openLCA (1.7.2)

How sustainable are Longer and Heavier Vehicles?

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Abbreviations

GHG	Green House Gas
LHV	Longer and Heavier vehicle
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
RER	Europe

1 Introduction

With a dense and efficient network of roads, railways, waterways, ports and airports, Germany is one of the global leaders in freight transport and logistics. Increased demand for freight traffic due to rising globalization and international trade could translate to more emissions of pollutants and carbon dioxide, more noise and more land use[1]. Federal Ministry of Transport and Digital Infrastructure reported that freight traffic will increase by 38 percent by 2030 against 2010 levels[2]. In 2012 Germany started a five-year trial of Long and Heavier Vehicles (LHVs) as a replacement for conventional trucks. The trial involves 60 companies and reported average economic benefits (i.e. cost savings of 16% compared to conventional vehicles, when the utilization rate of LHVs above 83%[3]). This study aims to evaluate the environmental impact of introducing Longer and Heavier Vehicles (LHVs), measuring up to 25.25 m and weighing up to 60 tons, to the German transport context, using the life cycle assessment (LCA) methodology, as described in ISO 14040. The question whether LHV have benefits for the environment is now new and has been addressed in several studies already, with mostly differing outcomes. The new approach of this study, and thus motivation to add "yet another" study on this topic, is to put more emphasis on understanding and structuring the situation and the impact of LHVs, in relation to also transport infrastructure and other transport modes, by use of a qualitative, screening model initially. This analysis leads to a structured approach to the question of the potential benefits of LHVs, by identification of different "layers of complexity", for which different results are obtained. These different layers are:

- Quantification of the impact of LHVs compared to normal-sized trucks,
- Effects on road infrastructure in addition to the truck transport itself
- Effects of an increase in the share of LHVs in the total freight transport, and
- Effects of an increase in the overall volume of freight transport, keeping the share of LHV constant, in the German context.

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[1] Freight Transport and Logistics Action Plan- Towards a Sustainable and Efficient Future, Federal Ministry of Transport and Digital Infrastructure, https://www.bmvi.de/SharedDocs/EN/publications/freight-transport-logistics-action-plan.pdf?__blob=publicationFile

[2] https://www.bmvi.de/EN/Topics/Mobility/Freight-Transport-Logistics/Logistics-in-a-nutshell/logistics-in-a-nutshell.html

[3] Vehicle Weight, Modal Split, and Emissions—An Ex-Post Analysis for Sweden, Vierth et al., http://www.mdpi.com/2071-1050/10/6/1731/htm

The open source software openLCA, version 1.7.1 was used as the software, for conducting the life cycle assessment for this case-study[4]. The ecoinvent 3.4 database was used for the life cycle inventory (LCI) and the ReCiPe Endpoint (Heirarchist) method was chosen as the life cycle impact assessment (LCIA) method. This LCIA method translates, roughly speaking, emissions and resource extractions into environmental impact scores.

2 Background

In Germany, the transportation sector stands third in terms of GHG emissions, with around 160 million tonnes CO_2 equivalents emitted in 2015[5]. Most of the emissions were, however, from growing use of road freight transports, due to reduced fuel prices. As of 2017, road transport of goods carried more than 71.8% of metric-ton kilometres of freight in Germany, followed by rail transport at 16.8% and waterway transport at 8.3%[6]. The rest is transported by crude oil pipelines and air transport. [7]. The rest is transported by crude oil pipelines and air transport. As per the interim target set for 2030, Germany's total GHG emissions in the transport sector needs to be reduced by 40-42% compared to 1990 levels[8]. Given the significant contribution of transport to GHG emissions and the ambitious 2030 target, there is a need to explore possible alternatives to transport goods to meet the GHG emissions target set in the Climate Protection Action Program 2050 set by the German government.

With the adoption of longer and heavier vehicles in some countries across the European union, much research has been dedicated to quantifying the impacts of LHVs. The wide-spread interest

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[4] www.openlca.org

[5] Climate Action in Figures: The Transport Sector, published by: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB); https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutz_in_zahlen_verkehr_en_bf.pdf

[6] 'Economic Sectors - Goods Transport - Goods Transport - Federal Statistical Office (Destatis)'. https://www.destatis.de/EN/FactsFigures/EconomicSectors/TransportTraffic/GoodsTransport/Tables/GoodstransportLR.html

[7] 'Economic Sectors - Goods Transport - Goods Transport - Federal Statistical Office (Destatis)'. https://www.destatis.de/EN/FactsFigures/EconomicSectors/TransportTraffic/GoodsTransport/Tables/GoodstransportLR.html

[8] BMUB2, 'Climate Action Plan 2050: Principles and Goals of the German Government's Climate Policy', *Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB)*, 2016, 1–6.

on LHVs has generated a passionate discussion highlighting the pros and cons of potential introduction of LHVs. Studies made by Steer et al.[9], and Ortega et al.[10] presented the impacts of LHVs on traffic safety, road infrastructure and investments, while another study by Vierth et al[11]. focused on finding empirical evidence on the consequences of using LHVs in Sweden where the maximum truck weights were increased in 1990 and 1993. With regards to Germany, the effects of the adoption of LHVs by logistics service providers were studied by Rodrigues et al.[12]. Based on the study conducted by the authors, they reported favourable interest towards introduction of LHVs in Germany, by the participating companies. The research identified significant decreases in fuel consumption, as well as in CO_2 emissions to be the cause for the favorable response by the participating companies.

With this study, the aim is to carry out a life cycle assessment of LHVs to create a comprehensive understanding of the potential impacts of LHVs throughout their life cycle, in the German context.

3 The LCA methodology

Life cycle assessment is a standardised method, described in the international standards ISO 14040 and 14044, to assess comprehensively the potential environmental impact throughout a throughout the life of a product or a service. Several environmental aspects of the product life cycle (emissions into air, water and soil, waste, use of raw material and exploitation of nature) are considered. The method is performed in four phases. In the first phase the goal and scope of the study and the resulting system boundaries are defined. In the life cycle inventory analysis phase, all relevant materials and energy inputs and outputs are included in the system. In the assessment phase, the environmental effects of the system components are assigned to different impact categories. Different materials are weighted according to their damage potential

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[9] Steer Davies Gleave – James Steer and others, 'A REVIEW OF MEGATRUCKS Major Issues and Case Studies STUDY', 2013 <http://www.europarl.europa.eu/RegData/etudes/etudes/join/2013/513971/IPOL-TRAN_ET(2013)513971_EN.pdf> [accessed 23 July 2018].

[10] A. Ortega and others, 'Are Longer and Heavier Vehicles (LHVs) Beneficial for Society? A Cost Benefit Analysis to Evaluate Their Potential Implementation in Spain', *Transport Reviews*, 34.2 (2014), 150–68 <https://doi.org/10.1080/01441647.2014.891161>.

[11] Inge Vierth, Samuel Lindgren, and Hanna Lindgren, 'Vehicle Weight, Modal Split, and Emissions-an Ex-Post Analysis for Sweden', *Sustainability (Switzerland)*, 10.6 (2018) <https://doi.org/10.3390/su10061731>.

[12] Vasco Sanchez Rodrigues and others, 'The Longer and Heavier Vehicle Debate: A Review of Empirical Evidence from Germany', *Transportation Research Part D: Transport and Environment*, 40 (2015), 114–31 <https://doi.org/10.1016/j.trd.2015.08.003>.

and summarized in total impact indicators. In the final interpretation phase, the impacts are analysed and evaluated to draw conclusions or make recommendations. This comprehensive approach avoids the burden shifting of environmental effects and provides a summary of possible areas for impact reduction.

4 Goal and Scope definition

The purpose of this investigation is to perform a systematic assessment of the potential life cycle impacts of introducing LHVs on a larger scale for freight transportation in Germany. The qualitative modelling methodology is applied to model the impacts of using LHVs on the freight transportation infrastructure in Germany, where most of goods are transported via roads. Factors of interest include the impact on ecosystems, human health and resources, resulting from an increase in the share of LHVs for goods transportation. The qualitative model was designed to model transportation infrastructure and congestion, fossil fuel consumption, emission and resource pricing. Explicit assumptions regarding freight transportation in the German context were made and several aspects of increasing the share of LHVs were modelled.

