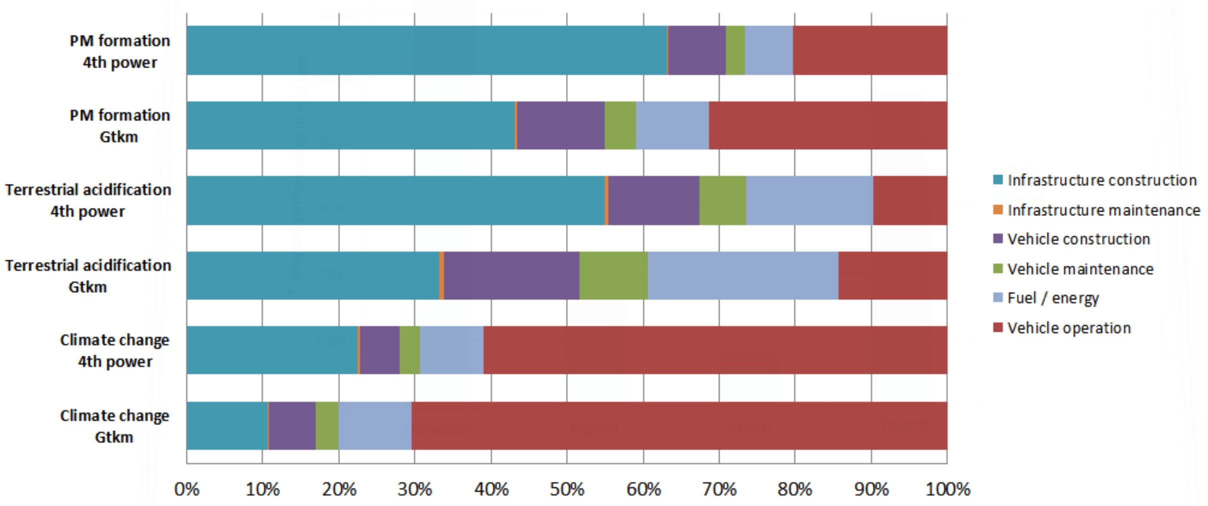
[40] European Commission, CATRIN, retrieved 04.11.2014 from: http://cordis.europa.eu/project/rcn/85675_en.html

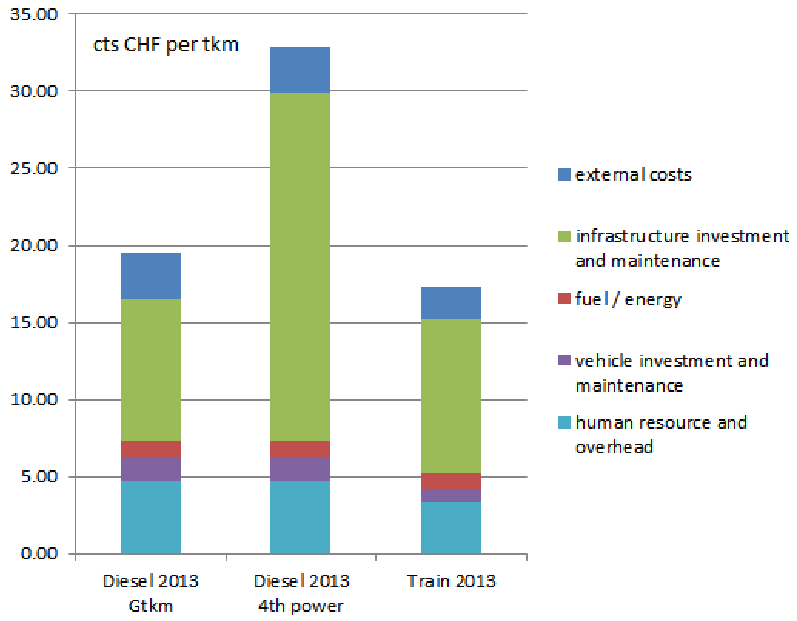
The graph below shows the growth in the relative share of infrastructure in all impact categories when changing the allocation rule (applied on Diesel 2013).

FIGURE 7-1 IMPACT OF INFRASTRUCTURE ALLOCATION MODEL ON LCIA



As the LCA allocation rule was also applied for cost assessment, changing the modeling assumptions also affects the general picture of the true costs of road transport. This is presented in the graph below.

FIGURE 7-2 IMPACT OF INFRASTRUCTURE ALLOCATION MODEL ON COST ASSESSMENT



To conclude on this point, the comparative assessment for the road sector is not changed, because we have considered trucks from the same weight category. But applying a “fourth power axle load” allocation rule would further penalize road freight in comparison to rail freight.

Leak from LNG infrastructure

There is a lack of data to properly compare LNG and Diesel environmental performance, and considerable uncertainty on LNG engines efficiency (Zhao et al. 2013). There are also some debates on leakage from the distribution network of natural gas.

For the pessimistic case presented here, a typical leakage of 5% of LNG infrastructure has been assumed, which is the upper value estimated in Alvarez et al. 2012. Alvarez data comes from the US, thus the upper value takes into account potential additional inefficiencies in the network of LNG suppliers of Switzerland.

This leakage contributes to an additional 27% to climate change category, and thus cancels out the relative advantage in this impact category that LNG truck have on diesel. The GWP of methane is 24 times the one of CO2, and thus a 5% leak of methane has much more impact than a 10-20% penalty in fuel consumption, because the methane is converted into carbon dioxide in the combustion.

Because these emissions occurs on the infrastructure side, it's not directly perceived, neither shown in operational efficiencies. These emissions, occurring mainly outside the borders of Switzerland, are difficult to allocate to one or the other country.

Efficiency of Hydrogen truck

A potential source of inaccuracies in the calculation, is that the background assumptions used in the CE Delft study (den Boer et al., 2013) for hydrogen trucks may be different than the ones for the diesel and LNG trucks (i.e. maybe the acceleration performance or driving test cycle used to calculate the performance were different).

This issue can be prevented by calculating the energy consumption based on a standardized driving cycle and energy efficiency of the different drivetrain configuration analyzed.

However, if we consider only hydrogen coming from electrolysis with a renewable mix of electricity, 10% increase in hydrogen consumption, will cause 3-5% more emissions in the impact categories considered and thus will not change the general picture.

Lifetime of fuel cell

As the lifetime of fuel cell system is higly speculative, it was found interesting to investigate the impacts of one complete renewal of fuel cell and battery during the lifetime of the truck. Thus the 20% decrease in vehicle life (subsection 4.2.2) is removed, assuming that all the other parts of the vehicle, including the other e-drive train components such as the electric motor, will last as long as in diesel trucks. The full LCA results are given in the appendix. The hydrogen production pathway used for this analysis is methane reforming.

The impact of a reduced lifetime of the fuel cell and battery remains limited with -1.6% in climate change, +3% in terrestrial acidification and no significant change in PM formation.

Two effects are counteracting in this analysis because on the one hand the overall lifetime of the vehicle is increased but on the other hand fuel cell and battery impacts are doubled. A further investigation shows that the fuel cell, if replaced once, is responsible of 45% of terrestrial acidification impacts of the lorry construction phase, which causes itself around25% of the total impacts of the transport service.

In any case such replacement of components must be anticipated in the design phase of the vehicle and can have significant economic implications in addition to environmental impacts.

Net gross ratio for freight trains

The average value of 0.52 Nt/Gt was used, but this depends a lot of the type of goods carried and therefore affects the share of infrastructure used. Considering the relative importance of infrastructure in rail transport it was found interesting to further investigate this question.

Bulk versus volume transport has significant impact on the net /gross mass ratio mentioned in section 3.1 Ecotransit 2011, with values in the range of 0.40 for volume to 0.60 for bulk. With specific goods the ratio can even be in the range of 1 for cereals to 3 for passenger cars in dedicated trains. Alternative method the compute this value is to take a typical mass of 84t per locomotive and to select the type of freight wagon based on the transported goods[41].

TABLE 7-2 NET / GROSS RATIO AND RAILWAY TRACK CONSTRUCTION ALLOCATION

Net mass per train	Net/Gross ratio	Gross mass per train	Rail construction demand factor
394 t*	0.40	985 t	6.56E-5
	0.52	757 t	5.47E-5
	0.60	657 t	4.94E-5

*see sub section 4.3.2

As infrastructure represents 41-45% of all impact categories considered, this is truly to consider. Facanha and Horvath (2006) mention that the main influence of commodity is the choice of mode itself. And thus the functional unit tkm is likely to underestimate rail impacts (carry more heavy cargo). Volume of goods (m^3km) or value of goods ($ km) are other possible functional units for freight transport of specific goods.

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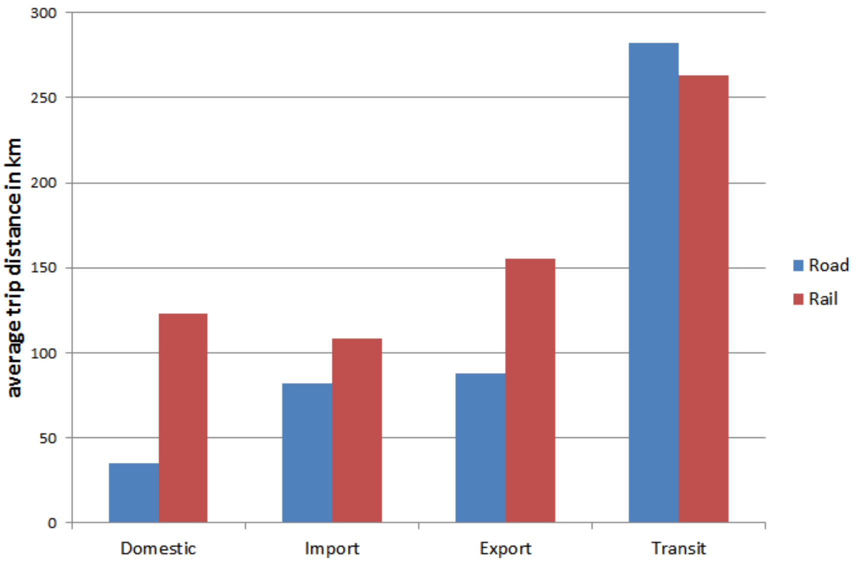
[41] SBB, Recherche de type de wagon, retrieved 04.11.2014 from: http://www.sbbcargo.com/fr/offre/wagons-et-marchandises/recherche-type-wagon.html

Modal repartition road/rail

Increasing the modal share of rail freight over road freight is often mentioned as a lever for reducing the environmental footprint of transport sector. Indeed the LCA results have shown that electric freight train outperforms all truck technologies in all impact categories.

However statistical data (BFS 2014) shows that the modal share of rail in goods transport is relatively stable in Switzerland at around 40% since almost on decade (to compare with below 18.6% EU average[42]). The reason for this stagnation must be found in trip profile of road and rail modes. The mentionned document makes the distinction between transit traffic and domestic traffic, and rail already represents 74% of transit traffic in tkm, but only 23% in domestic traffic. This finding relates to the average trip distance, and the trend towards small and flexible shipments. Trains only make sense for longer journey as the rail network doesn't cover the territory as densely as the road network. The graphs presented below summarize the consequences of this issue (based on BFS 2014).

FIGURE 7-3 AVERAGE TRIP DISTANCE IN SWISS FREIGHT TRANSPORT 2012



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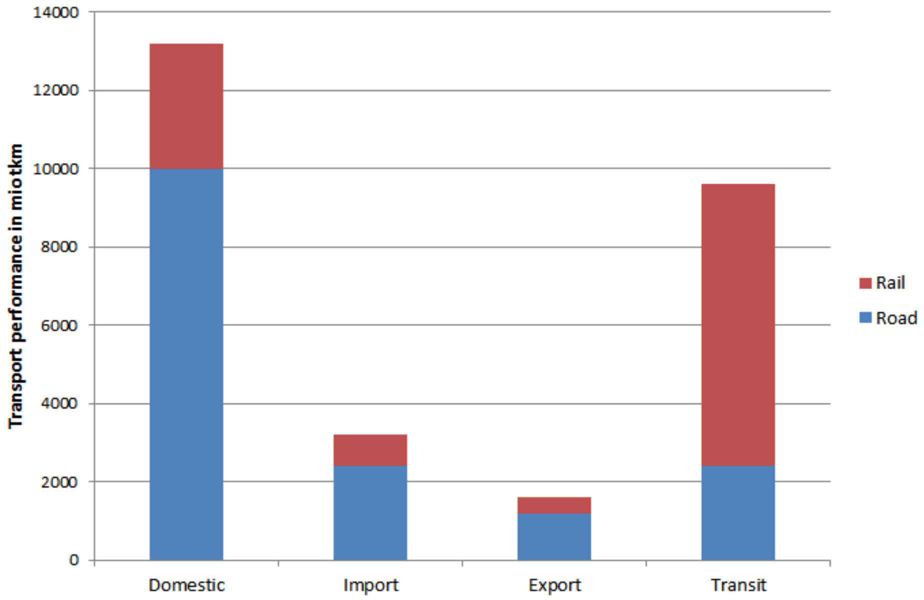
[42] European Commission, Eurostat. Freight transport statistics, retrieved 05.12.2014 from http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Freight_transport_in_the_EU-28,_modal_split_of_inland_transport_modes_2007_2012.png

FIGURE 7-4 MODAL DISTRIBUTION BY TRIP PROFILE



Decisions on both macro level (infrastructure planning) and micro level (decision behavior on company level) are required to keep the modal share of rail in Switzerland among the highest in Europe (Ruesch 2001), but mountain topography constrains network developments for both modes.

7.2. Future work

Future work was found to be most necessary on two different aspects. On the one hand, improvements can be made in the database design and LCA techniques to apply on freight transport assessments. On the other hand, additional data must be collected for some specific activities and demand factors.

When discussing LCA results it is important ot keep in mind that all the emissions mentioned are not happening in the same time and are not emitted in the same place. Thus total lifecycle emissions presented in this thesis might not be fully allocated to the fleet of the country considered. In particular emissions for the vehicle and hydrocarbon fuels production chain are very uncertain and mostly occurring outside Switzerland. Additionally, the impact assessment performed does not take into account the location of emissions, and this can have important consequences when applying the methodology in highly populated areas. New LCA techniques can integrate regionalization aspects, but it adds a lot of complexity in the model and further research is required to assess the relevance of this approach.

Regarding the modeling of the database, the impact of fuel regulation (section 5.2), has shown the relevance of dynamic LCA approaches. A database were engines can be modeled with respect to their generation and aftertreatment solutions, and then having the engine linked directly with the amount of pollutants with respect to the fuel consumption and composition would facilitate further data updates.