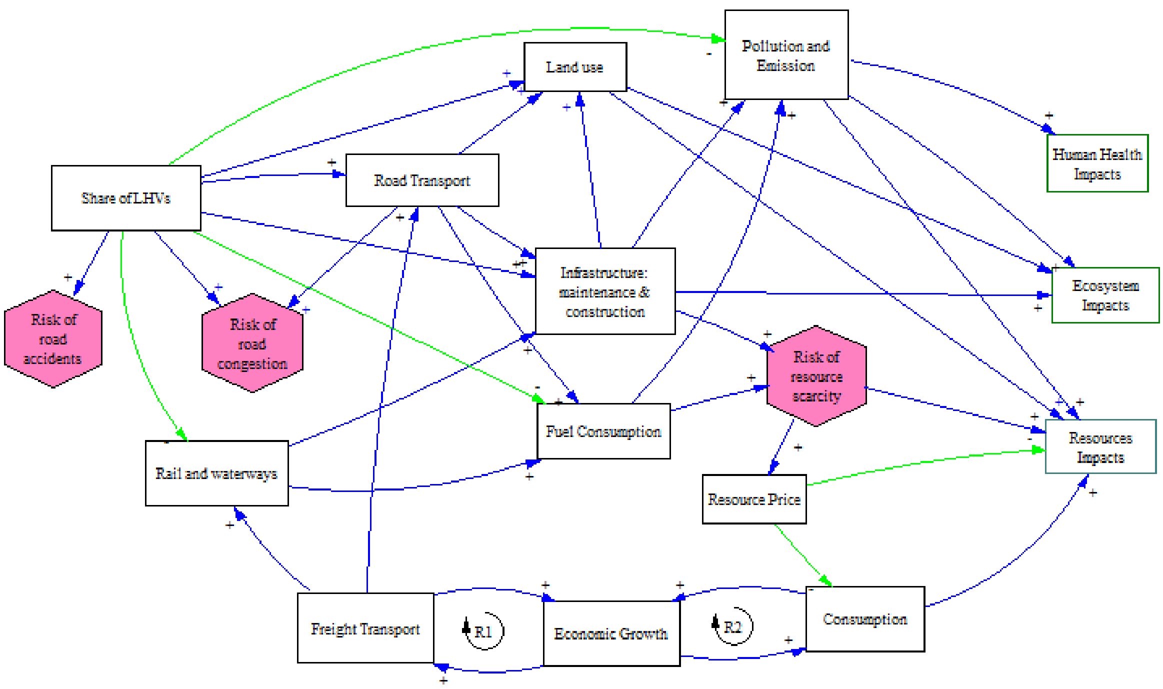

Figure 1 A qualitative model for a share of LHVs in German inland freight transport system

The model (figure 1) is created using Vensim software. The qualitative model includes all the elements involved in the product system under study and the relations among them.

- The white boxes with black border contain the elements influencing the impacts, while the pink hexagonal boxes contain the risks associated with element.
- The white boxes with green border contain the impacts categories.
- Arrows show relations in the diagram. Blue arrows indicate a positive relationship (a → b, b increases if 'a' increases), whereas green arrows indicate negative relationship

In particular, "share of LHVs" is connected to "road transport", "land use", etc with a positive relationship. The positive relationship between share of LHVs and road transport, infrastructure (maintenance and construction) and land use indicates that with an increase in the share of LHVs, there is increase in the use of roads for transport, increased need for road expansion and maintenance, and thereby, more land cleared from road expansions. On the other hand, more LHVs, also lead to reduced consumption of fossil fuels per t*km of goods transported, and subsequently less emissions compared to normal trucks. It is interesting to note that while the risk of road accidents is inherent to every vehicle on the road, an increase in the share of LHVs also introduces the risk of road congestions due to its massive proportions.

The scope of the case study was guided by the following research questions:

- What is the life cycle impacts of a longer and heavier vehicle compared to a normal truck?
- How does road infrastructure influence the impacts of a longer and heavier vehicle compared to a normal truck?
- What are the implications of increasing the share of LHVs for freight transportation in the German context?
- What is the impact of LHVs while the market volume of freight transportation has increased?

Accordingly, a four-layered approach (see table 1) is defined: (i) initially, the life cycles of a LHV and a normal truck are compared; (ii) secondly, the two technologies are compared adding the impacts due to road construction, maintenance and end of life phase into the model; (iii) thirdly, different situations of LHV shares in the road transport modal share for freight transport are compared, (iv) followed with identifying the effects of increase in the overall market share for freight transport.

Table 1 : Description of the different research questions addressed by the case study in the form of layers.

	Layer 1: Simple model	Layer 2: Full model	Layer 3: Total freight transport, including LHVs	Layer 4: German Freight Transport Volume
LHV	Life cycle impacts of LHV vs Normal Truck	Life cycle impacts of LHV vs normal trucks, with road construction, maintenance and end of life phase	Impact of increasing the share of LHV on overall German freight transport	Impact of increase in the market volume of the German freight transport
Normal truck				

5 Data and life cycle inventory assessment in openLCA

For this study, the swiss database ecoinvent version 3.4 is used as a primary data source, while additional data was sourced from the literature. The Swiss database ecoinvent is an established LCI database complying with the ISO standard 14040 since 2000, it is developed in Zurich and supported by ETH Zurich (Swiss Federal Institute of Technology), EMPA (The Swiss Federal Laboratories for Materials Science and Technology), and Paul Scherrer Institute, to name a few, and the Swiss Federal Offices. It is the world leader for life cycle inventory database known for its most consistent and transparent database.

The ecoinvent 3.4 database already contains a comprehensive and transparent life cycle dataset of transport services in Europe which was directly used for the life cycle inventory analysis of the present case study. For the LHV, the dataset of the heaviest trucks ("transport, freight, lorry >32 metric ton, EURO6, cut-off, U, RER") in Europe is considered. The input data included road construction, lorry production and maintenance, road, tyre and brake wear emission treatment, low-sulfur diesel production (Europe without Switzerland) processes. This data was further modified to align with the specifications of an LHV with data from literature.

Similarly, the dataset for normal trucks was derived from the dataset "transport, freight, lorry, 16-32 metric ton, EURO6, cut-off, U, RER", as most of the trucks used for goods transport in Germany[13] fall in this range.

6 Impact Assessment method: Recipe 2016 Midpoint (H)

The ReCiPe 2016 Midpoint (H) LCIA method used for the present study, provided 18 impact categories, primarily focussing on ecosystems, human health and resources. These indicators express the potential impact for different categories that are highlighted in the tables 2 below.

[13] The economics of the trucking industry, https://inconvenienttruck.eu/the-economics-of-trucks-industry/

Table 2: ReCiPe 2016 Midpoint (H); impact categories and reference unit.

	Impact category	Reference unit
Ecosystem impacts	Fine particulate matter formation	kg PM2.5 eq
	Freshwater ecotoxicity	kg 1,4-DCB
	Freshwater eutrophication	kg P eq
	Global warming	kg CO2 eq
	Ionizing radiation	kBq Co-60 eq
	Marine ecotoxicity	kg 1,4-DCB
	Marine eutrophication	kg N eq
	Ozone formation, Terrestrial ecosystems	kg NOx eq
	Stratospheric ozone depletion	kg CFC11 eq
	Terrestrial acidification	kg SO2 eq
	Terrestrial ecotoxicity	kg 1,4-DCB
Human health impacts	Ozone formation, Human health	kg NOx eq
	Human carcinogenic toxicity	kg 1,4-DCB
	Human non-carcinogenic toxicity	kg 1,4-DCB
Resource impacts	Fossil resource scarcity	kg oil eq
	Land use	m2a crop eq
	Mineral resource scarcity	kg Cu eq
	Water consumption	m3

7 System modelling

This chapter describes the system boundary and the functional units of the four layers considered for the impact assessments in this study.

7.1 LHV vs NORMAL TRUCK (Layer 1&2)

Here, the focus is on the first two layers of the case study (Table 1), i.e. the simple model of a LHV vis-à-vis Normal truck, and the complete model of a LHV vis-à-vis Normal truck. The functional unit in the present case is 1 t*km of goods transported by freight road transport mode in Germany. The system boundary includes the raw material extraction, the construction of road (relating to infrastructure planning), manufacture and maintenance of the vehicle, fuel production and resource consumption of operation phase, since the ecoinvent data contains up- and downstream process.