Data collection is the second aspect requiring further work. As infrastructure is playing a growing role in the overall assessment of the transport system, a specific modeling of road damage and demand renewal is necessary (section 7.1). One other limitation of this thesis is that the same production conditions were assumed for 2030 (but more energy intensive material such as plastics, composites and aluminum are expected in vehicles), and Diesel and LNG supply chains for 2030 are not yet known. Chapter 5 has shown the growing importance of these non operating processes in overall impacts and further studies should concentrate on these elements.

In this this thesis it was assumed that road and rail vehicles enter directly the end-of-life phase after the economic life in Switzerland. However, potential impacts of second-hand market and methods to account for a second economic life of vehicles in different operating conditions was not documented.

To conclude on this point, this thesis was written in the early phase of SCCER Mobility, therefore more specific and accurate data from other capacity areas (e.g. minimization of vehicular energy demand, integration and optimization) can be gathered in a later phase. After treatment solutions such as diesel particle filters, selective reduction catalysts, and three way catalysts, are investigated in the capacity area A2 of SCCER Mobility, lead by EMPA (Chemical energy converters and catalysts). Therefore, in a later phase, it would be possible to implement their results in the model developed for this thesis. And with a fleet model of the transport sector in Switzerland, results can be used for policy decision making.

8. Conclusion

In this thesis the environmental impacts and total costs of goods transport by road and by rail in Switzerland were quantified and compared using LCA and LCC methodology. Environmental impacts were considered for climate change, terrestrial acidification and PM formation.

Road freight transport is at a turning point with EURO standards setting very low levels of pollutant emissions for new registrations, and probably targeting fuel economy for the next version. The regulatory framework with specific emission targets has encouraged the development of after treatment solutions and was wisely accompanied by regulation on fuel composition with EN590. Except for GHG, tailpipe emissions are not anymore the hotspot in the life cycle of trucks. In 2030, compared to 2013, terrestrial acidification and PM formation impacts are expected to slightly reduce by 13 to 22% for transport with ICE vehicles, but using FCV will exceed the emissions levels from current diesel trucks by 16 to 50%. Indeed the fuel cell technology is heavily penalized by the production of the fuel cell itself and other e-drivetrain components, in addition to the production of hydrogen. Better results are foreseen for climate change impacts. Efficiency improvements in the operating phase and LNG fuels are expected to provide up to 40% reduction in CO_2 eq emissions compared to current diesel trucks. And FCVs, if the electricity for electrolysis is produced from renewables, can even achieve a 65% reduction. Sensitivity analysis shows that this is strongly dependant on the leakage of methane in the fuel supply chain, which could actually lead to high GHG emissions from LNG trucks if methane leakages are as high as some recent publications predict.

Due to their construction, electric trains are more efficient than freight trucks. They benefit from a low rolling resistance due to steel/steel contact, aerodynamic drag is reduced with the composition of large shipments, more predictability in the driving cycle and electric motors offer a better efficiency than combustion engines. The rail sector is continuously improving in terms of infrastructure management and is in the process of replacing its diesel shunting fleet with hybrids. For 2030, the environmental impacts of goods transport per electric train in Switzerland are expected to be 24 to 32% lower than in 2013 depending on the impact category.

For both modes, infrastructure is expected to be predominant in future environmental impacts.and costs, representing 42 to 60% of total costs and causing more than 40% of impacts in several impact categories. Infrastructure is a long lasting asset, whose impacts are distributed over its entire lifetime. Reducing costs and impacts of goods transport in general will therefore require more innovative solutions including reduction of transport as such. In order to achieve the goals of the energy strategy 2050, better improvements in terms of energy efficiency would be required for short and medium haul transport as the ones expected for long haul transport.

Finally, rail transport has significantly lower impacts than road transport, with equivalent emissions per tkm up to four times lower (climate change). The total costs seen by society are also lower for rail transport. Thus, the polital attempts to shift freight transport from road to rail are justified from both economic and environmental points of view. However, the costs perceived by the operator are lower for road transport than rail, reducing the incentive for modal shifts. As long as the full costs of infrastructure and environmental impacts are not fully transferred to the end customer the modal shift from road to rail will not be encouraged.

Transport is a major component for the energy policy for both environmental impacts and energy independency. This thesis highlights the hotspots in life cycle stages of transport services by road and by rail, and provides a basis for future work in the context of LCA of freight transport in general and SCCER Mobility in particular.

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Appendix

The following data is provided in this section:

- **Full list of pollutants**
- **External costs calculation methods**
- **Extended LCIA results for:**
- **Diesel 2000 (EURO III)**
- **Diesel 2013 (EURO VI)**
- **Diesel 2030**
- **LNG 2030**
- **Hydrogen Swiss mix 2030**
- **Hydrogen Methane Reforming 2030**
- **Hydrogen Short Vehicle Lifetime, Methane Reforming 2030**
- **Hydrogen Renewables 2030**
- **Freight Train 2004**
- **Freight Train 2013**
- **Freight Train 2030**
- **Costs**

Full list of pollutants

(*transport, freight, lorry >32t, EURO5,* 2010, ecoinvent 3.1)

Pollutant	*Amount*	*Unit*	*Class*	*Pollutant*	*Amount*	*Unit*	*Class*
Acetaldehyde	*6.5E-8*	*kg*	*NMVOC*	*Lead*	*8.8E-10*	*kg*	*Heavy metal*
Acrolein	*2.5E-8*	*kg*	*NMVOC*	*Mercury*	*9E-11*	*kg*	*Heavy metal*
Arsenic	*1.7E-12*	*kg*	*Heavy metal*	*M-Xylene*	*1.4E-8*	*kg*	*NMVOC*
Benzaldegyde	*1.9E-8*	*kg*	*NMVOC*	*Nickel*	*1.5E-10*	*kg*	*Heavy metal*
Benzene	*9.9E-10*	*kg*	*NMVOC*	*O-xylene*	*5.7E-9*	*kg*	*NMVOC*
Butane	*2.1E-9*	*kg*	*NMVOC*	*PAH*	*1.3E-9*	*kg*	*PAH*
Cadmium	*1.5E-10*	*kg*	*Heavy metal*	*Pentane*	*8.E-10*	*kg*	*NMVOC*
Chromium	*5.1E-10*	*kg*	*Heavy metal*	*Propane*	*1.4E-9*	*kg*	*NMVOC*
Chromium VI	*1.0E-12*	*kg*	*Heavy metal*	*Selenium*	*1.7E-12*	*kg*	*Heavy metal*
Copper	*3.6E-10*	*kg*	*Heavy metal*	*Styrene*	*7.9E-9*	*kg*	*NMVOC*
Ethane	*4.3E-10*	*kg*	*Hydrocarbon*	*Toluene*	*1.4E-10*	*kg*	*NMVOC*
Formaldehyde	*1.2E-7*	*kg*	*NMVOC*	*Zinc*	*2.9E-8*	*kg*	*Heavy metas*
Heptane	*4.3E-9*	*kg*	*NMVOC*				