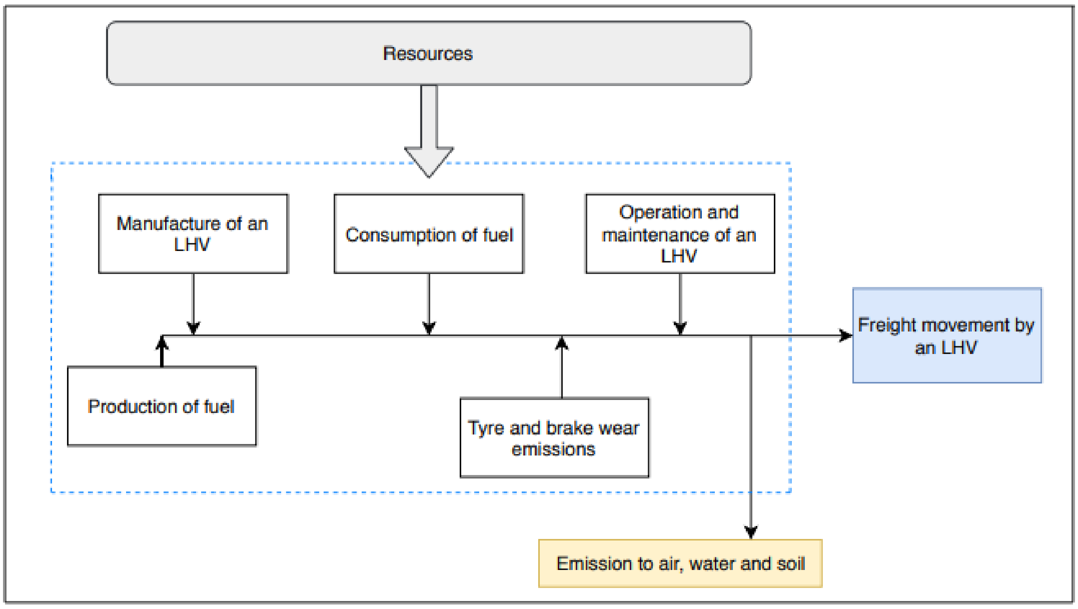

Figure 2: System boundary for Layer 1 (Simple Model)

Figures 2 and 3 show the system boundary for the first two layers, where the inputs for layer 1 (simple model) is inside the blue dashed lines and the inputs for layer 2 (full model) is within the green dashed lines, respectively. The outermost boundary in black encloses the system boundary for both the simple model and full model. The same system boundaries were applied for a normal truck.

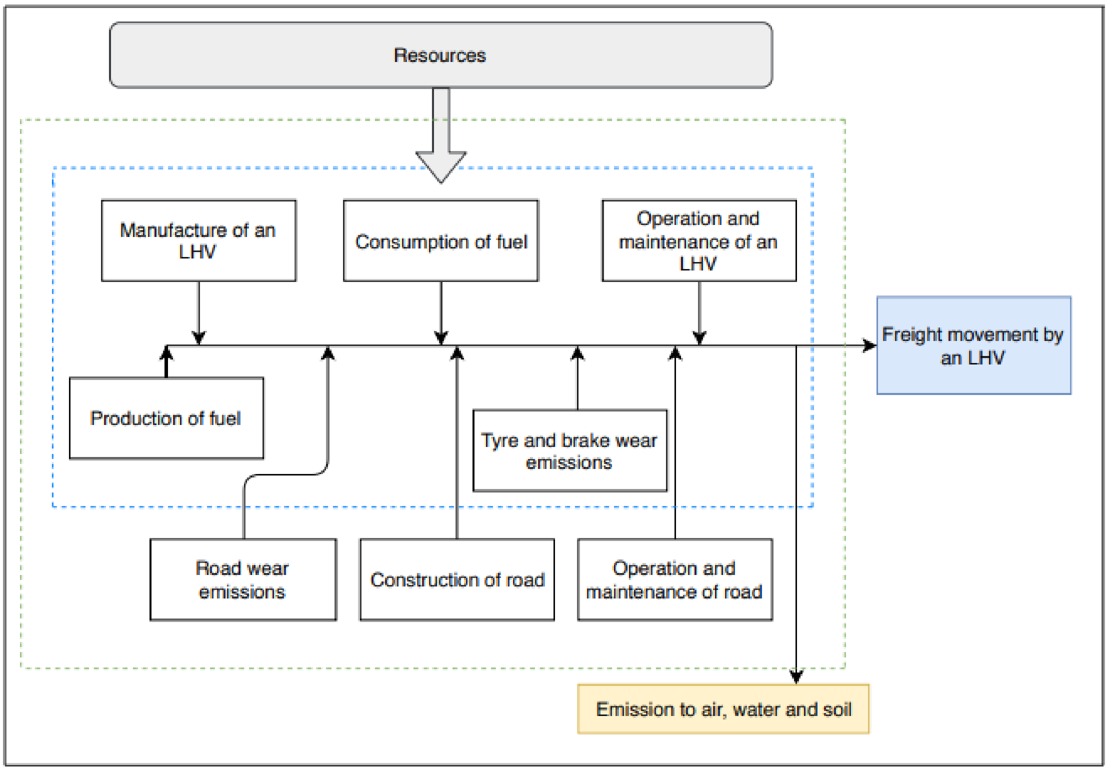

Figure 3: System boundary for Layer 2 (Full Model)

7.2 Total freight transport, including LHVs (Layer 3)

For Layer 3 (Table 1), the aim was to assess the impact of increasing the share of LHVs and the share of road freight transport on the total freight transport system. The system boundary, therefore, includes the freight transport by three modes of transport (road, rail and waterway) where LHV is included in the road transport. Figure 4 shows the system boundary with the system processes including all upstream chains (raw materials production, freight, production of materials, production of machines and their use etc.) that were examined. The dashed lines enclose the inputs of the process to be evaluated. The functional unit for this stage is 666,103 million t*km of goods transported, which is explained further in section 8.2, inventory analysis.

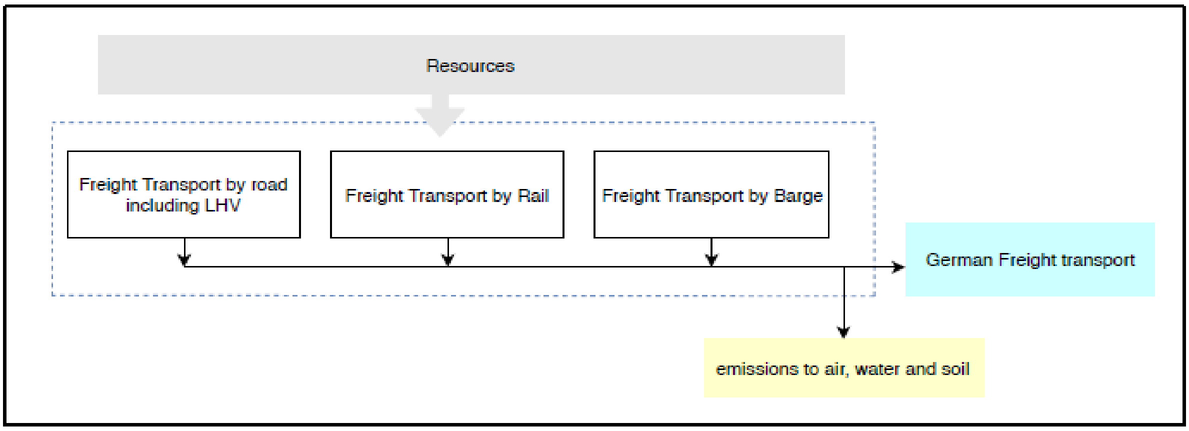

Figure 4: System boundary for the German freight transportation system

7.3 German Freight Transport Volume (Layer 4)

For the final layer of the model (Layer 4, see Table 1), the aim is to investigate the effect of an increase in the market volume of the German freight transport. If increasing the share of LHVs lead to a reduction in CO2 emissions, it would be interesting to note when the reductions cease to exist with an increase in the market volume of the German freight transport. Since Layer 4 is an extension of layer 3, both the system boundaries and the functional unit for this investigation area maintained equal to ones of Layer 3 (i.e., Figure 5 and the total freight transport of 666,103 million tonne-kilometres, respectively).

8 Inventory analysis

8.1 LHV vs NORMAL TRUCK (Layer 1&2)

This section covers the analysis for layer 1 and 2 of this study. The dataset for an LHV and a normal truck was based on the datasets available in ecoinvent 3.4. The inventory of the LHV can be seen in the inputs and outputs table of the model graphs presented in figure 5 (simple model) and 6 (Full Model) below.

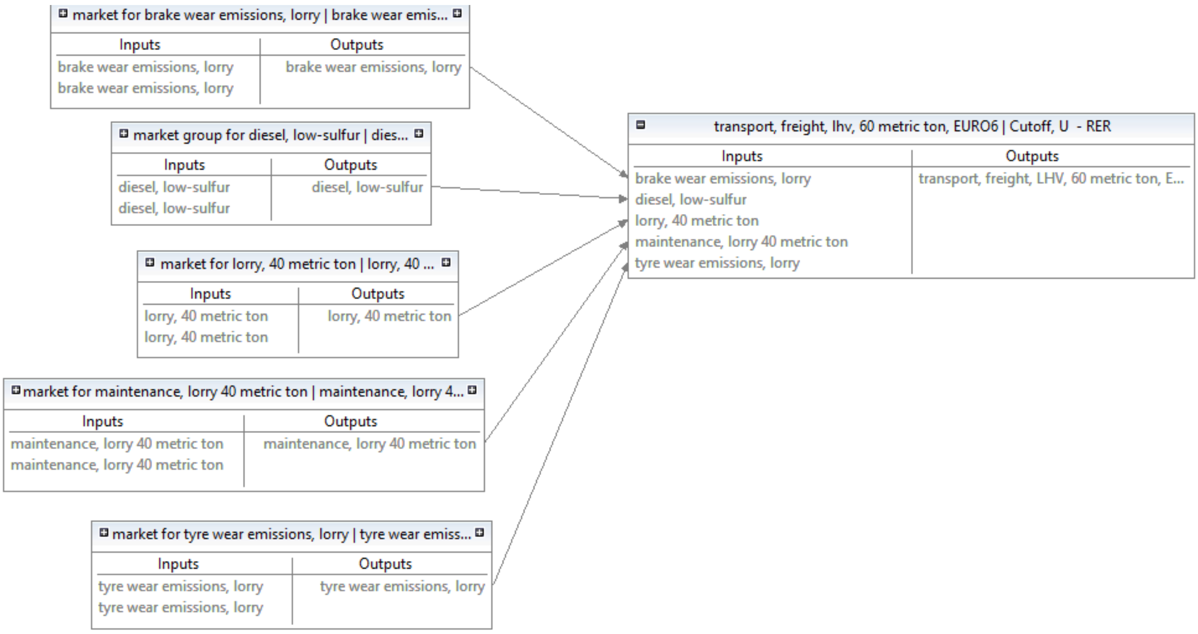

Figure 5: Model graph for layer 1, depicting the input and output dataset of an LHV, simple model.