External costs calculations

Restranscription from ARE 2014

Cost type	Method
Health costs as a result of air pollution	Medical treatment costs, net lost output, replacement recruitment costs, intangible costs owing to shorter life expectancy and illness (all damage cost approach)
Building damage as a result of air pollution	a. costs of additional renovations (locations exposed to traffic); b. shorter life of building facade (locations not exposed to traffic); c. additional cleaning costs (all damage cost approach)
Crop shortfalls as a result of air pollution	Reduction in agricultural income as a result of high ozone levels (damage costs)
Forest degradation as a result of air pollution	a. Lower income from timber harvests as a result of high ozone levels; b. lower income from timber harvests as a result of soil acidification; c. costs of higher levels of windthrow as a result of soil acidification (all damage cost approach)
Loss of biodiversity as a result of air pollution	Costs of (virtual) measures to restore biodiverse ecosystems (replacement cost approach)
Noise	Nuisance (falling housing prices) and health costs (similar to the health costs caused by air pollution – all damage costs)
Climate change	Costs of avoidance measures to achieve long-term global climate targets (avoidance cost approach)
Nature and the landscape	Replacement cost approach: a. Loss of habitats: costs of the (virtual) restoration of lost biotopes or defined ecosystems (habitats); b. Habitat fragmentation: costs of the (virtual) creation of defragmentation infrastructure
Soil degradation from toxic substances	Costs of the (virtual) clean-up of toxic substances from contaminated soil (repair cost approach)
Costs of upstream and downstream processes	Climate change and air pollution costs associated with the manufacture, maintenance and disposal of vehicles (means of transport), energy sources (fuels, electricity) and infrastructures
Accidents	Medical treatment costs, net lost output, replacement recruitment costs, intangible costs, administrative costs, property damage, police and subsequent legal costs (all damage cost approach)
Additional costs in urban areas	a. Time-related costs for non-motorised transport owing to geographical separation (damage costs); b. impairment of local character and appeal: costs of upgrading heavily used local thoroughfares (repair cost approach)

Diesel 2000 (EURO III)

Per tkm	Climate change	Ozone depletion	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Human toxicity	Photochemical oxidant formation	PM formation	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Ionising radiation	Agricultural land occupation	Urban land occupation	Natural land transformation	Water depletion	Metal depletion	Fossil depletion
	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM10 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	7.57E-2	5.47E-9	3.32E-4	5.72E-6	1.97E-5	2.65E-2	5.84E-4	1.93E-4	4.94E-5	2.33E-4	5.90E-4	7.58E-3	4.50E-4	6.80E-4	2.58E-5	4.76E-2	4.22E-3	2.60E-2
Vehicle Operation	5.39E-2	0.00E+0	2.19E-4	0.00E+0	1.46E-5	0.00E+0	3.93E-4	9.16E-5	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Vehicle maintenance	2.71E-3	1.88E-10	1.40E-5	7.92E-7	4.28E-7	8.40E-4	1.17E-5	5.50E-6	1.60E-7	2.21E-5	2.23E-5	3.45E-4	1.85E-4	2.20E-5	7.38E-7	5.34E-3	3.29E-4	1.29E-3
Vehicle Production	5.19E-3	2.98E-10	2.76E-5	3.46E-6	1.31E-6	5.86E-3	2.40E-5	1.58E-5	6.49E-7	1.43E-4	1.42E-4	3.86E-4	1.23E-4	6.43E-5	7.62E-7	1.53E-2	2.84E-3	1.37E-3
Road provision	6.75E-3	1.18E-9	3.79E-5	1.00E-6	2.13E-6	1.20E-3	9.35E-5	3.74E-5	4.98E-7	3.65E-5	4.10E-5	3.01E-3	9.17E-5	8.12E-5	8.04E-6	1.90E-2	8.83E-4	4.45E-3
Road operation and maintenance	1.92E-4	8.45E-11	6.59E-7	1.31E-7	7.95E-8	1.44E-4	7.46E-7	2.58E-7	8.12E-8	3.66E-6	3.63E-6	6.44E-4	1.55E-5	4.56E-4	3.99E-8	4.01E-3	2.43E-5	5.54E-5
Diesel at fueling station	6.99E-3	3.72E-9	3.23E-5	3.39E-7	1.16E-6	5.44E-4	6.11E-5	1.08E-5	3.57E-7	1.72E-5	4.04E-5	3.20E-3	3.50E-5	5.69E-5	1.62E-5	3.92E-3	1.45E-4	1.89E-2
Treatment of brake wear emissions	0.00E+0	0.00E+0	5.00E-7	0.00E+0	8.74E-10	1.71E-2	4.06E-8	1.39E-5	4.46E-5	8.08E-6	3.32E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of road wear emissions	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.05E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of tyre wear emissions	0.00E+0	0.00E+0	8.05E-8	0.00E+0	4.03E-8	7.80E-4	6.53E-9	1.17E-5	3.05E-6	1.76E-6	8.83E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Diesel 2013 (EURO VI)

Per tkm	Climate change	Ozone depletion	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Human toxicity	Photochemical oxidant formation	PM formation	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Ionising radiation	Agricultural land occupation	Urban land occupation	Natural land transformation	Water depletion	Metal depletion	Fossil depletion
	kg CO_2 eq	kg CFC-11 eq	kg SO_2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM_{10} eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	6.38E-2	4.75E-9	1.14E-4	4.62E-6	5.64E-6	2.47E-2	2.01E-4	1.01E-4	4.93E-5	1.90E-4	5.43E-4	6.94E-3	4.05E-4	6.78E-4	2.27E-5	4.24E-2	3.42E-3	2.20E-2
Vehicle Operation	4.49E-2	0.00E+0	1.58E-5	0.00E+0	1.04E-6	0.00E+0	2.80E-5	6.01E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Vehicle maintenance	2.00E-3	1.38E-10	1.03E-5	5.85E-7	3.16E-7	6.20E-4	8.65E-6	4.05E-6	1.18E-7	1.63E-5	1.64E-5	2.55E-4	1.37E-4	1.62E-5	5.45E-7	3.94E-3	2.43E-4	9.53E-4
Vehicle Production	3.83E-3	2.20E-10	2.04E-5	2.55E-6	9.69E-7	4.33E-3	1.77E-5	1.16E-5	4.79E-7	1.06E-4	1.05E-4	2.85E-4	9.04E-5	4.74E-5	5.62E-7	1.13E-2	2.10E-3	1.01E-3
Road provision	6.75E-3	1.18E-9	3.79E-5	1.00E-6	2.13E-6	1.20E-3	9.35E-5	3.74E-5	4.98E-7	3.65E-5	4.10E-5	3.01E-3	9.17E-5	8.12E-5	8.04E-6	1.90E-2	8.83E-4	4.45E-3
Road operation and maintenance	1.92E-4	8.45E-11	6.59E-7	1.31E-7	7.95E-8	1.44E-4	7.46E-7	2.58E-7	8.12E-8	3.66E-6	3.63E-6	6.44E-4	1.55E-5	4.56E-4	3.99E-8	4.01E-3	2.43E-5	5.54E-5
Diesel at fueling station	6.08E-3	3.13E-9	2.86E-5	3.54E-7	1.06E-6	5.65E-4	5.23E-5	9.66E-6	3.81E-7	1.78E-5	3.69E-5	2.75E-3	7.08E-5	7.71E-5	1.35E-5	4.16E-3	1.71E-4	1.55E-2
Treatment of brake wear emissions	0.00E+0	0.00E+0	5.00E-7	0.00E+0	8.74E-10	1.71E-2	4.06E-8	1.39E-5	4.46E-5	8.08E-6	3.32E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of road wear emissions	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.05E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of tyre wear emissions	0.00E+0	0.00E+0	8.05E-8	0.00E+0	4.03E-8	7.80E-4	6.53E-9	1.17E-5	3.05E-6	1.76E-6	8.83E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Diesel 2030