Owing to the lack of data for an LHV in the ecoinvent 3.4 database, the study uses data from literature to create a suitable dataset for an LHV[14]. To obtain a dataset aligned to the specifications of an LHV, the following changes were made (table 3):

Table 3: Additional data from the literature review for design of an LHV dataset

Inputs	Modifications
Brake wear emissions[15], lorry	Given that the relative mass of the vehicles is proportional to the relative energy required to stop the vehicles, brake emission rate of LHV will be 1.5 times greater than conventional trucks, since LHVs are 1.5 times heavier.
Diesel, low-sulfur	Fuel savings of up to 24% is possible with the use of LHVs[16].
Road (construction) Road Maintenance	LHVs require 20% more road space, hence 20% more construction and maintenance of road[17].
Road wear emissions, lorry	This work assumed that road wear emissions is dependent on the number of tyres of a truck. The number of wheels installed on a normal truck is 12, while it is 18 for an LHV. But it takes 1,57 vehicles of 44 metric ton conventional truck to carry the same payload as an LHV. Therefore, the road wear emission is of an LHV is 0,95 times that of 44 metric ton truck[18].
Tyre wear emissions[19], lorry	This works assumed that the relative tyre material exhausted in the period of the transporting goods is proportional to the number of tyres installed on a truck. Thus, the same calculation for road wear emission applies here.

For a normal truck, the inventory is taken from the ecoinvent 3.4 database, in its original state. The dataset considered from the ecoinvent 3.4 database was the dataset "transport, freight, lorry, 16-32 metric ton, EURO6, cut-off, U, RER".

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[14] The data was sourced from the literature review conducted as part of a master thesis titled ‘Life cycle assessment of scenarios including Longer and Heavier Vehicles in Germany´s FTIP 2030’, undertaken at GreenDelta GmbH.

[15] U.S. ENVIRONMENTAL PROTECTION AGENCY, Brake and Tire Wear Emissions from On-road Vehicles in MOVES, (2014); file:///C:/Users/User/Desktop/LCA/LCA%20for%20LHV%20in%20Germany/Lit_review/420R14013.PDF

[16] http://www.tut.fi/verne/aineisto/LiimatainenNyk%C3%A4nen.pdf

[17] Newton, W., et al. Longer and/or Longer and Heavier Goods Vehicles (LHVs): A study of the likely effects if permitted in the UK: Final Report. No. PPR 285.IHS, 2008.;

[18] Johansson, Christer, et al. "NOTRIP-Non-exhaust road traffic induced particle emissions: Development of a model for assessing the effect on air quality and exposure." (2012).

[19] U.S. ENVIRONMENTAL PROTECTION AGENCY, Brake and Tire Wear Emissions from On-road Vehicles in MOVES, (2014); file:///C:/Users/User/Desktop/LCA/LCA%20for%20LHV%20in%20Germany/Lit_review/420R14013.PDF

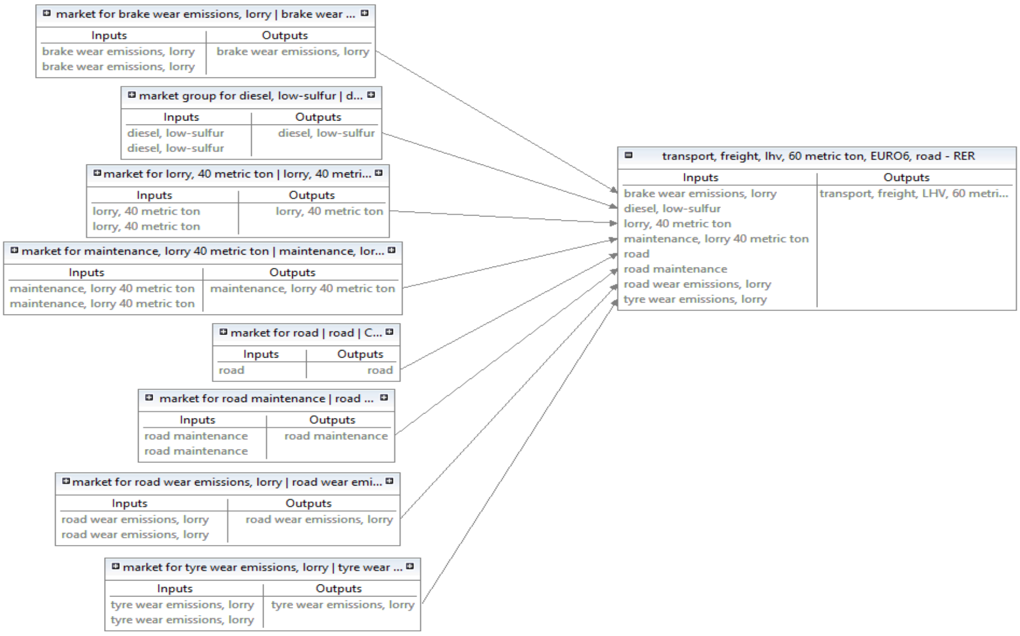

Figure 6: Model graph depicting the input and output dataset of an LHV, full model.

The inputs and outputs of the normal truck in ecoinvent 3.4 are similar to the input-outputs for LHVs, with differences in some flows as explained in Table 3. Also, for the normal truck, a 16-metric ton lorry is considered for the normal truck, unlike the case of LHV, where a 40-metric ton lorry is considered in the dataset.

8.2 Total freight transport, including LHVs (Layer 3)

For this layer, a comparison is made between three situations, where the freight transport is shared by three different modes, namely, road (including LHVs), railway, and waterway. Modal shares of freight transport in Germany were taken as the references in this comparison.

The first *baseline* situation is based on the 2017 data on transport performance obtained from Eurostat, shown in figure 7. Only road transport by national lorries was considered in this study. The alternate situation reported in Table 4 were created to carry out the comparison in terms of life cycle impacts.

Table 4: Overview of the situations with different share of LHVs in freight transport for Germany assessed in Layer 3.

Situations	Description
Situation a	Road transport is at 72% of total transport, with normal trucks at 100% of road transport and LHV at 0% of road transport.
Situation b	Road transport is at 72% of total transport, with normal trucks at 60% of road transport and LHV at 40% of road transport.

Situation c	Road transport is at 82% of total transport, with normal trucks at 60% of road transport and LHV at 40% of road transport.

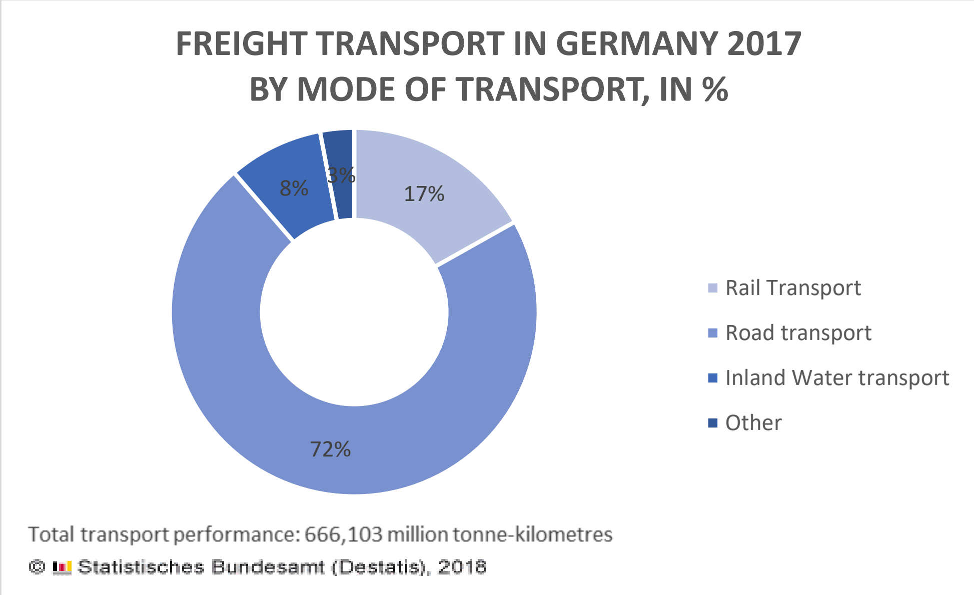

Figure 7: modal shift, German freight transport

While making calculations for the railway and waterway transport, the following assumptions are made:

- The share of railway and waterway transport is assumed at 17% and 8%, respectively.
- When the share of road transport increases in the total modal share, there is proportionate decrease in the share of railway and water transport. Share of other means of freight transport stays constant.

Figure 9 shows the model graph highlighting the input-output data for the road freight system for this study, where the truck transport includes transport by LHV, 60 metric ton, EURO6 and transport by a normal truck, 16-32 metric ton, EURO6.

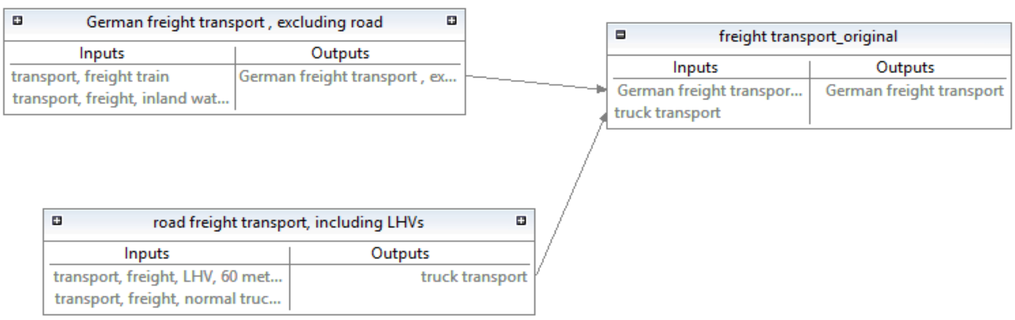

Figure 8: Model graph presenting the input-output data for German freight transport system

8.3 German Freight Transport Volume (Layer 4)

The transport performance (market volume of goods transported) by the different modes of freight transportation in 2017 is known (see Figure 7). In this layer, the idea is to investigate the global warming impact caused by increases in market for freight transport, due to e.g. rising trade, or easier and cheaper transport possibilities guaranteed by reduced fuel consumption[20], such as LHVs. It is worth noting that in this layer, the share of LHV stays unchanged (i.e., equal to 40%), irrespective of the increase in the market volume of the freight transportation.

Five different situations are considered here. In situation a and b, the total freight transport is the same as in 2016, while it changes in the other scenarios. Table 5 includes the description of the situations compared in this layer.

Table 5: Overview of the situations for assessing the impact of increase in the market volume of freight transport

Situation	Description
situation a	No LHV in road transport modal share; No market increase
situation b	40% LHV in road transport modal share; No market increase
situation c	40% LHV in road transport modal share; Freight market increase from 666103 million t*km of goods transported to 750,000 million t*km (28.1 % increase)
situation d	40% LHV in road transport modal share; Freight market increase from 666103 million t*km of goods transported to 775,000 million t*km (33.5 % increase)
situation e	40% LHV in road transport modal share; Freight market increase from 666103 million t*km of goods transported to 800,000 million t*km (38.8 % increase)

9 Evaluation: Life Cycle Impact Assessment

Using openLCA, the results of the impacts of the four layers were obtained. The absolute values of the assessment can be found in tables below (i.e., Table 6-9), where the green boxes indicate lowest impacts, pink boxes indicate highest impacts, and yellow boxes indicate medium impact, obtained when comparing LHV and trucks of normal size. The obtained results have been also reported in relative terms in Figures 10-12, where the highest impact value is represented with 1.

[20] The longer and heavier vehicle debate: A review of empirical evidence from Germany, Rodrigues, Vasco Sanchez, Piecyk, Maja, Mason, Robert, Boenders, Tim; http://dx.doi.org/10.1016/j.trd.2015.08.003

9.1 Results: Layer 1, Simple model

Table 6: Result of the impact assessment of simple model, LHV vs Normal truck

	Impact category	Reference unit	LHV	Normal truck
Ecosystem impacts	Fine particulate matter formation	kg PM2.5 eq	6.26E-05	1.16E-04
	Freshwater ecotoxicity	kg 1,4-DCB	1.59E-03	2.27E-03
	Freshwater eutrophication	kg P eq	5.71E-06	1.01E-05
	Global warming	kg CO2 eq	7.47E-02	1.52E-01
	Ionizing radiation	kBq Co-60 eq	1.05E-03	2.43E-03
	Marine ecotoxicity	kg 1,4-DCB	4.51E-03	5.24E-03
	Marine eutrophication	kg N eq	4.43E-07	8.61E-07
	Ozone formation, Terrestrial ecosystems	kg NOx eq	7.88E-05	1.68E-04
	Stratospheric ozone depletion	kg CFC11 eq	5.05E-08	1.05E-07
	Terrestrial acidification	kg SO2 eq	1.14E-04	2.55E-04
	Terrestrial ecotoxicity	kg 1,4-DCB	2.43E+00	2.21E+00
Human health impacts	Ozone formation, Human health	kg NOx eq	7.54E-05	1.61E-04
	Human carcinogenic toxicity	kg 1,4-DCB	1.67E-03	2.78E-03
	Human non-carcinogenic toxicity	kg 1,4-DCB	8.05E-02	1.01E-01
Resource impacts	Fossil resource scarcity	kg oil eq	2.07E-02	4.97E-02
	Land use	m2a crop eq	3.23E-04	6.84E-04
	Mineral resource scarcity	kg Cu eq	1.72E-04	2.62E-04
	Water consumption	m3	1.75E-04	3.68E-04

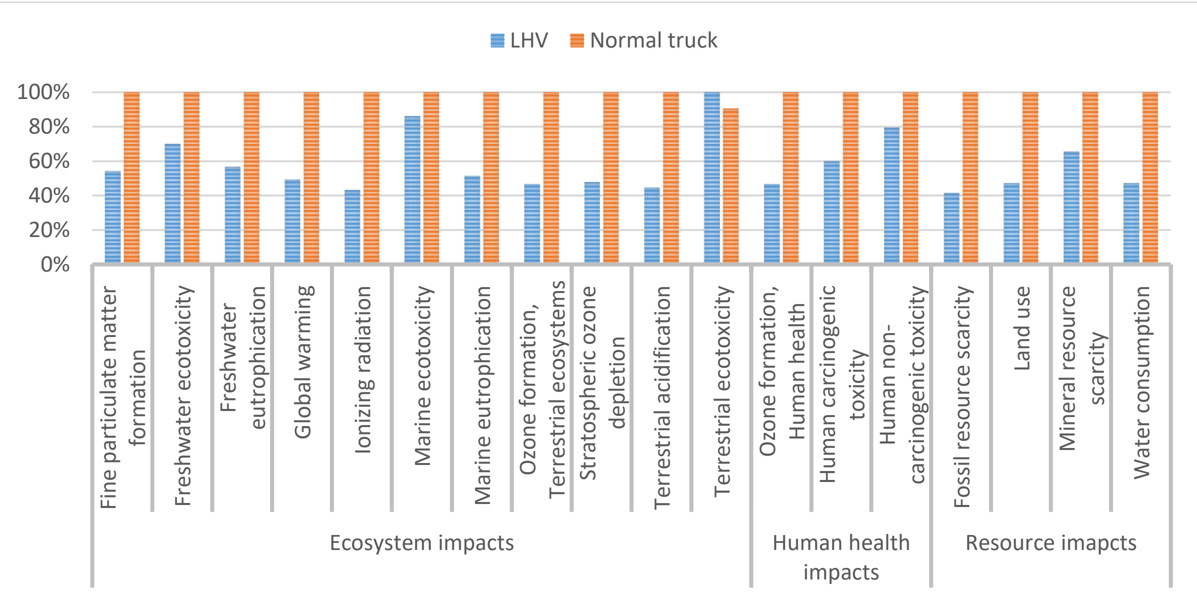

Figure 9: Relative impacts between LHVs and normal trucks; Simple model

Figure 9 presents the comparative analysis of the life cycle impacts of an LHV compared to a normal truck, for a simple model. The impact categories (see table 6) are further divided into ecosystem, human health and resource impacts. For a functional unit of 1 t*km, an LHV clearly has lower impacts compared to a normal truck. In the case of terrestrial ecotoxicity, the major contribution of impacts is from brake wear emissions for both LHV and normal trucks. The brake wear emissions from LHVs are 1.5 times higher than that of normal truck, as such the impacts from LHVs is 14% more than normal trucks.