Per tkm	Climate change kg CO2 eq	Ozone depletion kg CFC-11 eq	Terrestrial acidification kg SO2 eq	Freshwater eutrophication kg P eq	Marine eutrophication kg N eq	Human toxicity kg 1,4-DB eq	Photochemical oxidant formation kg NMVOC	PM formation kg PM10 eq	Terrestrial ecotoxicity kg 1,4-DB eq	Freshwater ecotoxicity kg 1,4-DB eq	Marine ecotoxicity kg 1,4-DB eq	Ionising radiation kg U235 eq	Agricultural land occupation m2a	Urban land occupation m2a	Natural land transformation m2	Water depletion m3	Metal depletion kg Fe eq	Fossil depletion kg oil eq
Total	4.54E-2	3.56E-9	9.34E-5	4.20E-6	4.62E-6	2.07E-2	1.63E-4	8.83E-5	4.01E-5	1.71E-4	4.53E-4	5.60E-3	3.56E-4	5.47E-4	1.74E-5	3.77E-2	3.14E-3	1.63E-2
Vehicle Operation	2.96E-2	0.00E+0	9.82E-6	0.00E+0	6.51E-7	0.00E+0	1.74E-5	3.77E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Vehicle maintenance	1.88E-3	1.30E-10	9.69E-6	5.49E-7	2.96E-7	5.81E-4	8.12E-6	3.80E-6	1.11E-7	1.53E-5	1.54E-5	2.39E-4	1.28E-4	1.52E-5	5.11E-7	3.70E-3	2.28E-4	8.94E-4
Vehicle Production	3.59E-3	2.06E-10	1.91E-5	2.40E-6	9.09E-7	4.06E-3	1.66E-5	1.09E-5	4.50E-7	9.92E-5	9.85E-5	2.67E-4	8.48E-5	4.45E-5	5.27E-7	1.06E-2	1.97E-3	9.48E-4
Road provision	6.19E-3	1.08E-9	3.48E-5	9.17E-7	1.96E-6	1.10E-3	8.58E-5	3.43E-5	4.57E-7	3.35E-5	3.76E-5	2.76E-3	8.41E-5	7.45E-5	7.37E-6	1.74E-2	8.10E-4	4.08E-3
Road operation and maintenance	1.52E-4	6.70E-11	5.22E-7	1.04E-7	6.30E-8	1.14E-4	5.91E-7	2.05E-7	6.43E-8	2.90E-6	2.88E-6	5.11E-4	1.23E-5	3.61E-4	3.16E-8	3.17E-3	1.93E-5	4.39E-5
Diesel at fueling station	4.03E-3	2.07E-9	1.89E-5	2.35E-7	7.03E-7	3.74E-4	3.47E-5	6.40E-6	2.52E-7	1.18E-5	2.44E-5	1.82E-3	4.69E-5	5.11E-5	8.93E-6	2.75E-3	1.13E-4	1.03E-2
Treatment of brake wear emissions	0.00E+0	0.00E+0	4.00E-7	0.00E+0	6.99E-10	1.37E-2	3.25E-8	1.11E-5	3.57E-5	6.47E-6	2.65E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of road wear emissions	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.05E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of tyre wear emissions	0.00E+0	0.00E+0	8.05E-8	0.00E+0	4.03E-8	7.80E-4	6.53E-9	1.17E-5	3.05E-6	1.76E-6	8.83E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

LNG 2030

Per tkm	Climate change	Ozone depletion	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Human toxicity	Photochemical oxidant formation	PM formation	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Ionising radiation	Agricultural land occupation	Urban land occupation	Natural land transformation	Water depletion	Metal depletion	Fossil depletion
	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM10 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	3.67E-2	1.52E-9	8.85E-5	4.21E-6	4.88E-6	2.07E-2	1.53E-4	8.77E-5	3.99E-5	1.68E-4	4.38E-4	3.86E-3	3.24E-4	4.99E-4	8.53E-6	3.61E-2	3.21E-3	6.11E-3
Vehicle Operation	2.45E-2	0.00E+0	2.24E-5	0.00E+0	1.53E-6	0.00E+0	4.03E-5	8.72E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Vehicle maintenance	2.00E-3	1.38E-10	1.03E-5	5.85E-7	3.16E-7	6.20E-4	8.65E-6	4.05E-6	1.18E-7	1.63E-5	1.64E-5	2.55E-4	1.37E-4	1.62E-5	5.45E-7	3.94E-3	2.43E-4	9.53E-4
Vehicle Production	3.81E-3	2.32E-10	1.98E-5	2.60E-6	9.74E-7	4.37E-3	1.76E-5	1.15E-5	4.94E-7	1.07E-4	1.06E-4	3.32E-4	9.13E-5	4.72E-5	5.69E-7	1.15E-2	2.14E-3	1.01E-3
Road provision	6.19E-3	1.08E-9	3.48E-5	9.17E-7	1.96E-6	1.10E-3	8.58E-5	3.43E-5	4.57E-7	3.35E-5	3.76E-5	2.76E-3	8.41E-5	7.45E-5	7.37E-6	1.74E-2	8.10E-4	4.08E-3
Road operation and maintenance	1.52E-4	6.70E-11	5.22E-7	1.04E-7	6.30E-8	1.14E-4	5.91E-7	2.05E-7	6.43E-8	2.90E-6	2.88E-6	5.11E-4	1.23E-5	3.61E-4	3.16E-8	3.17E-3	1.93E-5	4.39E-5
LNG at fueling station	1.63E-5	2.64E-12	2.25E-7	1.06E-9	1.10E-9	5.08E-6	5.38E-8	5.02E-8	4.45E-9	3.25E-7	1.30E-7	9.42E-7	3.46E-8	2.83E-8	1.47E-8	1.34E-5	4.07E-7	2.13E-5
Treatment of brake wear emissions	0.00E+0	0.00E+0	4.00E-7	0.00E+0	6.99E-10	1.37E-2	3.25E-8	1.11E-5	3.57E-5	6.47E-6	2.65E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of road wear emissions	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.05E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of tyre wear emissions	0.00E+0	0.00E+0	8.05E-8	0.00E+0	4.03E-8	7.80E-4	6.53E-9	1.17E-5	3.05E-6	1.76E-6	8.83E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Hydrogen Swiss mix 2030

Per tkm	**Climate change**	**Ozone depletion**	**Terrestrial acidification**	**Freshwater eutrophication**	**Marine eutrophication**	**Human toxicity**	**Photochemical oxidant formation**	**PM formation**	**Terrestrial ecotoxicity**	**Freshwater ecotoxicity**	**Marine ecotoxicity**	**Ionising radiation**	**Agricultural land occupation**	**Urban land occupation**	**Natural land transformation**	**Water depletion**	**Metal depletion**	**Fossil depletion**
	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM10 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	4.71E-2	2.06E-8	2.08E-4	2.83E-5	1.07E-5	5.60E-2	1.88E-4	1.28E-4	3.03E-5	9.37E-4	1.16E-3	3.25E-2	7.78E-4	7.79E-4	1.53E-5	2.17E+0	1.67E-2	1.72E-2
Vehicle Operation	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Vehicle maintenance	1.00E-3	6.92E-11	5.17E-6	2.92E-7	1.58E-7	3.10E-4	4.32E-6	2.03E-6	5.92E-8	8.17E-6	8.21E-6	1.27E-4	6.83E-5	8.11E-6	2.72E-7	1.97E-3	1.21E-4	4.76E-4
Vehicle Production	6.85E-3	5.85E-9	4.70E-5	6.17E-6	2.11E-6	9.96E-3	2.78E-5	2.04E-5	9.09E-7	2.27E-4	2.26E-4	1.14E-3	1.57E-4	8.09E-5	1.05E-6	2.92E-2	4.89E-3	1.84E-3
Road provision	6.75E-3	1.18E-9	3.79E-5	1.00E-6	2.13E-6	1.20E-3	9.35E-5	3.74E-5	4.98E-7	3.65E-5	4.10E-5	3.01E-3	9.17E-5	8.12E-5	8.04E-6	1.90E-2	8.83E-4	4.45E-3
Road operation and maintenance	1.92E-4	8.45E-11	6.59E-7	1.31E-7	7.95E-8	1.44E-4	7.46E-7	2.58E-7	8.12E-8	3.66E-6	3.63E-6	6.44E-4	1.55E-5	4.56E-4	3.99E-8	4.01E-3	2.43E-5	5.54E-5
H2 at fueling station	3.23E-2	1.34E-8	1.17E-4	2.08E-5	6.14E-6	3.50E-2	6.15E-5	4.30E-5	3.42E-6	6.56E-4	7.03E-4	2.76E-2	4.45E-4	1.53E-4	5.90E-6	2.11E+0	1.08E-2	1.03E-2
Treatment of brake wear emissions	0.00E+0	0.00E+0	2.50E-7	0.00E+0	4.37E-10	8.55E-3	2.03E-8	6.94E-6	2.23E-5	4.04E-6	1.66E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of road wear emissions	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.05E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of tyre wear emissions	0.00E+0	0.00E+0	8.05E-8	0.00E+0	4.03E-8	7.80E-4	6.53E-9	1.17E-5	3.05E-6	1.76E-6	8.83E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Hydrogen Methane Reforming 2030

Per tkm	**Climate change**	**Ozone depletion**	**Terrestrial acidification**	**Freshwater eutrophication**	**Marine eutrophication**	**Human toxicity**	**Photochemical oxidant formation**	**PM formation**	**Terrestrial ecotoxicity**	**Freshwater ecotoxicity**	**Marine ecotoxicity**	**Ionising radiation**	**Agricultural land occupation**	**Urban land occupation**	**Natural land transformation**	**Water depletion**	**Metal depletion**	**Fossil depletion**
	kg CO_2 eq	kg CFC-11 eq	kg SO_2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM10 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	3.08E-2	1.89E-8	1.71E-4	1.32E-5	8.28E-6	2.84E-2	1.80E-4	1.17E-4	3.28E-5	5.18E-4	6.98E-4	1.19E-2	7.51E-3	8.15E-4	1.38E-5	4.22E-1	1.11E-2	1.16E-2
Vehicle Operation	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Vehicle maintenance	1.00E-3	6.92E-11	5.17E-6	2.92E-7	1.58E-7	3.10E-4	4.32E-6	2.03E-6	5.92E-8	8.17E-6	8.21E-6	1.27E-4	6.83E-5	8.11E-6	2.72E-7	1.97E-3	1.21E-4	4.76E-4
Vehicle Production	6.85E-3	5.85E-9	4.70E-5	6.17E-6	2.11E-6	9.96E-3	2.78E-5	2.04E-5	9.09E-7	2.27E-4	2.26E-4	1.14E-3	1.57E-4	8.09E-5	1.05E-6	2.92E-2	4.89E-3	1.84E-3
Road provision	6.75E-3	1.18E-9	3.79E-5	1.00E-6	2.13E-6	1.20E-3	9.35E-5	3.74E-5	4.98E-7	3.65E-5	4.10E-5	3.01E-3	9.17E-5	8.12E-5	8.04E-6	1.90E-2	8.83E-4	4.45E-3
Road operation and maintenance	1.92E-4	8.45E-11	6.59E-7	1.31E-7	7.95E-8	1.44E-4	7.46E-7	2.58E-7	8.12E-8	3.66E-6	3.63E-6	6.44E-4	1.55E-5	4.56E-4	3.99E-8	4.01E-3	2.43E-5	5.54E-5
H_2 at fueling station	1.61E-2	1.17E-8	7.98E-5	5.63E-6	3.76E-6	7.48E-3	5.39E-5	3.19E-5	5.92E-6	2.38E-4	2.45E-4	6.93E-3	7.18E-3	1.89E-4	4.36E-6	3.68E-1	5.14E-3	4.81E-3
Treatment of brake wear emissions	0.00E+0	0.00E+0	2.50E-7	0.00E+0	4.37E-10	8.55E-3	2.03E-8	6.94E-6	2.23E-5	4.04E-6	1.66E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of road wear emissions	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.05E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of tyre wear emissions	0.00E+0	0.00E+0	8.05E-8	0.00E+0	4.03E-8	7.80E-4	6.53E-9	1.17E-5	3.05E-6	1.76E-6	8.83E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Hydrogen Short Fuel Cell Lifetime, Methane Reforming 2030

Per tkm	**Climate change** kg CO2 eq	**Ozone depletion** kg CFC-11 eq	**Terrestrial acidification** kg SO2 eq	**Freshwater eutrophication** kg P eq	**Marine eutrophication** kg N eq	**Human toxicity** kg 1,4-DB eq	**Photochemical oxidant formation** kg NMVOC	**PM formation** kg PM10 eq	**Terrestrial ecotoxicity** kg 1,4-DB eq	**Freshwater ecotoxicity** kg 1,4-DB eq	**Marine ecotoxicity** kg 1,4-DB eq	**Ionising radiation** kg U235 eq	**Agricultural land occupation** m2a	**Urban land occupation** m2a	**Natural land transformation** m2	**Water depletion** m3	**Metal depletion** kg Fe eq	**Fossil depletion** kg oil eq
Total	3.04E-2	2.24E-8	1.76E-4	1.29E-5	8.14E-6	2.80E-2	1.78E-4	1.17E-4	3.28E-5	5.08E-4	6.87E-4	1.18E-2	7.50E-3	8.07E-4	1.37E-5	4.19E-1	1.15E-2	1.15E-2
Vehicle Operation	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Vehicle maintenance	1.00E-3	6.92E-11	5.17E-6	2.92E-7	1.58E-7	3.10E-4	4.32E-6	2.03E-6	5.92E-8	8.17E-6	8.21E-6	1.27E-4	6.83E-5	8.11E-6	2.72E-7	1.97E-3	1.21E-4	4.76E-4
Vehicle Production	6.35E-3	9.43E-9	5.21E-5	5.84E-6	1.97E-6	9.50E-3	2.58E-5	2.03E-5	8.35E-7	2.16E-4	2.15E-4	1.07E-3	1.47E-4	7.36E-5	9.53E-7	2.69E-2	5.32E-3	1.68E-3
Road provision	6.75E-3	1.18E-9	3.79E-5	1.00E-6	2.13E-6	1.20E-3	9.35E-5	3.74E-5	4.98E-7	3.65E-5	4.10E-5	3.01E-3	9.17E-5	8.12E-5	8.04E-6	1.90E-2	8.83E-4	4.45E-3
Road operation and maintenance	1.92E-4	8.45E-11	6.59E-7	1.31E-7	7.95E-8	1.44E-4	7.46E-7	2.58E-7	8.12E-8	3.66E-6	3.63E-6	6.44E-4	1.55E-5	4.56E-4	3.99E-8	4.01E-3	2.43E-5	5.54E-5
H2 at fueling station	1.61E-2	1.17E-8	7.98E-5	5.63E-6	3.76E-6	7.48E-3	5.39E-5	3.19E-5	5.92E-6	2.38E-4	2.45E-4	6.93E-3	7.18E-3	1.89E-4	4.36E-6	3.68E-1	5.14E-3	4.81E-3
Treatment of brake wear emissions	0.00E+0	0.00E+0	2.50E-7	0.00E+0	4.37E-10	8.55E-3	2.03E-8	6.94E-6	2.23E-5	4.04E-6	1.66E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of road wear emissions	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.05E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of tyre wear emissions	0.00E+0	0.00E+0	8.05E-8	0.00E+0	4.03E-8	7.80E-4	6.53E-9	1.17E-5	3.05E-6	1.76E-6	8.83E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Hydrogen Renewables 2030