9.2 Results: Layer 2, Full model

Table 7: Result of the impact assessment of full model, LHV vs Normal truck

	Impact category	Reference unit	LHV	Normal truck
Ecosystem Impacts	Fine particulate matter formation	kg PM2.5 eq	1.52E-04	1.90E-04
	Freshwater ecotoxicity	kg 1,4-DCB	2.37E-03	2.89E-03
	Freshwater eutrophication	kg P eq	2.05E-05	2.19E-05
	Global warming	kg CO2 eq	1.14E-01	1.83E-01
	Ionizing radiation	kBq Co-60 eq	4.37E-03	5.09E-03
	Marine ecotoxicity	kg 1,4-DCB	5.60E-03	6.11E-03
	Marine eutrophication	kg N eq	1.58E-06	1.78E-06
	Ozone formation, Terrestrial ecosystems	kg NOx eq	2.38E-04	2.96E-04
	Stratospheric ozone depletion	kg CFC11 eq	6.85E-08	1.20E-07
	Terrestrial acidification	kg SO2 eq	2.72E-04	3.82E-04
	Terrestrial ecotoxicity	kg 1,4-DCB	2.50E+00	2.26E+00
Human Health impacts	Ozone formation, Human health	kg NOx eq	2.25E-04	2.81E-04
	Human carcinogenic toxicity	kg 1,4-DCB	3.34E-03	4.12E-03
	Human non-carcinogenic toxicity	kg 1,4-DCB	1.00E-01	1.17E-01
Resource impacts	Fossil resource scarcity	kg oil eq	3.48E-02	6.10E-02
	Land use	m2a crop eq	8.67E-03	7.38E-03
	Mineral resource scarcity	kg Cu eq	2.67E-04	3.38E-04
	Water consumption	m3	5.12E-04	6.39E-04

The table 7 shows the comparative analysis of the impacts of an LHV and a normal truck, when life cycle of a road is also included in the impact assessment calculation. In the full model, the impacts of the life cycle of an LHV combined with the life cycle of road is again lower compared to that of normal road (see figure 10). Unlike the simple model, the land use imapct of LHV is higher, which is evident from the 20% higher usage of road for an LHV. Considering both the first two layers, it can be determined that for a 1 t*km of good transported by road, the imapcts of an LHV are lower than that of a conventional truck.

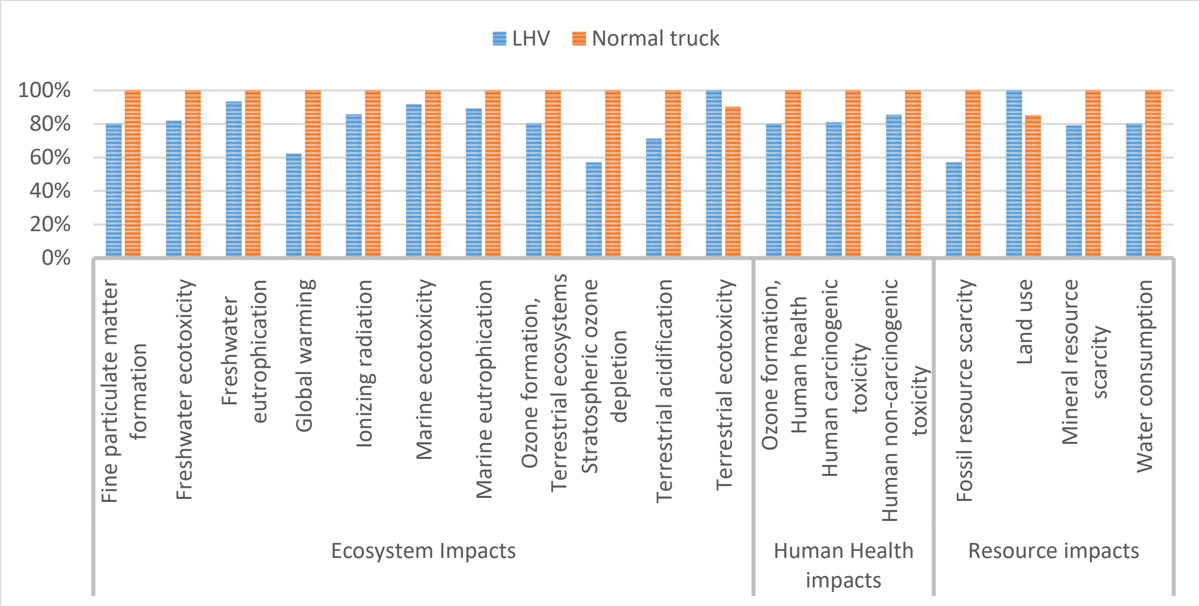

Figure 10: Relative impacts between LHVs and normal trucks; Full model, that includes the life cycle of a road

9.3 Results: Total freight transport, including LHVs (Layer 3)

Table 8: Results of the impact assessment of the increase in share of LHVs and share of road transport in the modal share for freight transport.

	Impact category	Unit	Situation a	Situation b	Situation c
Ecosystems impacts	Fine particulate matter formation	kg PM2.5 eq	9.51E+07	8.79E+07	9.81E+07
	Freshwater ecotoxicity	kg 1,4-DCB	1.46E+09	1.36E+09	1.51E+09
	Freshwater eutrophication	kg P eq	1.25E+07	1.22E+07	1.29E+07
	Global warming	kg CO2 eq	9.04E+10	7.71E+10	8.65E+10
	Ionizing radiation	kBq Co-60 eq	2.76E+09	2.62E+09	2.83E+09
	Marine ecotoxicity	kg 1,4-DCB	3.03E+09	2.93E+09	3.29E+09
	Marine eutrophication	kg N eq	9.78E+05	9.41E+05	1.01E+06
	Ozone formation, Terrestrial ecosystems	kg NOx eq	1.56E+08	1.45E+08	1.58E+08
	Stratospheric ozone depletion	kg CFC11 eq	5.92E+04	4.94E+04	5.54E+04
	Terrestrial acidification	kg SO2 eq	1.95E+08	1.73E+08	1.92E+08
	Terrestrial ecotoxicity	kg 1,4-DCB	1.09E+12	1.13E+12	1.29E+12
Human health impacts	Ozone formation, Human health	kg NOx eq	1.49E+08	1.38E+08	1.50E+08
	Human carcinogenic toxicity	kg 1,4-DCB	2.19E+09	2.04E+09	2.22E+09
	Human non-carcinogenic toxicity	kg 1,4-DCB	5.82E+10	5.49E+10	6.15E+10
Resource impacts	Fossil resource scarcity	kg oil eq	3.00E+10	2.50E+10	2.81E+10
	Land use	m2a crop eq	3.66E+09	3.91E+09	4.39E+09
	Mineral resource scarcity	kg Cu eq	1.73E+08	1.60E+08	1.76E+08
	Water consumption	m3	3.21E+08	2.97E+08	3.31E+08

Results from Layer 3 (see table 8, figure 11) indicate that while increasing the share of LHVs in the road transport modal share lowers the impacts, the increase in modal share of conventional trucks and LHVs result in higher impacts. In case of land use and terrestrial ecotoxicity impacts, increasing the share of LHVs did not result in lower impacts. Although increasing the modal share of road transport showed relatively better results for global warming, stratospheric ozone depletion, fossil fuel scarcity and terrestrial acidification, results suggest that increasing the share of LHVs while keeping the modal share of road freight transport constant will have lower impacts.

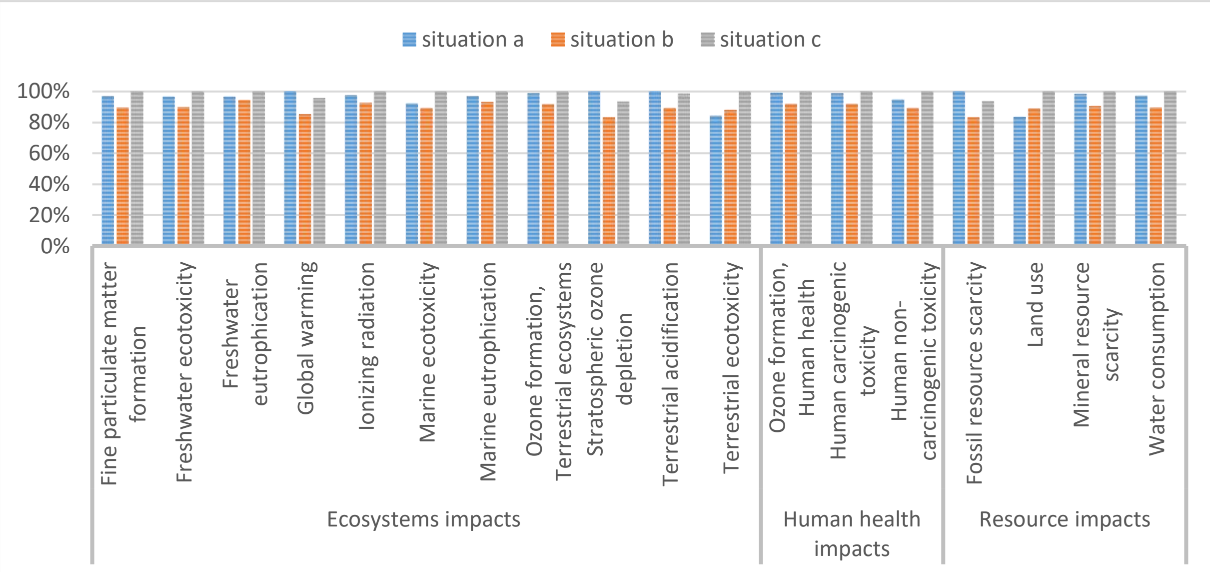

Figure 11 : Overview of the impacts of the increase in the share of LHVs and road freight share on the German freight transport.