Per tkm	Climate change	Ozone depletion	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Human toxicity	Photochemical oxidant formation	PM formation	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Ionising radiation	Agricultural land occupation	Urban land occupation	Natural land transformation	Water depletion	Metal depletion	Fossil depletion
	kg CO_2 eq	kg CFC-11 eq	kg SO_2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM_{10} eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	2.10E-2	1.73E-8	1.77E-4	2.07E-5	8.09E-6	5.06E-2	1.57E-4	1.18E-4	3.01E-5	8.14E-4	1.03E-3	5.66E-3	6.95E-4	7.46E-4	1.10E-5	3.63E+0	1.67E-2	8.14E-3
Vehicle Operation	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Vehicle maintenance	1.00E-3	6.92E-11	5.17E-6	2.92E-7	1.58E-7	3.10E-4	4.32E-6	2.03E-6	5.92E-8	8.17E-6	8.21E-6	1.27E-4	6.83E-5	8.11E-6	2.72E-7	1.97E-3	1.21E-4	4.76E-4
Vehicle Production	6.85E-3	5.85E-9	4.70E-5	6.17E-6	2.11E-6	9.96E-3	2.78E-5	2.04E-5	9.09E-7	2.27E-4	2.26E-4	1.14E-3	1.57E-4	8.09E-5	1.05E-6	2.92E-2	4.89E-3	1.84E-3
Road provision	6.75E-3	1.18E-9	3.79E-5	1.00E-6	2.13E-6	1.20E-3	9.35E-5	3.74E-5	4.98E-7	3.65E-5	4.10E-5	3.01E-3	9.17E-5	8.12E-5	8.04E-6	1.90E-2	8.83E-4	4.45E-3
Road operation and maintenance	1.92E-4	8.45E-11	6.59E-7	1.31E-7	7.95E-8	1.44E-4	7.46E-7	2.58E-7	8.12E-8	3.66E-6	3.63E-6	6.44E-4	1.55E-5	4.56E-4	3.99E-8	4.01E-3	2.43E-5	5.54E-5
H2 at fueling station	6.23E-3	1.01E-8	8.54E-5	1.31E-5	3.57E-6	2.97E-2	3.11E-5	3.30E-5	3.17E-6	5.34E-4	5.81E-4	7.40E-4	3.62E-4	1.20E-4	1.58E-6	3.58E+0	1.08E-2	1.33E-3
Treatment of brake wear emissions	0.00E+0	0.00E+0	2.50E-7	0.00E+0	4.37E-10	8.55E-3	2.03E-8	6.94E-6	2.23E-5	4.04E-6	1.66E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of road wear emissions	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.05E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Treatment of tyre wear emissions	0.00E+0	0.00E+0	8.05E-8	0.00E+0	4.03E-8	7.80E-4	6.53E-9	1.17E-5	3.05E-6	1.76E-6	8.83E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Freight Train 2004

Per tkm	Climate change	Ozone depletion	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Human toxicity	Photochemical oxidant formation	PM formation	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Ionising radiation	Agricultural land occupation	Urban land occupation	Natural land transformation	Water depletion	Metal depletion	Fossil depletion
	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM10 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	1.96E-2	3.59E-9	1.09E-4	6.95E-6	5.15E-6	1.05E-2	1.19E-4	6.14E-5	1.73E-6	2.86E-4	2.89E-4	2.89E-2	9.01E-4	1.69E-3	4.67E-6	3.45E-1	7.28E-3	4.65E-3
Train Operation	2.28E-3	0.00E+0	2.13E-5	0.00E+0	1.46E-6	0.00E+0	4.13E-5	1.56E-5	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Diesel for shunting processes	2.81E-4	1.50E-10	1.30E-6	1.36E-8	4.67E-8	2.19E-5	2.46E-6	4.33E-7	1.44E-8	6.91E-7	1.62E-6	1.29E-4	1.41E-6	2.29E-6	6.53E-7	1.58E-4	5.84E-6	7.59E-4
Wagon maintenance	3.53E-3	1.25E-10	1.84E-5	9.07E-7	5.07E-7	1.03E-3	9.80E-6	6.72E-6	2.91E-7	1.99E-5	2.03E-5	2.34E-4	2.26E-4	2.23E-5	3.70E-7	3.46E-3	2.17E-4	7.74E-4
Wagon Production	4.35E-3	1.75E-10	2.30E-5	2.38E-6	9.07E-7	3.19E-3	1.85E-5	1.41E-5	4.21E-7	1.08E-4	1.06E-4	3.56E-4	4.76E-4	5.86E-5	5.39E-7	2.51E-2	3.70E-3	1.01E-3
Railway trak construction	7.45E-3	5.93E-10	3.50E-5	2.35E-6	1.69E-6	3.08E-3	4.07E-5	1.87E-5	7.04E-7	8.55E-5	8.79E-5	2.72E-3	1.32E-4	1.59E-3	2.66E-6	2.64E-2	2.49E-3	1.76E-3
Locomotive maintenance	1.66E-4	7.45E-12	9.02E-7	9.02E-8	3.46E-8	1.31E-4	6.54E-7	4.62E-7	1.57E-8	2.90E-6	2.99E-6	1.46E-5	6.46E-6	1.71E-6	1.97E-8	4.13E-4	8.11E-5	3.92E-5
Locomotive Production	5.91E-4	4.74E-11	5.43E-6	9.33E-7	2.67E-7	1.95E-3	2.46E-6	2.08E-6	1.42E-7	3.19E-5	3.47E-5	5.81E-5	2.66E-5	7.24E-6	7.22E-8	2.39E-3	5.46E-4	1.46E-4
Electricity high voltage for SBB	9.22E-4	2.50E-9	4.10E-6	2.77E-7	2.45E-7	1.15E-3	3.45E-6	3.31E-6	1.42E-7	3.68E-5	3.58E-5	2.54E-2	3.25E-5	1.32E-5	3.62E-7	2.87E-1	2.40E-4	1.71E-4