9.4 Results: German Freight Road Transport (Layer 4)

Table 9: Results of the impact assessment of the increase in the market volume of freight transport.

Impact Category	situation a	situation b	situation c	situation d	situation e	unit
Global warming	1.22E+11	1.03E+11	1.16E+11	1.20E+11	1.24E+11	kg CO2 eq

In the final layer, the impact for global warming is considered. The results show that increasing the share of LHVs by 40% (i.e., situation b, see table 4) in the modal share of road led freight transport lead to 20% lower impacts with respect to situation a. However, when the overall share of freight transport increases to around 30%, the impacts are the same as situation a, i.e. when no LHVs are in use (see figure 12).

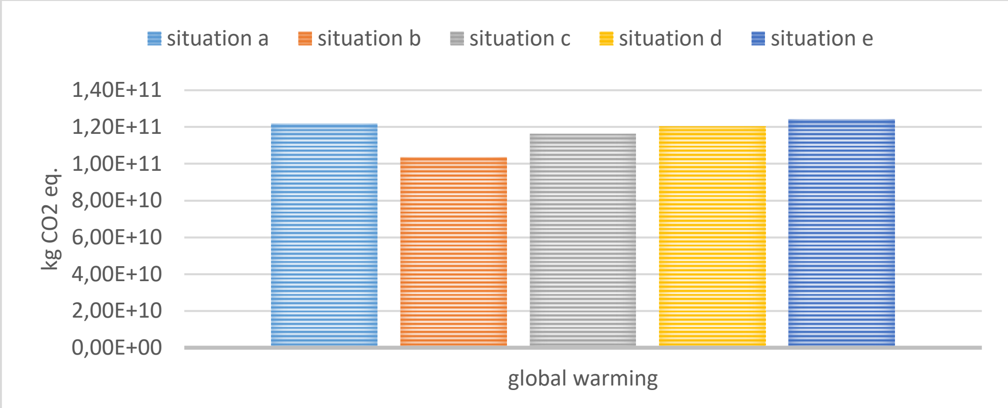

Figure 12: Overview of the impacts of the increase in the market volume of freight transport.

10 Interpretation & Outlook

From the results on tables 6 and 7, for both the simple model and full model, LHVs clearly has lower impact compared to normal trucks. However, it should be noted that with the inclusion of life cycle of roads (i.e., road construction and maintenance), the impacts of LHVs increase. The impact categories (e.g. climate change, stratospheric ozone depletion) less influenced by road is characterized by lower impacts for LHV, which is also evident from the qualitative model that highlighted the positive relationship between road infrastructure (construction and maintenance) and the share of LHVs (Figure 1). As for normal trucks, fuel consumption is the major contributor that leads to the higher environmental impacts, followed by the lorry production. This can be seen in figures 13 to 16 in the annex that provides a view of the impacts from each life stage of a normal truck, with a help of a contribution tree, an analytical tool, that is part of the openLCA software.

Furthermore, results of Layer 3 suggest that increasing the share of LHVs in the road freight transport may be a better option only if the modal share of road transport stays constant or close to constant, i.e. the current share at 71.8%. Diesel consumption was the leading cause for higher impacts of normal trucks, which would further increase with the increased share of road transport. Even if the share of LHVs are increased, terrestrial ecotoxicity impacts due to high brake wear emissions, as well as land use impacts due to increased road use from LHVs remain high.

In the fourth layer, the results show that while an increase in the share of LHVs lead to reduced impacts, the increase in the market volume of freight transport end up negating the effects of introducing LHVs. The qualitative model described earlier in the study highlighted the positive connection between increase in freight transport and the other variables, such as fuel consumption, road, tracks and port infrastructure, and land use. Clearly, the burden on transport infrastructure and resources increases with increasing demand for freight transport. The key takeaway from the impact assessment of this layer was, however, that even if the share of LHVs and normal trucks do not increase, there will be increase in the environmental impacts from use of other modes of transport (railway and waterway in this case). It can, thus, be said that the eventual rebound effect diminishes the advantages of introducing LHVs on a large scale as a mode of freight transport.

Table 10: Overview of the outcome of the layers of the case-study.

	Layer 1	Layer 2	Layer 3	Layer 4
LHV	✓	✓	✕	✕
Normal truck	✕	✕	✕	✕

Table 10 summarises the outcome of this case study, which demonstrates that when a basic comparison between an LHV and normal truck is performed, clearly, LHV has an upper hand. But when considered for the entire freight transport, the environmental impacts of LHVs are similar to a normal truck, and hence, LHVs may pose to be an additional burden on the existing infrastructure.

While reducing the impact due to road use and maintenance may lead to in even lower environmental impacts for LHVs, reducing fuel consumption can result in lower environmental impact for normal trucks. It can be concluded that LHVs can be a good option in the future where the road infrastructure is equipped to cater to the growing road traffic and the continual increase in international trade.

11 Feedback & Contact

If you have other questions not addressed by this document, or should you need further clarifications on any of the points commented, then please contact us:

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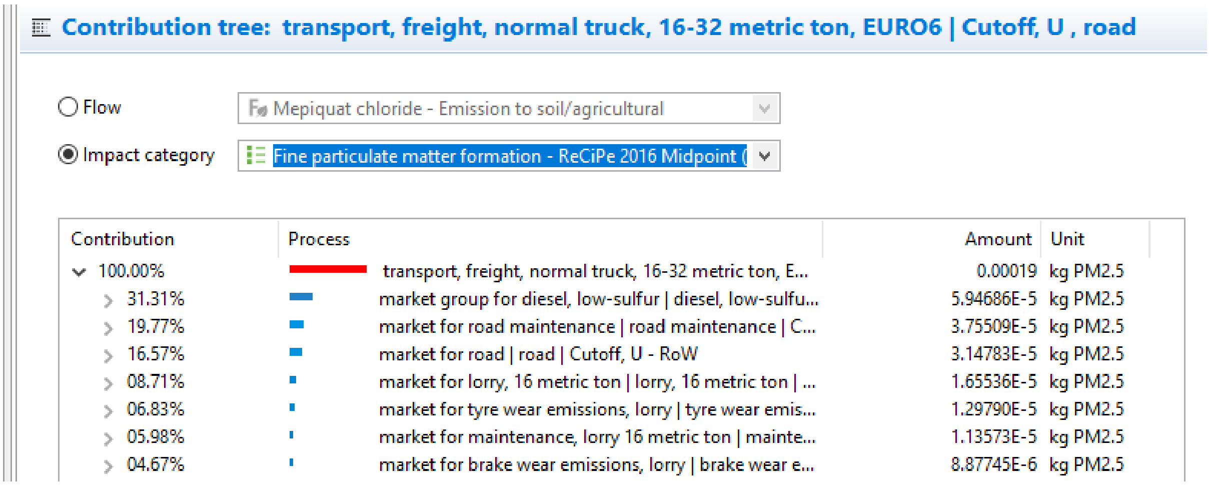
12 Annex



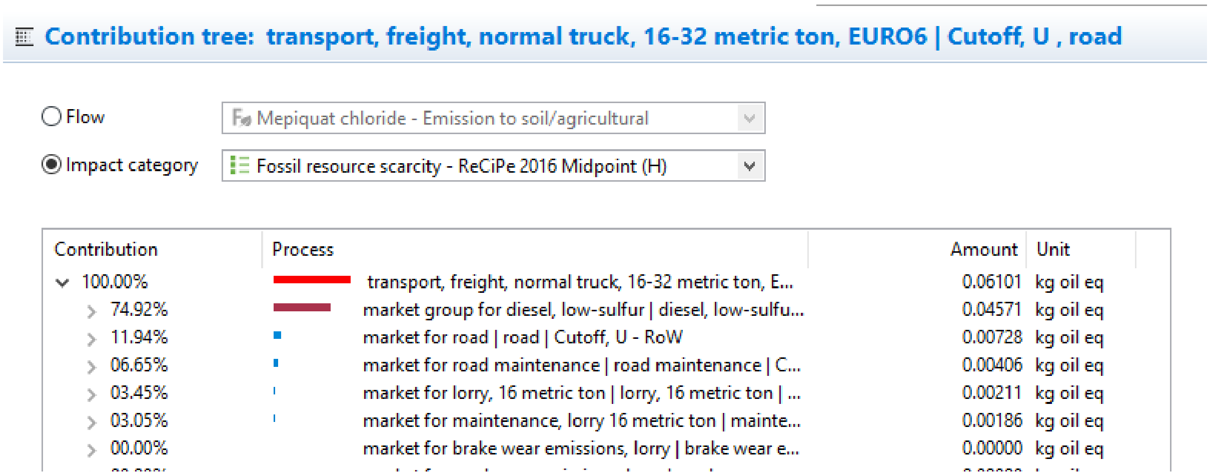
Contribution tree: transport, freight, normal truck, 16-32 metric ton, EURO6 | Cutoff, U , road

Flow: Mepiquat chloride - Emission to soil/agricultural

Impact category: Fine particulate matter formation - ReCiPe 2016 Midpoint (

Contribution	Process	Amount	Unit
100.00%	transport, freight, normal truck, 16-32 metric ton, E...	0.00019	kg PM2.5
31.31%	market group for diesel, low-sulfur | diesel, low-sulfu...	5.94686E-5	kg PM2.5
19.77%	market for road maintenance | road maintenance | C...	3.75509E-5	kg PM2.5
16.57%	market for road | road | Cutoff, U - RoW	3.14783E-5	kg PM2.5
08.71%	market for lorry, 16 metric ton | lorry, 16 metric ton | ...	1.65536E-5	kg PM2.5
06.83%	market for tyre wear emissions, lorry | tyre wear emis...	1.29790E-5	kg PM2.5
05.98%	market for maintenance, lorry 16 metric ton | mainte...	1.13573E-5	kg PM2.5
04.67%	market for brake wear emissions, lorry | brake wear e...	8.87745E-6	kg PM2.5

Figure 13: Contribution tree- Fine particulate matter formation



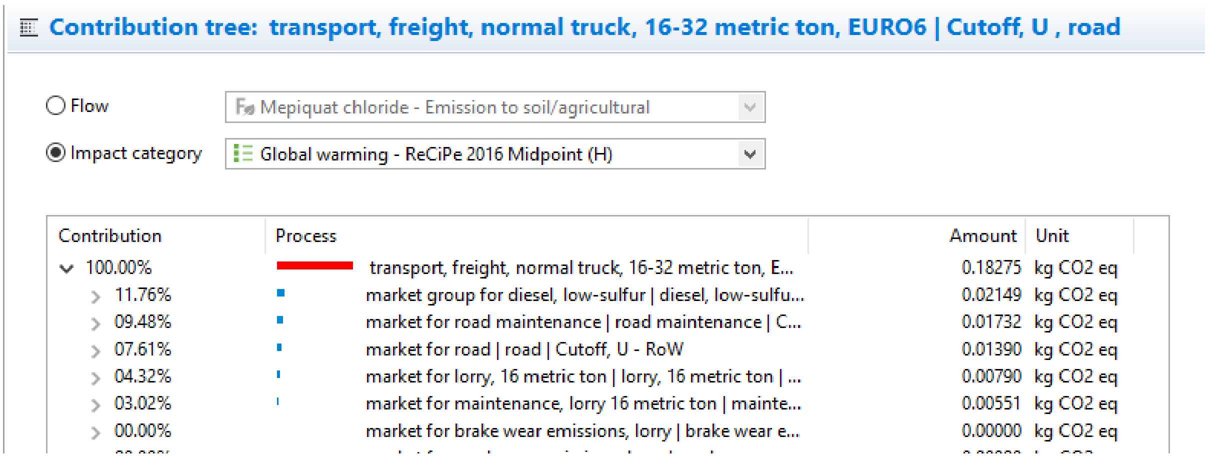
Contribution tree: transport, freight, normal truck, 16-32 metric ton, EURO6 | Cutoff, U , road

Flow: Mepiquat chloride - Emission to soil/agricultural

Impact category: Fossil resource scarcity - ReCiPe 2016 Midpoint (H)

Contribution	Process	Amount	Unit
100.00%	transport, freight, normal truck, 16-32 metric ton, E...	0.06101	kg oil eq
74.92%	market group for diesel, low-sulfur | diesel, low-sulfu...	0.04571	kg oil eq
11.94%	market for road | road | Cutoff, U - RoW	0.00728	kg oil eq
06.65%	market for road maintenance | road maintenance | C...	0.00406	kg oil eq
03.45%	market for lorry, 16 metric ton | lorry, 16 metric ton | ...	0.00211	kg oil eq
03.05%	market for maintenance, lorry 16 metric ton | mainte...	0.00186	kg oil eq
00.00%	market for brake wear emissions, lorry | brake wear e...	0.00000	kg oil eq

Figure 14: Contribution tree- Fossil resource scarcity



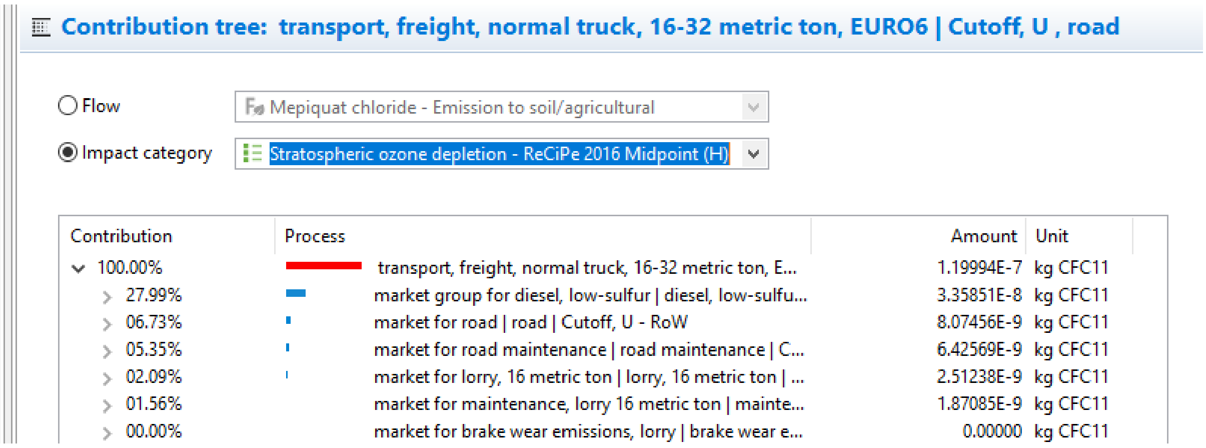
Contribution tree: transport, freight, normal truck, 16-32 metric ton, EURO6 | Cutoff, U , road

Flow: Mepiquat chloride - Emission to soil/agricultural

Impact category: Global warming - ReCiPe 2016 Midpoint (H)

Contribution	Process	Amount	Unit
100.00%	transport, freight, normal truck, 16-32 metric ton, E...	0.18275	kg CO2 eq
11.76%	market group for diesel, low-sulfur | diesel, low-sulfu...	0.02149	kg CO2 eq
09.48%	market for road maintenance | road maintenance | C...	0.01732	kg CO2 eq
07.61%	market for road | road | Cutoff, U - RoW	0.01390	kg CO2 eq
04.32%	market for lorry, 16 metric ton | lorry, 16 metric ton | ...	0.00790	kg CO2 eq
03.02%	market for maintenance, lorry 16 metric ton | mainte...	0.00551	kg CO2 eq
00.00%	market for brake wear emissions, lorry | brake wear e...	0.00000	kg CO2 eq

Figure 15: Contribution tree – Global warming



Contribution tree: transport, freight, normal truck, 16-32 metric ton, EURO6 | Cutoff, U , road

○ Flow: Mepiquat chloride - Emission to soil/agricultural

◉ Impact category: Stratospheric ozone depletion - ReCiPe 2016 Midpoint (H)

Contribution	Process	Amount	Unit
100.00%	transport, freight, normal truck, 16-32 metric ton, E...	1.19994E-7	kg CFC11
27.99%	market group for diesel, low-sulfur | diesel, low-sulfu...	3.35851E-8	kg CFC11
06.73%	market for road | road | Cutoff, U - RoW	8.07456E-9	kg CFC11
05.35%	market for road maintenance | road maintenance | C...	6.42569E-9	kg CFC11
02.09%	market for lorry, 16 metric ton | lorry, 16 metric ton | ...	2.51238E-9	kg CFC11
01.56%	market for maintenance, lorry 16 metric ton | mainte...	1.87085E-9	kg CFC11
00.00%	market for brake wear emissions, lorry | brake wear e...	0.00000	kg CFC11

Figure 16: Contribution tree – Stratospheric ozone depletion