Freight Train 2013

Per tkm	**Climate change**	**Ozone depletion**	**Terrestrial acidification**	**Freshwater eutrophication**	**Marine eutrophication**	**Human toxicity**	**Photochemical oxidant formation**	**PM formation**	**Terrestrial ecotoxicity**	**Freshwater ecotoxicity**	**Marine ecotoxicity**	**Ionising radiation**	**Agricultural land occupation**	**Urban land occupation**	**Natural land transformation**	**Water depletion**	**Metal depletion**	**Fossil depletion**
	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM10 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	1.45E-2	3.06E-9	6.98E-5	4.72E-6	3.25E-6	7.32E-3	7.32E-5	3.93E-5	1.23E-6	1.98E-4	2.01E-4	2.52E-2	5.41E-4	1.42E-3	3.80E-6	2.93E-1	4.89E-3	3.49E-3
Train Operation	2.19E-3	0.00E+0	8.20E-6	0.00E+0	5.70E-7	0.00E+0	1.54E-5	6.87E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Diesel for shunting processes	2.74E-4	1.46E-10	1.27E-6	1.33E-8	4.55E-8	2.13E-5	2.39E-6	4.21E-7	1.40E-8	6.73E-7	1.58E-6	1.25E-4	1.37E-6	2.23E-6	6.36E-7	1.54E-4	5.68E-6	7.39E-4
Wagon maintenance	1.89E-3	6.70E-11	9.84E-6	4.85E-7	2.71E-7	5.52E-4	5.24E-6	3.59E-6	1.56E-7	1.07E-5	1.08E-5	1.25E-4	1.21E-4	1.19E-5	1.98E-7	1.85E-3	1.16E-4	4.14E-4
Wagon Production	2.33E-3	9.33E-11	1.23E-5	1.27E-6	4.85E-7	1.70E-3	9.88E-6	7.53E-6	2.25E-7	5.76E-5	5.67E-5	1.90E-4	2.55E-4	3.14E-5	2.88E-7	1.34E-2	1.98E-3	5.39E-4
Railway trak construction	6.48E-3	5.11E-10	3.04E-5	2.03E-6	1.46E-6	2.66E-3	3.53E-5	1.63E-5	6.06E-7	7.41E-5	7.61E-5	2.33E-3	1.14E-4	1.36E-3	2.30E-6	2.27E-2	2.16E-3	1.52E-3
Locomotive maintenance	1.09E-4	4.90E-12	5.93E-7	5.93E-8	2.27E-8	8.58E-5	4.30E-7	3.04E-7	1.04E-8	1.90E-6	1.97E-6	9.60E-6	4.24E-6	1.13E-6	1.29E-8	2.72E-4	5.33E-5	2.58E-5
Locomotive Production	3.88E-4	3.12E-11	3.57E-6	6.13E-7	1.75E-7	1.28E-3	1.62E-6	1.37E-6	9.34E-8	2.10E-5	2.28E-5	3.82E-5	1.75E-5	4.76E-6	4.75E-8	1.57E-3	3.59E-4	9.63E-5
Electricity high voltage for SBB	8.13E-4	2.20E-9	3.62E-6	2.45E-7	2.16E-7	1.01E-3	3.05E-6	2.92E-6	1.25E-7	3.25E-5	3.16E-5	2.24E-2	2.87E-5	1.16E-5	3.19E-7	2.53E-1	2.12E-4	1.51E-4

Freight Train 2030

Per tkm	**Climate change**	**Ozone depletion**	**Terrestrial acidification**	**Freshwater eutrophication**	**Marine eutrophication**	**Human toxicity**	**Photochemical oxidant formation**	**PM formation**	**Terrestrial ecotoxicity**	**Freshwater ecotoxicity**	**Marine ecotoxicity**	**Ionising radiation**	**Agricultural land occupation**	**Urban land occupation**	**Natural land transformation**	**Water depletion**	**Metal depletion**	**Fossil depletion**
	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DB eq	kg NMVOC	kg PM10 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg U235 eq	m2a	m2a	m2	m3	kg Fe eq	kg oil eq
Total	1.10E-2	6.72E-10	4.93E-5	3.79E-6	2.13E-6	5.45E-3	4.72E-5	2.66E-5	9.17E-7	1.59E-4	1.60E-4	2.31E-3	3.91E-4	1.17E-3	3.03E-6	5.98E-2	3.90E-3	2.58E-3
Train Operation	1.18E-3	0.00E+0	3.93E-7	0.00E+0	2.59E-8	0.00E+0	6.98E-7	1.01E-6	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
Diesel for shunting processes	1.43E-4	7.60E-11	6.60E-7	6.91E-9	2.37E-8	1.11E-5	1.25E-6	2.19E-7	7.29E-9	3.50E-7	8.24E-7	6.52E-5	7.14E-7	1.16E-6	3.31E-7	8.01E-5	2.96E-6	3.85E-4
Wagon maintenance	1.33E-3	4.70E-11	6.91E-6	3.41E-7	1.91E-7	3.88E-4	3.68E-6	2.52E-6	1.09E-7	7.48E-6	7.61E-6	8.78E-5	8.49E-5	8.38E-6	1.39E-7	1.30E-3	8.15E-5	2.91E-4
Wagon Production	1.63E-3	6.56E-11	8.62E-6	8.93E-7	3.41E-7	1.20E-3	6.94E-6	5.29E-6	1.58E-7	4.05E-5	3.98E-5	1.34E-4	1.79E-4	2.20E-5	2.03E-7	9.42E-3	1.39E-3	3.79E-4
Railway trak construction	5.73E-3	4.32E-10	2.66E-5	1.76E-6	1.27E-6	2.29E-3	3.07E-5	1.42E-5	5.16E-7	6.41E-5	6.58E-5	1.94E-3	9.82E-5	1.13E-3	1.96E-6	1.94E-2	1.89E-3	1.32E-3
Locomotive maintenance	1.09E-4	4.90E-12	5.93E-7	5.93E-8	2.27E-8	8.58E-5	4.30E-7	3.04E-7	1.04E-8	1.90E-6	1.97E-6	9.60E-6	4.24E-6	1.13E-6	1.29E-8	2.72E-4	5.33E-5	2.58E-5
Locomotive Production	3.88E-4	3.12E-11	3.57E-6	6.13E-7	1.75E-7	1.28E-3	1.62E-6	1.37E-6	9.34E-8	2.10E-5	2.28E-5	3.82E-5	1.75E-5	4.76E-6	4.75E-8	1.57E-3	3.59E-4	9.63E-5
Electricity high voltage for SBB	5.38E-4	1.54E-11	1.92E-6	1.17E-7	8.27E-8	2.00E-4	1.95E-6	1.60E-6	2.28E-8	2.40E-5	2.15E-5	3.16E-5	6.27E-6	6.95E-6	3.34E-7	2.77E-2	1.24E-4	8.27E-5

Costs

Total costs in cts CHF per tkm

	Diesel 2013	Diesel 2030 low	Diesel 2030 high	LNG 2030 low	LNG 2030 high	Hydrogen 2030 low	Hydrogen 2030 high	Train 2013	Train 2030
external costs	2.98	2.67	2.67	1.90	1.90	1.77	2.15	2.08	1.18
fuel / energy	1.17	0.80	1.13	0.58	0.82	1.33	3.65	1.05	1.08
infrastructure investment and maintenance	9.14	8.38	8.38	9.14	9.14	9.14	9.14	10.01	8.87
vehicle investment and maintenance	1.50	1.43	1.43	1.78	2.05	1.68	1.84	0.84	0.68
human resource and overhead	4.68	4.68	4.68	4.68	4.68	4.68	4.68	3.33	3.00

Perceived costs in cts CHF per tkm

	Diesel 2013	Diesel 2030 low	Diesel 2030 high	LNG 2030 low	LNG 2030 high	Hydrogen 2030 low	Hydrogen 2030 high	Train 2013	Train 2030
external costs	0	0	0	0	0	0	0	0	0
fuel / energy	2.44	1.64	1.97	1.38	1.66	2.22	4.54	1.05	1.08
infrastructure investment and maintenance	4.10	4.10	4.10	4.10	4.10	4.10	4.10	10.01	8.87
vehicle investment and maintenance	1.50	1.43	1.43	1.78	2.05	1.68	1.84	0.84	0.68
human resource and overhead	4.68	4.68	4.68	4.68	4.68	4.68	4.68	3.33	3.00